Workshop Report: The Australian Coastal and Oceans Modelling and Observations Workshop (ACOMO 2012)

3-4th October 2012, Shine Dome, Australian Academy of Sciences, Canberra

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Executive Summary.

The first Australian Coastal and Oceans Modelling and Observations Workshop (ACOMO 2012) was held on the 3rd and 4th October 2012, at the Shine Dome, Australian Academy of Sciences, Canberra. The meeting brought together around 80 participants from 25 (including 3 international) organisations and was endorsed by the Oceans Policy Science Advisory Group (OPSAG) and led by the Integrated Marine Observing System (IMOS) on behalf of the national marine science community.

The aim of the meeting was to bring together the national observations and modelling community to work towards a national approach to ocean and coastal modelling, and strengthen links between the ocean observation and modelling.

The meeting was structured around 4 sessions on near-shore modelling and observations, regional/coastal modelling and observations, national/bluewater modelling and observations and next steps/emerging activities. Talks were invited, based on community level extended abstracts on the status and next steps in aspects of ocean and coastal observations and modelling (Appendix III). At the end of each session, a facilitated discussion session was held. The full agenda is in Appendix I.

Discussion sessions questions were:
- From a national perspective, what are the highest priority observations and datasets required by the modelling communities?
- Do we need to do more to foster collaboration within Australia between groups working at regional/coastal scales?
- What are the next steps for the use of models in observing system design?
- What are the potential/priority areas for future capacity/capability development?

Progress was made in key areas including an improved understanding of observational requirements into the shoreline and opportunities identified for improved connections between observations and models. Data access issues were identified; either the format, packaging and metadata requirements for IMOS data, or the need to bring together nationally consistent datasets through the AODN in partnership with federal and state partners. The potential for e-research activities so support observation and modelling activities was promoted.

In terms of concrete steps going forward, recommendations included:

1) **The development of the Australian Ocean Data Network**: the national observations and modelling community need to continue to sign up to making data available. This requires cultural changes in some areas, and guidance on priority datasets from the user community is needed.

2) **Better and Ongoing communications between modellers** would enable strategic modelling challenges to be identified and addressed, and open discussion and collaboration around areas such as model forcing and boundary conditions. This could involve a national community of practice in coastal modelling.
3) **Observing System Design**: has the potential to inform and support both observations and modelling; further discussion is needed on how to pursue this.

4) **A potential follow-up ACOMO workshop**: the potential timing and focus are up for discussion.

The Marine Virtual Laboratory (MARVL)\(^1\) was identified as a potential framework to pursue collaborative activities, as many modelling groups from Universities and Agencies around Australia are involved in the testing and development of the MARVL framework. Biogeochemical modelling could be a focus for a future ACOMO meeting. The IMOS Bio-optical working group and biogeochemical modellers have already met in Brisbane (11-12 December 2012) to discuss how to strengthen links between biogeochemical modelling and bio-optical observations. Connections to near-shore modelling and observations will be pursued through a special session at the Coasts and Ports conference in Sydney in September 2012\(^2\).

A number of other specific activities will be progressed, as identified in the actions and recommendations below.

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1. Summary of actions, questions and recommendations.

1.1. Nearshore observations and Modelling:

*Question:* Could some of the sea level products identified be made more broadly available? Would modellers find them useful?

*ACTION:* Convene an IMOS Session at Coasts and Ports 2013 to raise awareness of the role of collaborative activities in the coastal zone (IMOS Office/Ian Turner/Others?)

*Question:* Can IMOS/AODN help deliver the required datasets and quality control information for sediment transport modelling?

*ACTION:* Complete a list of priority datasets/products that the community would like to see made more broadly available (IMOS Office/ACOMO Attendees)

1.2. Regional and coastal observations and modelling

*Question:* Is a discussion needed on QC, flagging and metadata requirements for data assimilation?

*ACTION:* Develop a proposal (2 pages covering scope/potential work plan) for the formation of a coastal modelling user group/community of practice (John Middleton + others?).

- ROMS or coastal modelling as a whole?
- Physics and Biogeochemistry?
- Observational oceanographers as well as Modellers?
- A Workplan would need to be developed.

*Question:* There used to be an Australian Physical Oceanography Group that met at AMSA each year. Is there enough momentum/interest for this to be revitalised?

1.3. National/bluewater observations and Modelling

*Recommendation:* A coastally focussed CARS climatology supported by IMOS data should be explored in the future. An assessment of data requirements for a useful climatology would be needed.

*RECOMMENDATION:* Biogeochemical modellers are invited to meet with the IMOS Bio-optical working group to identify data requirements for data assimilation in biogeochemical models, and identify opportunities strengthen the connection between observations and modelling (Bio-optical working group/biogeochemical modellers).

*RECOMMENDATION:* Pursue approaches to interoperability of coastal model output through MARVL/US-IOOS

*Questions:*

- Can we recommend next steps in the observing system design space?
- Can we use models and observations together in observing system design, ie. Adapter Project, use of Gliders in adaptive sampling?
2. Introduction

IMOS Director, Tim Moltmann opened the workshop, and provided some background on the motivations for the workshop, and steps taken to date. The aim of the ACOMO workshop is to start taking an inclusive national approach to modelling and observations; and delivering to the broader community requirements. IMOS is taking the lead due to its strong connections with the marine and climate science community and stakeholders, and track record in fostering national collaborations. It is also important that a national approach to coastal modelling co-evolves with the development of the ocean observing system, and links between the two are strengthened for the benefit of both.

An inclusive national workshop of this scale has been some time in the planning; key steps included:

- IMOS Education Investment Fund (EIF) Planning Process, 2009
  - A Model-Data synthesis workshop held at Melbourne Airport in October 2009.
  - International Peer Reviews of Node Science and Implementation Plans provided consistent feedback that the development of a sustained observing system needed to be considered hand in hand with the development of modelling frameworks.
- National Coastal Observation System Workshop, August 2010
  - Held at Sydney Institute of Marine Sciences.
  - Sponsored by NSW-DECCW, IMOS and OPSAG
- Formation of OPSAG Coastal Observing System Working Group
  - Discussions on coastal modelling/observations workshop commenced October 2010
  - IMOS workshop proposal for ACOMO 2012 was approved by OPSAG in March 2012.

IMOS was funded as part of a package of research infrastructure capabilities, including a number aimed at information infrastructure (computing and storage resources); and the marine and climate community are well placed to make the most of these national resources. These include the Research Data Storage Initiative (RDSI)³, the National Computing Infrastructure (NCI)⁴, and National eResearch Collaboration Tools and Resources (NeCTAR)⁵.

Under NeCTAR, the Marine Virtual Laboratory (MARVL) has been funded to enable coastal ocean model runs to be set up quickly through choosing model type, grid and associated data (see extended abstract in appendix V). The MARVL system will be tested and benchmarked in regional model domains nationally. This national collaborative modelling activity is a good first step in taking a national inclusive approach to coastal modelling in Australia.

The Aims of the 2 day workshop included:

- Identifying priorities for improving access to data (via the Australian Ocean Data Network)
- Identifying gaps (in observations and modelling)
- Maximising new investments (such as MARVL as a platform for community level collaboration in modelling)

³ Research Data Storage Infrastructure (RDSI) http://rdsi.uq.edu.au
⁴ National Computing Infrastructure (NCI) http://nci.org.au
⁵ National eResearch Collaboration Tools and Resources (NeCTAR) http://www.nectar.org.au
- Improve coordination between the observing system and modelling communities, and between modelling groups/activities.

The scope of the workshop was intentionally focused on ocean to coastal scales and physics through to introducing biogeochemistry. There is potential to consider this the first of a series of ACOMO workshops that would have a subtly different focus each time; from Hydrodynamic towards ecosystem modelling, and developers/research applications to users/management applications.

Figure 1. A potential future trajectory of ACOMO workshops.
3. Near-shore modelling and observations

The session on near-shore modelling and observations included talks on the modelling and observations of sea level (including storm surges and tsunamis), waves, the littoral zone and coastal sediment transport. Talks focussed on the model frameworks being used, their status including errors and uncertainties, and how observations are used to support modelling activities.

3.1. Sea level, Storms and Tsunamis; Modelling and observations (Kathy McInnes et al.)

Kathy McInnes summarised the wide range of models which are used in the modelling of sea level; from large spatial scale, long timescale climate models for understanding anthropogenic climate change, to short timescale local models for assessing the impact of storms on a region or section of coastline.

Sea level research focuses largely on the attribution of sea level rise and its regional variations. Sea level rise attribution demands highly accurate observations of sea level, ocean temperature and salinity to determine the relative contributions of ocean thermal expansion and ice melt. Closing the sea level budget will allow observations to constrain future projections.

Storm surge research combines sea level rise scenarios with regional hydrodynamic modelling, reanalysis winds (with synthetic cyclones added), wave modelling and tidal regimes to give coastal inundation risk assessments.

Tsunami prediction is precluded by the unpredictability of earthquakes; and tsunami propagation is too fast for real-time dynamical modelling of the event. Therefore research is focussed on developing tsunami scenarios for different locations and magnitudes. When an earthquake occurs, the nearest scenario informs warnings, and observations are used to validate and improve the scenario information.

Datasets highlighted as important for sea level, storm surge and tsunami research included:

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<tr>
<th>Datasets</th>
<th>Sea Level</th>
<th>Storm Surges</th>
<th>Tsunamis</th>
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<tr>
<td>Argo Floats</td>
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<td>Altimeter SSH</td>
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<td>Gravity (GRACE)</td>
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<td>GPS Velocities</td>
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<td>Tide Gauges</td>
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<td>Bathymetry/Topography</td>
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<td>Wave data (waverider boys)</td>
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<td>Tsunameters (Dart boys)</td>
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<tr>
<td>Climate Model output.</td>
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<td>Atmospheric Reanalysis data</td>
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<td>Extreme events database</td>
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Some key observations were highlighted as either unavailable or only accessible from multiple sources in different formats across federal/state/local government agencies and the private sector. These include tide gauge data, and high resolution bathymetry/topography data.
Continuity of data-streams was highlighted as critical for understanding sea level changes. Key observational gaps include: observations in the deep ocean for understanding sea level rise, and high resolution bathymetry and wave data; particularly in near-shore regions for understanding the propagation of tsunami’s and storm surges. Tide gauges can be used for detecting the coastal impact of a Tsunami. However, existing climate quality tide gauges need to be upgraded to 1-minute sampling frequency to be useful in observing tsunamis. They can be useful in early warning if located strategically; eg. on offshore islands.

Products produced include:

Sea level rise:
- Global mean sea level rise (GMSL)
- Altimeter Products (i.e. Sea level anomaly and geostrophic currents).
- Ocean thermal expansion and heat content products
- Seasonal sea level predictions (soon to be delivered by BOM).

Storm Surges
- Australian coastal storm surge risk assessments

Tsunami’s
- Tsunami scenario database.

**Question: Could some of the sea level products identified be made more broadly available? Would modellers find them useful?**

### 3.2. Wave and near-shore modelling and observations (Bill Pierson et al.)

Bill Peirson described the applications of wave modelling, which included 3 primary applications; Climate sciences, requiring an understanding of how wave climate changes and varies with broader climate forcing; to inform design of coastal and offshore structures (primary focus on extreme events); and for operational day to day shipping/port activities. The challenges of working in the near-shore zone along Australia’s long coastline and across Federal/State and Local jurisdictions was emphasised, and presented challenges for regional integration.

Near shore wave modelling approaches, status and current challenges were highlighted; particularly the complex relationship between waves and currents, and the role of wind in both of these. Generally the direct wind/wave relationship dominates wave formation on shorter timescales and the energy is transferred into driving currents on longer timescales. Therefore, wave/current couplings are only modelled when necessary.

Challenges around the nesting of models were identified; generally models are nested from large scale to small scale (inwards), but the benefits of nesting outwards (i.e. start with local observations and extrapolate away) was advocated. Data is currently used for calibration/validation of models. Data assimilation was identified as complex in wave modelling, as errors in winds were uncoupled from wave processes. This is an active area of research.
Opportunities for strengthened integration between IMOS and near-shore observations/modelling were identified; and a request for more of the IMOS data to be delivered in real time. HF Radar data in particular has the potential be integrated into near-shore activities.

A lack of wave data equals significant uncertainty in our understanding of wave processes. Significant uncertainty means large engineering design safety factors need to be built into coastal/offshore structures. This means a large increase in costs.

In the discussion that followed, it was suggested that there is an opportunity engage the coastal engineering community in the development of the coastal observing system, ensuring that accurate information is delivered. One opportunity to engage coastal engineers and planners will be the Coasts and Ports Conference to be held in Sydney in September 2013.

**ACTION:** Convene an IMOS Session at Coasts and Ports 2013 to raise awareness of the role of collaborative activities in the coastal zone (IMOS Office/Ian Turner/Others)

### 3.3. Littoral Zone Modelling (Ian Turner et al.)

Ian Turner described the societal motivations for understanding processes in the littoral zone; and identified the dominant processes the timescales by which coastal erosion events evolve, as this influences the nature of the observations and modelling that are needed.

Three types of Littoral Zone modelling were described using 3 example models:

- Now-casting of surf-zone and beach conditions (Process Based; e.g. XBeach)
- Predicting “design event” storm erosion (Empirical/semi-process based; e.g. SBeach)
- Long term forecasting of shoreline variability and change (Behavioural; e.g. ShoreFor)

Gaining an understanding of variability and change in the coastline and it’s drivers can be a challenge, as short term extreme (storm) events can eclipse long term trends and variability. Storm driven erosion events generally happen rapidly and can wipe out a beach within a few hours-days; they are then followed by a slow recovery. The timescales of erosion/recovery processes have an influence on the approach taken to observing and modelling littoral zone processes. The open source XBeach model is the state of the art in this space; however, long term forecasting of coastlines is still a significant challenge as the noise (i.e. storm events) eclipses the (climate change/variability) signal. Hence behavioural modelling approaches are used on longer timescales.

There are very limited routine observations of the coastline. One exception is a survey dataset at Narabeen/Collaroy in New South Wales, where cross beach transects have been occupied since 1976. Since 2004, RTK-GPS (Real-time Kinematics - Global Positioning System) Quad bike surveys and an Argus coastal image station consisting of 5 cameras have been added. The Narabeen/Collaroy site is one of maybe 10 long term sites globally, and the only one in Australia; it is difficult to extrapolate these observations nationally. The formation of an Australian National Coastline Observatory (ANCO) was proposed, and advice was sought on how this would connect to
IMOS/TERN activities. An ARC funded ANCO pilot project is currently being established along the NSW Coast.

3.4. Sediment Transport Modelling (Nugzar Margvaleshvilli and Cedric Griffiths)

Nugzar Margvaleshvilli summarised the applications of sediment transport modelling in coastal erosion and coastal planning, water quality (e.g. on the GBR) and contaminant transport. Modelling sediment characteristics and behaviour remains a challenge due to the wide range of sediment properties, processes such as flocculation, and patchy observations for validation. It was noted that it can take a considerable amount of time to set up a pilot sediment model due to the effort involved in collecting underpinning data, and also issues around data quality. Two models were described; Mecosed and Sedsim.

Question: Can IMOS/AODN help deliver the required datasets and quality control information for sediment transport modelling? Perhaps MARVL could be applied in this space in the future?

Mecosed is a 3D coastal sediment transport model which is part of the CSIRO Environmental Modelling Suite, which includes hydrodynamic, biogeochemical and wave models (See Jones et. al., appendix III); as such, it is tailored to meet biogeochemical model requirements with coastal and shelf scale applications. It performs best with fine sediments, and runs from near real-time to annual timescales.

Observational needs include:

- Initialisation data: Sediment types; generally determined from the Marine Sediments (MARS) database, curated by Geoscience Australia. However, the data coverage in MARS is uneven and incomplete; coastal data is still scattered across institutions.
- Forcing data: provided by hydrodynamic/wave models
- Input from catchments: based on NRT catchment models and observations of Total Suspended Solids (TSS); either observed directly or derived from turbidity.
- Assimilation data: suspended and benthic sediment data to assimilate into models at adequate assimilation frequency and resolution (e.g. remote sensing, gliders, moorings, monthly monitoring, sensor networks).
- Data assimilation is being trialled in coastal sediment models, but is not yet run routinely. The main challenge is around the quality of sediment data.

Cedric Griffiths then described SedSim, which is a 2D model used to develop longer term predictions of future coastal changes in relation to sediment transport; the model includes processes such as: Sea level rise and fluctuations, and carbonate growth. Many of these processes are controlled by “fuzzy” rules.
3.5. DISCUSSION: From a National perspective, what are the highest priority observations and datasets required by the modelling communities? (led by Tim Moltmann).

There were two consistent themes across the session:

- Questions about how to integrate near shore activities into the broader observing system activities (i.e. IMOS)
- The need for consistent national datasets that are currently scattered across federal/state/local agencies and the private sector.

Steps towards the integration of coastal/nearshore activities in IMOS has been achieved through co-investment by state governments into IMOS, to ensure that state level observing needs are met, while leveraging the broader observing system resources and capability. Examples are WA State co-investment on the Northwest Shelf (primarily Moorings/Gliders in the Kimberly/Pilbara regions, respectively), and Queensland co-investment to upgrade some IMOS moorings to real-time and run gliders up the GBR Lagoon. In addition, the Australian Ocean Data Network (AODN) provides an opportunity to make coastal and near-shore data available from multiple providers at one point of access; this will enable gaps and overlaps to be identified and priorities for future observations to be set. Initial focus of the AODN has been in focussing on accessing data from the major federal agencies; but has recently developed a regional portal for Western Australia, where data can be accessed from Federal and State agencies, Universities and the private sector.

IMOS Observations are limited in the near-shore zone, and most routine observations that were identified in the session are taken by the Bureau of Meteorology (BOM), Geoscience Australia (GA) and State/Local governments. There is a clear role for the Australian Ocean Data Network to enable these datasets to be brought together in a single point of access. Gaps in current observational capability were also identified. In addition, it was noted that State Governments find the cost of storing data prohibitive; the substantial investment in data storage through the Research Data Storage Infrastructure (RDSI) may provide a solution. The National Plan for Environmental Information (NPEI) also provides motivations for bringing national datasets together.
### National Data Requirements:

<table>
<thead>
<tr>
<th>Platform/Dataset</th>
<th>Application</th>
<th>Location of data</th>
<th>Status/Availability</th>
</tr>
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<tbody>
<tr>
<td>Near-shore wave data (waverider buoys)</td>
<td>Storm surge, Wave modelling</td>
<td>Bureau of Meteorology (BOM), State Government, Private Sector.</td>
<td>Not available in one place/format.</td>
</tr>
<tr>
<td>Tide gauges</td>
<td>Tsunami/Storm surge modelling</td>
<td>BOM, State Government</td>
<td>Not available in one place/format.</td>
</tr>
<tr>
<td>Topography/Bathymetry Data</td>
<td>Tsunami, Storm Surge, Littoral Zone, Wave Modelling</td>
<td>BOM, State Government, RAN, Geoscience Australia (GA), State and Local government</td>
<td>Not available in one place/format. Particularly need high resolution data (10m horizontal, 10cm vertical resolution)</td>
</tr>
<tr>
<td>LIDAR (nearshore bathymetry)</td>
<td>Storm Surge, wave modelling</td>
<td>Geoscience Australia (GA), State and Local government</td>
<td>Not available in one place/format.</td>
</tr>
<tr>
<td>Sediment type data</td>
<td>Sediment transport modelling</td>
<td>GA, State and Local government</td>
<td>MARS (below) incomplete. Data not available in one place/format.</td>
</tr>
<tr>
<td>Bottom pressure data?</td>
<td></td>
<td>Numerous.</td>
<td>Get pressure records from moorings on common datum.</td>
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### National Data Products:

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<thead>
<tr>
<th>Product</th>
<th>Description</th>
<th>Location</th>
</tr>
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<tbody>
<tr>
<td>Marine Sediments Database (MARS)</td>
<td>Database of observations marine sediment types around Australia. Gridded product also produced</td>
<td>GA</td>
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**ACTION:** Complete a list of priority datasets/products that the community would like to see made more broadly available (IMOS Office/ACOMO Attendees)
4. Regional/Coastal Modelling and Observations.

Regional and coastal modelling can be split into two types in Australia; near real-time hydrodynamic modelling based on the Sparse Hydrodynamic Ocean Code (SHOC) carried out by CSIRO and partners with the aim of developing coastal ocean forecasts and scenarios; and process based modelling activities primarily carried out by University groups using the Regional Ocean Model (ROMS) open source code. While the modelling activities have different aims, there is much that can be learnt from each other.

4.1. Invited Talk: Integrated Modelling and Data Assimilation using ROMS with a Coastal Ocean Observing System for the US Middle Atlantic Bight (John Wilkin et al., Rutgers University)

John Wilkin described the application of ROMS for ocean forecasting in the Middle Atlantic Bight of the US east coast. The real-time system, named ESPreSSO (Experimental System for Predicting Shelf and Slope Optics), draws on the Mid Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) observations, a regional alliance of the US Integrated Ocean Observing System (IOOS). The modelling and observation system is set up as an integrated package, including quantitative skill assessment and observing system design. Data assimilation based on variability in 4 dimensions (4DVar) is used; ROMS has 3 versions of 4DVar data assimilation packages which can be incorporated into ROMS models. For the ESPreSSO modelling system, satellite altimeter sea surface height, satellite sea surface temperature, HF Radar (CODAR) and temperature and salinity are assimilated. Recovered coastal altimetry is also used. It was noted that bias correction of prognostic fields was crucial to achieve improvement in data assimilation; particularly correction to Mean Sea Level Height. It was also noted that biases in the model providing the boundary conditions need to be assessed and corrected. With Seven models run in real time, predicting circulation in the Middle Atlantic Bight, multi-model skill assessments have been carried out.

The challenges experienced with assimilating data-streams was discussed following the talk; notably, the applications of altimetry data in the coastal zone, and using HF Radar surface currents to inform surface winds.

4.2. ROMS Modelling in Australia: status and aspirations (John Middleton et al.).

John Middleton summarised the groups, projects and applications of ROMS in Australia, which totalled 11 known footprints in Western Australia, South Australia and New South Wales. It was acknowledged that modelling activities are quite disjointed with no overall coordination. There is plenty of opportunity to collaborate and contribute to each other’s work, in areas such as providing backward/upstream boundary conditions, testing initialisation/forcing fields and building capability.

Generic challenges identified were:

- Meteorological forcing: forcing fields are not produced at the appropriate resolution for coastal models. In addition it was suggested that data is not archived at the resolution at which it is measured, and there is a charge to access it. Is this something BOM can help with?
- Initial conditions: CARS has not been updated since 2009 due to lack of funding: is this something that IMOS can help with?
- Skill gaps: NPZ modelling, data assimilation, model nesting.

Aspirations included:
- UNSW: Assessing predictability of the East Australian Current using 4DVar.
- SARDI/CSIRO: Development of a model footprint in the Great Australia Bight.
- SARDI/MISA: Modelling in the Spencer Gulf.

4.3. Observations Uptake: Present Status and way forward (Craig Steinberg et al.)

Craig Steinberg introduced the focus and activities of the IMOS coastal Nodes and Facilities, including examples of how IMOS observations were being used to support modelling activities around Australia. Parallels were also made with observing activities in New Zealand. Examples included:
- eReefs, QLD; prototype 4km model. Mooring data are currently being used for validation, and will be assimilated in the future. Local downscaling to reef scale is being trialed at Heron Island; the model is validated using sensor networks data.
- EAC ROMS Modelling, NSW; moorings data is used for validating cross shelf scale dynamics.
- Adapter Project, WA; An internal tide modelling and observations experiment on the Northwest Shelf, exploring how to filter glider data for optimal use in data assimilation.

IMOS data-streams are currently being used for calibration and validation of coastal models, but aren’t routinely used in data assimilation. Indeed, data assimilation in coastal models is being tested, but is not yet routine in Australian coastal models as many models are still in the development stages.
4.4. INVITED: The data assimilation component of the real time ocean forecast system implemented off of Oregon, US West Coast (Alex Kurapov et al.).

Alex Kurapov described the ocean forecasting model developed for the Oregon coast. Similar to the modelling system for the Middle Atlantic Bight region described by John Wilkin, a ROMS based model has been combined with 4DVar assimilation of observations from the US-IOOS Regional Alliance (NANOOS) to provide 3 days forecasts. Data assimilated includes altimetry, HF radar, and hourly GOES satellite SST. While this is a University-run, non-operational system, NOAA uses forecasts from this system for operational purposes, e.g. running oil spill models, monitoring drifting objects (i.e. Japan tsunami debris). Regional fishermen are also providing feedback. The most recent version of the model is 2km horizontal resolution, and includes Columbia River freshwater discharge. The main focus of the presentation was the approaches to data assimilation and validation. Biogeochemical forecasting had been trialled, but the depth of the mixed layer caused spurious errors in oxygen values.

4.5. Australian Coastal and Information Systems: assisting management decision making (Emlyn Jones et al.).

Emlyn Jones described the history of coastal modelling in CSIRO and AIMS, followed by an introduction to the CSIRO Environmental Modelling System (EMS) which has a focus on near real time modelling and forecasting and includes:

- A core hydrodynamic model (SHOC)
- A multilayer sediment model (MECSED: see section 2.4).
- A biogeochemical model
- A wave model (SWAN).
- A statistical toolbox
- Data assimilation capabilities

Current footprints include:

- Southeast Tasmania (SETas, plus Derwent Estuary, Huon Estuary, Huon/D’Entrecasteau Channel)
- Southeast Queensland (Moreton Bay; Healthy Waterways project)
- Great Barrier Reef (eReefs Project)

Observations are currently mostly used for calibration and validation in hindcast and near real time mode. Moorings and gliders have been assimilated on a trial basis; gliders help correct spatial structure; particularly in areas with strong horizontal gradients, such as Estuaries; and vertical structure (e.g. mixed layer depth). For near real time coastal applications, low coast networks of sensors were advocated, such as the TasMAN network of low coast nodes used in the Derwent Estuary. They can be deployed at relatively high spatial density, delivering real time data. The volume of data and near real time delivery demands mean that automated approaches to data quality assessment are needed. Automated nutrient observations are also being trialed for validating the model in southeast Tasmania.
The hydrodynamic model has also been used to inform observing system design, through the development of a Gaussian process regression model to support sensor placement on mooring strings, e.g. to capture variability in mixed layer depth.

A key challenge, particularly in the eReefs project on the GBR, is the ability to parameterise sub-grid scale processes, e.g. around the reef structures.

The future vision would be to evolve the EMS into a national coastal information system using a ribbon model for the Australian shelf, two-way nesting and data assimilation. Such a model could provide the foundation to investigate marine carbon budgets and fluxes (Blue Carbon).

**Question: Is a discussion needed on QC, flagging and metadata requirements for data assimilation?**

### 4.6 National Plan for Environmental Information (NPEI): pilot project (Greg Stuart).

The aims of the NPEI are to enhance discovery and integration of and access to environmental information through web services, supported by a metadata catalogue. The eReefs project referred to in section 3.5, is a pilot project of the NPEI. The project is end user driven with a phased delivery. Phase 1 will focus on a test environment (portal), report card, water quality “dashboard” and hydrodynamic modelling. It has now been confirmed that the AODN source code will underpin the eReefs information system.

### 4.7 DISCUSSION: Do we need to do more to foster collaboration within Australia between groups working at regional/coastal scales? (led by John Gunn).

Following on from the talks in this session, it was noted that there was mutual benefits to coastal modellers working together more closely. Following the talk on ROMS modelling in Australia, it was recommended that ROMS modellers in Australia could benefit from closer collaboration and coordination; in addition, there is plenty to be gained from modellers in universities (mostly using ROMS) and agencies such as CSIRO, BOM and AIMS to work more closely together. For instance, the university community embarks on research and development work which could be valuable to modelling activities in federal agencies; similarly capability in federal agencies (often driven by management needs) in biogeochemical modelling, near real time systems, data assimilation and automated QC could benefit the (R&D focussed) university modelling activities.

For ocean observations, IMOS is an example of the benefits that can arise from taking an inclusive community approach. It has taken time (and investment) for IMOS to galvanise the community. A first step would be a community of practice in coastal ocean modelling.

Two funded community activities could be a catalyst for a community of practice: The Marine Virtual Laboratory (see appendix V) and the CSIRO Coastal Carbon Cluster, a collaborative activity led
by the University of Technology, Sydney and the University of Western Australia. It was recommended that physics and biogeochemical modellers should be included and there would also be benefit in bringing observational oceanographers and modellers together.

It was noted that while there are communities of practice in the US, they are generally model specific (e.g. ROMS, HYCOM). Recently through US-IOOS a modelling “Testbed” project has been established. The Testbed will serve as connect the modelling activities and requirements of the federal operational and research communities and allow sharing of numerical models, observations and software tools. A cyber infrastructure component will provide tools and techniques to enable model-model and model-data comparison as well as promoting and supporting community standard data formats. The CI allows models and data to be accessed from a distributed repository via web services, and provides tools for quantitative analysis and visualization.

**ACTION:** Develop a proposal (2 pages) for the formation of a coastal modelling user group/community of practice (John Middleton + others?).
- ROMS or coastal modelling as a whole?
- Physics and Biogeochemistry?
- Observationalists as well as Modellers?
- Workplan?

**Question:** There used to be an Australian Physical Oceanography Group that met at AMSA each year. Is there enough momentum/interest for this to be revitalised?

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5. National/Bluewater Observations and Modelling

This session covered observation and modelling activities at a national and global level, and particularly how they support coastal modelling.

5.1. BlueLINK: Status, challenges, and future (Gary Brassington).

Gary Brassington summarised the focus and capabilities of the CSIRO/BOM BlueLINK Ocean Forecasting program; in its 3rd iteration, BlueLINK 3 includes a move to global 1/10 degree resolution and an increasing focus on moving into the coasts and littoral zone; particularly in support of Navy activities (details of the model activities, setup and performance are included in the extended abstract in appendix IV).

Observational requirements for global modelling and ocean forecasting has been the focus of a number of international activities in recent years; particularly through the Global Ocean Data Assimilation Experiment (GODAE) and its successor, GODAE Oceanview.

GODAE –class model systems globally show similar performance, and continue to make improvements. All data assimilating models are dependent on remote sensing data, and the calibration/validation of satellite data-streams is seen as critical. Further optimisation and gains can be made in:

- Data Assimilation (4DVar, Ensemble Kalman Filtering, and Initialisation)
- Observations (Operationalisation/reliability of datastreams, wide swath altimetry)

In general, there are no redundant observations in the global ocean observing system; with up to 4 altimeters and multi-sensor satellite sea surface temperature reducing uncertainties in models. In particular, 4 altimeters in real time are needed to achieve a similar accuracy as 2 altimeters in delayed mode (hindcasting). In addition, the in situ observing system under-samples the mesoscale ocean.

Requirements for bringing datastreams into the data assimilation system include:

- Temporal/spatial coverage: either homogeneous or optimised/adaptive.
- Error estimations and quality control (documented with the data using metadata standards, i.e. Argo, Group for High Resolution Sea Surface Temperature (GHRSST)).

The steps for implementation of new data-streams into the system take around 6 months, including data evaluation and implementation, quality control, parallel research hindcasts and operational trials; it was asked whether IMOS can help to minimise these; particularly through the provision of the required error estimations, quality control and metadata.

Question: Is a discussion needed on QC, flagging and metadata requirements for data assimilation? (again)

Specific data-stream issues and requirements were identified as:
**Satellite Altimetry:** There are concerns about the maintenance of altimetry coverage, with multiple new platforms coming online, and the effort that will be required to bring them into the data assimilation system. Efforts in applying altimetry in the coastal space are also showing some promise.

**Satellite sea surface temperature (SST):** As with altimetry, there are concerns about the maintenance of satellite coverage; for both microwave and infrared (AVHRR) data. Geostationary satellite data is a high priority for the coastal zone (delivered through weather forecasting satellites). The maintenance of calibration and validation activities and optimisation of quality control was highlighted, although this is currently well managed internationally through the GHRSSST project.

**HF-Radar:** Is not yet assimilated, but delayed mode (quality controlled) products and standard formats were identified as being useful for data assimilation experiments, and near real time QC would be needed for the data to be used operationally. Error estimates, both observation error and representation error would also be needed.

**Ocean Gliders:** An international data centre for glider data was recommended, with data being delivered to common standards and in common formats (similar to Argo data). Error estimation and real time quality control are also needed for assimilation and initialisation of forecasts. There is currently no active international coordination of glider deployment and data-streams. However, the EU/US/Aus marine data management project ODIP (Ocean Data Interoperability Platform) started in October and had kickoff meetings in London (19th November) and San Francisco (6th December). The outcomes of these meetings highlighted glider data management strategy as a potential focus activity.

For littoral zone modelling, requirements include high resolution bathymetry, directional wave spectra (observed and modelled), sea level, winds and coastal currents (see further discussion in section 2).

In summary, Bluelink has developed a range of capability in support of ocean forecasting, and to date, a large emphasis has been on the open ocean. With increasing focus on coastal applications, there are opportunities to collaborate to improve modelling in the coastal zone; multiple model frameworks will support research and development in this space, and the recently funded Marine Virtual Laboratory (MARVL: abstract in appendix V) will help improve links and interoperability between models. Specific activities that could improve the BlueLINK reanalysis (BRAN) and forecasting (OceanMaps) in the coastal zone include:

- Improving initial and boundary conditions
- The development of coastal observation products (delayed mode and real time, with associated error estimates).
- Coastal model evaluation and comparison
- Development of data assimilation capability into coastal models.
5.2. Key Bluewater in situ Observations: applications to modelling (Ken Ridgway)

Ken Ridgway began by noting that the observational requirements and modelling connections for open ocean physics are generally mature and well defined; key components of the Global Ocean Observing System (GOOS) were outlined, followed by a focus on how bluewater observations were being implemented in Australia (largely under IMOS), such as Argo, XBT networks, repeat hydrography and deepwater moorings; Biogeochemical/biological observations were also described (mostly from ships of opportunity) including underway biogeochemistry, the continuous plankton recorder and bioacoustics.

The global ocean observing system underpins the CSIRO Atlas of Regional Seas (CARS), which is used to initialise models (both global and coastal). CARS has increased in resolution since 2000 and is now 0.5 degree horizontal resolution globally. It has benefited from the broadscale coverage delivered by Argo, which has improved representation of mesoscale structures such as frontal zones in the Southern Ocean.

Recommendation: The feasibility of a coastally focussed CARS supported by IMOS data should be explored in the future. An assessment of data requirements for a useful climatology would be needed.

Air sea fluxes data was highlighted as critical for climate science, and parameterisation of climate model; yet, differences between global flux products can be as large as the mean fields, with the largest uncertainties in the Southern Ocean. The SOOP Air Sea fluxes, and Southern Ocean Fluxes Station data have vastly increased data coverage spatially and temporally, and will deliver into these products.

It was noted that there is an increasing need for real-time delivery of data, in support of now-casting and forecasting; this is delivered by Argo and XBT data; however, there are large gaps in the Banda Sea, Gulf of Carpentaria and Coral Seas, as well as in the Southern Ocean sea-ice zone.

Recommendations included:

- Maintain current networks at existing levels
- Extend Argo and gliders into the deep ocean
- Expand coverage of biological sampling
- Include new sensors on Argo floats
- Explore developing technologies for biological observations
- Ensure observing programs are coordinated internationally
- Expand sustainable systems at choke points.

Observing System Design (Andreas Schiller and Peter Oke).

Andreas Schiller described recent progress and further opportunities for using models in observing system design.
Recent activities include a NSW IMOS study to determine the placement of observations along the NSW coast; and an “observation footprint” study for the network of IMOS National Reference Stations, where the footprint of an observation for different parameters (sea surface temperature, sea surface height, velocity) was assessed on intra-seasonal and inter-annual timescales. The benefit of the “footprint” approach is it gives insights into the scales of variability in the ocean.

Potential areas of observing system design research include:

1) Extending a Footprint study to multiple models, spatial and temporal scales, more variables, covariances between variables, and the subsurface ocean
2) Regional coastal observing system experiments (OSEs) to assess the impact of IMOS data on regional models
3) Observing System Simulation Experiments (OSSEs) by assimilation of “synthetic observations” extracted from one model (i.e. a ROMS model) into another (i.e. SHOC). However, OSSE’s are considered to be “doomed to succeed”.
4) Routine computation of assimilation diagnostics to quantify the impact of observations in assimilating model runs
5) Adaptive sampling to support operational systems (e.g. OceanMAPS, eReefs).

The discussions that followed focussed on the need to look at observing system design on different timescales, from synoptic to decadal.

5.3. Remote Sensing: Observing a big country (David Griffin and Edward King)

David Griffin gave a summary of remote sensing data-streams, and what they provide to modelling with the 3 main products being sea surface temperature, sea surface height, and ocean colour. New and emerging satellite products are Gravity (GRACE) and Salinity (SMOS).

Remote sensing data are the principle means of making models track reality; particularly mesoscale features). However, the oceanography has to be carefully teased from the raw satellite data, and calibrated using in situ observations.

While the Australian modelling community rely on satellite data-streams, Australia does not put satellites into space. The Australian marine science community typically contributes in two ways:

- The collection and delivery of calibration data.
- Participation in mission specific science teams.

Biogeochemical Modelling and data assimilation: status in Australia (Richard Matear et al.)

Richard Matear summarised the drivers and approaches to Biogeochemical modelling, which is being used to understand carbon-climate feedbacks, ocean acidification and de-oxygenation, and carbon accounting. The Australian global biogeochemical model developed at CSIRO is the World Ocean Model with Biogeochemistry and Trophic-dynamics (WOMBAT). WOMBAT is now tested as part of BlueLINK and also as part of the Australian Community Climate and Earth System Simulator (ACCESS) model. WOMBAT components include Nitrate, Phytoplankton, Zooplankton and Detritus. It also has an iron cycle and carbon cycle (organic and inorganic). Thermocline nitrate is taken from
observations, and mid layer depth from either observations or models. Downscaling activities are being undertaken; nesting down to shelf scale (i.e. e-Reefs) and then to the scale of individual reefs.

Errors that arise in model biogeochemistry highlight where biogeochemistry could improve the parameterisation of ocean physics. For instance, WOMBAT overestimates phytoplankton due to too much recycling of nutrients caused by over-mixing of the water column.

Biogeochemical data assimilation is being trialled in Australia, primarily through the assimilation of satellite ocean colour. However, the assimilation of biogeochemical data can bring some new challenges. For instances, there are new sources of error and uncertainty in biogeochemistry-while physics has some nice governing equations, biogeochemistry relies on empirical relationships. Relationships can also be non-linear, and many traditional approaches rely on a quasi-linear model. In addition, biogeochemical observations are sparse in time and space; and in many cases, what is observed is not necessarily what is explicitly modelled.

Internationally, coordination and benchmarking of biogeochemical modelling and data assimilation is being progressed through GODAE Oceanview. Activities include:

- Exploiting the GODAE Physical State Estimation Products by coupling to Biogeochemical models.
- The development of biogeochemical data assimilation methodology and comparison
- Observing System design (e.g. observing strategy for quantifying Southern Ocean CO2 uptake).

Two key challenges were identified in adding biogeochemistry into data assimilation models; firstly, spurious vertical processes can be introduced when nudging the ocean state physics towards observations causing artificial mixing across the thermocline, and hence nutrient fluxes into the surface ocean; secondly, effort needs to be focussed on determining how much information can be gleaned from what we can commonly measure; e.g. a satellite can measure ocean colour, when what is required are estimates of rate processes; e.g. Primary Production, Secondary Production, CO2 fluxes. Research efforts are also focussed around and the assimilation of raw irradiance data (where error estimates can be quantified), as opposed to derived estimates such as chlorophyll a concentrations.

In the discussion that followed, it was noted that in the coastal ocean, a focus on prioritising observational requirements and spatial and temporal scales is also needed. Such a discussion could be coordinated by connecting biogeochemical modellers to the Bio-optical Working Group to explore issues such as:

- Vertical resolution (in observations and models)
- Deriving rate processes (i.e. rate of Primary Production) from observations, e.g. Pulsed fluorometers
- Capabilities of optical sensors including newer optical nutrient sensors.
- The role of sediment traps for determining the carbon budget and benthic/pelagic coupling.
Roger Proctor provided a summary of the IMOS and Australian Ocean Data Network Data Network (AODN) Portals, including a summary of the infrastructure, standards behind the portal, and an update on progress made with building partnerships, data available and portal functionality.

Particular developments of interest to the modelling community are:

- The ability to provide aggregations of commonly used data bundles, in both space and time
  - E.g. Argo basin scale datasets, XBT transects as a dataset, yearly bundles.
- The delivery of model datasets on the AODN.
- Machine searching interface, Ramadda provides a web query service for IMOS and AODN Data, which is being used by other external services such as the Marine Virtual Laboratory.
- Development of an interactive data aggregator tool for gridded data such as satellite remote sensing, gridded products, and model output (to be made available by Christmas).

The IMOS portal now contains over 2 million data files, 30TB of data, and around 2000 metadata records. For the AODN, this scales up to ~11000 metadata records, 50% of which have some data attached to them.

In the discussion that followed, concerns were raised about making model data available, and how the broader user community might use or interpret it in ways other than those intended. It was recommended that only model runs are made available with a peer reviewed publication associated which describes their intended use, limitations and uncertainties.

**5.5. DISCUSSION: What are the next steps for the use of models in observing system design? (led by Neville Smith).**

While the focus of the preceding session was national bluewater modelling and observations, it was noted that other sessions provide important context; a number of questions were posed for discussion:

1. For ocean modelling, re-analysis and prediction (BLUElink, Oke/Schiller, Matear) 'infrastructure': Are we yet at the point where we are comfortable that BLUELink and related models/systems are mature enough to provide the best pathway for integrating and getting value from data? That is, being seen as an integral part of the IMOS fabric.
2. For the observing system (Ridgway), one conclusion was that we should "Maintain networks at current levels", but then look for a range of enhancements. Are we satisfied there is evidence to support this conclusion, or is this simply an output of the culture of never ever conceding territory that has been hard won?

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3. Oke/Schiller provided a sample of how OSE/OSSEs may be used to guide system design; an aid rather than a deterministic approach. Should such capability be an explicit element of future IMOS systems?

4. David Griffin pointed to the issue around scientific capability for satellite data. What should out future pitch be in order to ensure we do have the appropriate level of effort?

5. After the presentations to this point, are we comfortable that the Integrated and Systematic parts of IMOS are being delivered well, or do we need to do more?

6. There is always a choice between the degree of diversity in our modelling and data assimilation efforts and the degree to which we wish to focus and rationalise in order to deliver efficiencies. Are we in the right place?

7. A theme through both days is that systematic errors are still significant in both coastal and bluewater models. Does this require greater urgency, for example some focused process experiments?

8. From the outset, we have aimed to have 10% of the IMOS investment focused in data and information management. Are there any regrets around this? Roger Proctor described a trend toward an AODN that includes aggregation and higher-level data products. Is this trend something we support?

The benefits of assembling and standardising new data streams for validation and assimilation into ocean models has been demonstrated though programs such as Argo. The regularisation of these data systems has made the use of data a much simpler and more efficient exercise.

In terms of model development, the ability to bring data to models is a key strategy for addressing systematic errors, there are still key datasets needed which are not available. Diversity in modelling approaches needs to be maintained, so that multiple models can be run (eg. with different approaches to grids) in the same region.

There was discussion around the ability of sparse BGC data to guide observing system design; it is considered useful, but is only one approach that needs to be considered; however, it was suggested that perhaps gliders could be used for adaptive sampling.

Cautions around the use of models in observing system design included the model dependency of results, so the use of multiple models is recommended. The results of the footprint work was noted to be model dependant, and restricted to specific time horizons. There was also recognition that OSE’s are not prescriptive.

A need to ensure model output is interoperable was highlighted, and there was suggestion this could be pursued through MARVL. US-IOOS are developing ISO-standard metadata for describing coastal model output that we may be able to capitalise on. Ultimately, it was noted that a joint strategy is needed: what are the big issues that we can, and need to tackle through bringing observations and modelling together?

**RECOMMENDATION:** Pursue approaches to interoperability of coastal model output through MARVL/US-IOOS (Roger Proctor to lead).

**Questions:**
- **Can we recommend next steps in the observing system design space?**
- **Can we use models and obs together in observing system design, ie. Adapter Project, use of Gliders in adaptive sampling?**
6. Emerging/other modelling approaches

6.1. The CAWCR-WfO ocean modelling review – from climate to coasts (Peter Craig and Andreas Schiller)

Peter Craig gave an overview of the review of ocean modelling in the CSIRO/BOM Centre for Australian Weather and Climate Research (CAWCR), which is aimed at addressing the following question: If the Bureau wants to forecast the (physical) state of the coastal ocean, what model would they use?

Due to the limits around running multiple model frameworks operationally, there is pressure to use one model for both open-ocean and coastal applications. As an analogue, in atmospheric modelling, a move was made from 2 model frameworks for broad scale (the Global Analysis and Prediction model, GASP) and regional scale (the Local Analysis and Prediction System, LAPS) applications, to a single framework called the Unified Model developed by the UK Met Office.

The Modular Ocean Model (MOM) developed at GFDL is generally used within CAWCR (CSIRO and BOM) for all open ocean modelling activities including seasonal forecasting (POAMA), ocean forecasting (BlueLINK Oceanmaps) and coupled climate/earth system modelling (ACCESS). However, MOM does not include (and does not intend to include) coastal capability. The European model, NEMO is being considered as an alternative, run by the UK Met Office. It has coastal capability, is coupled to the Unified Model, has a big development community, and has comprehensive ancillary models.

Key assessment criteria are:

- Capability (in the published literature).
- Development trajectory (i.e. plans and capability for developing the model and how this relates to Australian modelling requirements).

A background paper and terms of reference for the review have been drafted; and a working group is being established. Recommendations should be made at the end of the year.

Groups that are likely to be affected include:

- The ARC Centre of Excellence for Climate System Science
- CSIRO Coastal Modelling (currently using ROMS, SHOC, and Delft3D)
- Other Australian Coastal Modellers.

Littoral zone modellers will be unaffected. In terms of relevance to IMOS, it is likely to influence the uptake and use of IMOS data for coastal data assimilation.

In the discussion that followed, some concerns were highlighted including:

- Contributions to the process and representation on the working group outside CAWCR was recommended (particularly, those involved in ACCESS).
- Whether the data assimilating capabilities of the models were being considered.
- The significant effort involved in moving between model frameworks (based on experience with NEMO in Europe, and the move to the Unified Model).
- The model requirements described seemed to focus on the Bureau’s operational forecasting requirements; however, CSIRO’s modelling has a strong research driver which still needs to be delivered on.
- While NEMO is moving onto the continental shelf, near-shore regions, bays and estuaries will not be included; hence SHOC will still be needed.
- The notion that extra effort is involved in supporting 2 model codes was questioned, and caution was expressed against throwing eggs in one basket.
- Strong links are already being developed between MOM and SHOC regarding applications in the coastal zone.

6.2. Modelling activities in New Zealand: Development of an adaptive modelling framework (Graham Rickard et al.)

Graham Rickard summarised modelling activities in New Zealand and contrasted them with approaches taken in Australia. Through the National Institute of Water and Atmospheres (NIWA), four models are used for ocean and coastal modelling.

1) ROMS (Nesting approach)
2) RICOM (unstructured, finite element)
3) Delft 4D
4) GERRIS (adaptive model)

The GERRIS Model is developed within NIWA, and the code is freely available for others to use. The NIWA Modelling group are keen to collaborate more strongly with Australian modelling. Notably, in data assimilation capability (particularly in ROMS) and in further testing and development of the GERRIS adaptive model, including taking it from a single layer model to multiple layers.

6.3. The Marine Virtual Laboratory (MARVL) and Information System (MARVLIS) (Roger Proctor et al.)

The Marine Virtual Laboratory has been established through the NeCTAR (National eResearch Collaboration Tools and Resources) program, and led by CSIRO and the University of Tasmania. NeCTAR funds activities under 3 categories: research tools, research clouds and a national server program.

The Aim of MARVL is to make it quicker and easier to set up and run a model in a domain of your choice, by configuring the model and input datasets to your requirements. An “early activity” was funded, using the Derwent Estuary as a test bed, and then the system will be expanded and tested nationally through collaboration with key partners using a range of models and forcing data. This will allow the MARVL system to be benchmarked against existing model frameworks. MARVLIS, will be used to deliver the data from the model in forms of relevance and interest to specific stakeholders. In the Derwent Estuary, a key group of stakeholders is the Derwent Estuary Program.¹¹

The MARVL system will not initially have data assimilation, but this could be available in the future. Further discussions were focused on the interoperability of model inputs and outputs.

6.4. Establishing the Climate and Weather Science Laboratory (Tim Pugh et al.)

The Weather and Climate Science Laboratory is a collaboration between CAWCR, the National Computing Infrastructure (NCI) and the Centre of Excellence for Climate System Science for running and analysis of climate system models and IPCC class model output. The laboratory will enable consistent analysis to be carried out across multiple models, as well as model downscaling activities.

6.5. DISCUSSION: What are the potential and priority areas for future capacity/capability development? (led by Jason Middleton)

Observational capability capacity was discussed in the context of the needs for research and operational ocean observations. It was noted that the distinction between research and operational is not black and white, with available real-time data-streams seen as valuable for both research and operational applications. Hence, there are benefits to IMOS maintaining a research focus at its core, but partnering for relevance in the coastal zone; by ensuring that data is made available through the AODN and by direct partnerships, e.g. with state governments in programs such as eReefs. This also means that we can grow the observing capability incrementally drawing on the capacity in observing and information infrastructure established under IMOS. Further discussion was around whether a National Coastline Observatory should be established as a separate entity or through partnering as part of IMOS and/or TERN.

The need to extract more benefit from satellite data was highlighted, specifically in the coastal zone; and Australia has limited scientific capability in processing and analysis of satellite data.

The limited capability in Biogeochemistry and biogeochemical modelling was highlighted, with suggestions that a Marine Biogeochemistry Summer School would help bring students into the field. The CSIRO Carbon Cluster being led by UTS and UWA was identified as an opportunity to foster collaboration and education in coastal biogeochemistry. One of the main drivers of the cluster is to develop carbon budgets for the coastal oceans; ecosystems such as salt marshes and mangroves are poorly defined in terms of shoreline boundary and extent. As discussed earlier in the meeting (see section 5.4), it was also noted that the IMOS Bio-optical working group could be leveraged to strengthen links between observations and modelling in the biogeochemistry space.

Operational applications were discussed, and it was noted that operational use of data doesn’t require operational delivery. However, Quality Control methods need to be seen as a critical component, and automated QC methods need to be developed/refined for near real-time delivery.
7. DISCUSSION: Wrap up (led by Ian Poiner)

For IMOS to be a success, Ian Poiner identified that strong connections are needed between modellers, observations and data. There is a need to articulate national level needs, and some progress was made in key areas at this meeting including:

- Improved understanding of observational requirements into the shoreline
- Ideas for improved connections between observations and models
- Data access issues to address (through IMOS and partners)
- A better understanding of e-research activities which can support observations and modelling activities.

In terms of concrete steps going forward, recommendations included:

5) Promoting the development of the Australian Ocean Data Network: the national observations and modelling community need to continue to sign up to making data available. This requires cultural changes in some areas, and guidance on priority datasets from the user community is needed.

6) Better and Ongoing communications between modellers would enable strategic modelling challenges to be identified and addressed, and open discussion and collaboration around areas such as model forcing and boundary conditions.

7) Observing System Design; further discussion is needed on how to pursue this.

8) A potential follow-up ACOMO workshop; the potential timing and focus are up for discussion.

MARVL was identified as a potential framework to pursue collaborative activities, as a number of modelling groups from around the country are involved in testing the MARVL tools.

There was strong support for a follow up ACOMO meeting on the 18 month – 2 year timeframe; potentially with stronger focus on biogeochemical modelling.
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## Appendix I: Agenda

### Integrated Marine Observing System (IMOS)

**Australian Coastal Ocean Modelling and Observations Workshop (ACOMO) 2012**  
The Shine Dome, Australian Academy of Sciences, Canberra. 3-4th October 2012.

**Wednesday 3rd October.**

<table>
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<th>Time</th>
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<tr>
<td>8.00-8.30</td>
<td>Arrival, registration and coffee</td>
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<tr>
<td>8.30-8.35</td>
<td><strong>Katy Hill</strong></td>
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<td>Housekeeping.</td>
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<tr>
<td>8.35-8.45</td>
<td><strong>Tim Moltmann/TBD</strong></td>
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<td>Welcome/introduction</td>
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<tr>
<td><strong>Near shore observations and modelling. Chair: Katy Hill, Rapporteur: Roger Proctor</strong></td>
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<tr>
<td>8.45-9.15</td>
<td><strong>Kathy McInnnes</strong>, John Church, Neil White, Chari Pattiaratchi, Diana Greenslade, Jane Sexton.</td>
<td></td>
<td>Sea levels, storm surges and Tsunamis; modelling and observations</td>
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<tr>
<td>9.15-9.45</td>
<td><strong>Bill Peirson</strong>, Mike Banner, Mark Hemer and Chari Pattiaratchi</td>
<td></td>
<td>Wave and near shore modelling, status and observation requirements in Australia.</td>
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<tr>
<td>9.45-10.15</td>
<td><strong>Ian Turner</strong>, Graham Symonds, Ron Cox and James Carley</td>
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<td>Littoral Zone Modelling; status and observational requirements in Australia.</td>
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<tr>
<td>10.15-10.45</td>
<td><strong>Nugzar Margvaleshghi</strong>, Cedric Griffiths, Chris Dyt, Barbara Robson and Scott Nichol.</td>
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<td>Coastal sediment-transport modelling and observational needs</td>
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<tr>
<td>10.45-11.15</td>
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<tr>
<td>11.15-11.45</td>
<td>DISCUSSION led by Tim Moltmann</td>
<td></td>
<td>From a national perspective, what are the highest priority observations and datasets required by the modelling communities?</td>
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<tr>
<td><strong>Regional/Coastal Observations and Modelling: Chair: Roger Proctor, Rapporteur: Andreas Schiller</strong></td>
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<tr>
<td>11.45-12.15</td>
<td><strong>John Wilkin</strong>, Julia Levin, Javier Zavala-Garay and Hernan Arango</td>
<td></td>
<td>Integrating modelling and data assimilation using ROMS with a Coastal Ocean Observing System for the U.S. Middle Atlantic Bight</td>
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<td>12.45-1.30</td>
<td>Lunch</td>
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<tr>
<td>1.30-2.00</td>
<td>Observation Update</td>
<td>Craig Steinberg, Chari Pattiaratchi, Moninya Roughan, Mark Baird, Lucy Wyatt.</td>
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<tr>
<td>2.00-2.30</td>
<td>The data assimilation component of the real-time coastal ocean forecast system implemented off Oregon (US West coast)</td>
<td>Alex Kurapov and Peng Yu</td>
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<tr>
<td>2.30-3.00</td>
<td>Australian coastal modelling and information systems: assisting management decision making.</td>
<td>Emlyn Jones, Mike Herzfeld, Phil Gillibrand, Karen Wild Allen, Greg Timms, Chris Sharman, Richard Brinkman, Hemerson Tonin, Nuzgar Margvelasvili, Paul Rigby</td>
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<td>3.00-3.30</td>
<td>Coffee</td>
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<td>3.30-4.00</td>
<td>National Plan for Environmental Information: pilot project</td>
<td>Greg Stuart, Andrew Woolf</td>
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<td>4.00-4.30</td>
<td>Do we need to do more to foster collaboration within Australia between groups working at regional/coastal scales?</td>
<td>DISCUSSION led by John Gunn</td>
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4.30-6.00pm: Poster Session (including refreshments).
6.15pm: Bus leaves the Shine Dome to go to the Lobby.
6.30pm: Bus leaves the Ridges Lakeside Hotel to go to the Lobby.
7.00pm: Dinner at “The Lobby” Restaurant, Canberra: [www.thelobby.com.au](http://www.thelobby.com.au)
### Thursday 4th October

#### National/Bluewater Observations and Modelling: Chair: Moninya Roughan, Rapporteur: Chari Pattiaratchi

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<td>Peter Craig, <strong>Gary Brassington</strong>, Joanne Haynes, Andreas Schiller, Tim Pugh, Paul Sandery, Peter Oke and Graham Symonds. BLUElink – status, challenges and future.</td>
</tr>
<tr>
<td>9.00-9.30</td>
<td><strong>Ken Ridgway</strong>, Susan Wijffels, Boris Kelly-Gerreyn, Eric Schulz, Pete Strutton, Peter Oke. Key bluewater observing systems and datasets; and their use in modelling.</td>
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<td>9.30-10.00</td>
<td><strong>Andreas Schiller</strong>, Peter Oke, Pavel Sakov. Observing system experiments: Recent progress and future plans.</td>
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<td>10.00-10.30</td>
<td><strong>David Griffin</strong> and Edward King. Remote Sensing: observing a big country</td>
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<td>10.30-11.00</td>
<td>Coffee</td>
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<td>11.30-12.00</td>
<td><strong>Roger Proctor</strong>, Peter Blain, Sebastien Mancini. IMOS/AODN Ocean Portal: tools for data delivery.</td>
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</table>
| 12.00-12.30  | **DISCUSSION led by Neville Smith**. What are the next steps for the use of models in observing system design, e.g.  
|              | - Multiple modelling approaches,  
|              | - Coastal models  
|              | - International collaboration. |
| 12.30-1.30   | Lunch                                                                               |

#### Emerging/other modelling approaches (Chair: Chari Pattiaratchi, Rapporteur: Katy Hill)

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<td><strong>Roger Proctor</strong>, Peter Oke, Uwe Rosebrock, Brendan Davey. The Marine Virtual Laboratory (MARVL) and Information System (MARVLIS).</td>
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<td>3.30-4.00</td>
<td><strong>Tim Pugh</strong>, Martin Dix and Ben Evans. Establishing the Climate and Weather Science Laboratory.</td>
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<td>4.00-4.30</td>
<td><strong>DISCUSSION led by Jason Middleton</strong>. What are potential/priority areas for future capacity/capability development?</td>
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<td>4.30-5.00</td>
<td><strong>DISCUSSION led by Ian Poiner</strong>. Conclusions/next steps.</td>
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<td>5.00-5.30</td>
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<td>3</td>
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<td>Yasha Hetzel, Charitha Pattiaratchi, Ryan Lowe, Richard Hofmeister</td>
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<td>Florence Verspecht, Charitha Pattiaratchi, John Simpson</td>
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<td>6</td>
<td>Modelling meso-scale dynamics along western and southern Australian shelf and slopes: A ROMS modelling approach</td>
<td>E.M.S. Wijeratne, Charitha Pattiaratchi and Roger Proctor</td>
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<td>Observations and modelling of the seasonal cycle of sea level around Australia</td>
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<td>Eric C. J. Oliver, Neil J. Holbrook</td>
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<td>Mark Doubell, Charles James, John Luick and John Middleton</td>
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<td>13</td>
<td>The evolution of a Cold-Core Eddy in a Western Boundary Current</td>
<td>Helen Macdonald, Moninya Roughan, Mark Bair and John Wilkin</td>
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IMOS is supported by the Australian Government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative. It is led by the University of Tasmania on behalf of the Australian marine & climate science community.

This workshop is also supported by:
Appendix II: Extended Abstracts

Venue:  Shine Dome, Canberra
Date & Time:  3 & 4 October, 2012

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   Peter Craig, Gary Brassington, Joanne Haynes, Andreas Schiller, Tim Pugh
   Paul Sandery, Peter Oke and Graham Symonds  6

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   Richard Matear, Andrew Lenton, Matt Chamberlain, Mathieu Mongin, Mark Baird  17

4. Sea levels, storm surges and Tsunamis; modelling and observations
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5. Key Bluewater observing systems and datasets; and their use in modelling
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6. IMOS/AODN Ocean portal: tools for data delivery
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10. Australian coastal modelling and information systems: assisting management decision making.
   Emlyn Jones, Richard Brinkman, Phil Gillibrand, Mike Herzfeld, Nugzar Margvelashvili, Mathieu Mongin, Paul Rigby, Chris Sharman, Greg Timms, Hemerson Tonin and Karen Wild-Allen. 60

11. National Plan for Environmental Information Pilot Project
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12. Observation Update
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13. Ocean Observing Systems: recent progress, opportunities and future plans
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19. The Marine Virtual Laboratory (MARVL) and Information System (MARVLIS)
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Integrating modeling and data assimilation using ROMS with a Coastal Ocean Observing System for the U.S. Middle Atlantic Bight

John Wilkin, Javier Zavala-Garay and Julia Levin

Institute of Marine and Coastal Sciences
Rutgers, the State University of New Jersey

Hydrodynamic models are used in coastal oceanography to simulate the circulation of limited-area domains for studies of regional ocean dynamics, biogeochemistry, geomorphology and ecosystem processes; for example, to deduce transport pathways for nutrients, sediments, pollutants or larvae. When operated as real-time now-cast or forecast systems, these models offer predictions that assist decision-making related to water quality and public health, coastal flooding, shipping, maritime safety, and other applications. Here we describe the configuration and operation of such a modeling system for the shelf waters of the Middle Atlantic Bight (MAB) – a region with a diversity of real-time models in operation and a dense in situ observational data set for assimilation and skill assessment.

The MAB spans the U.S. East Coast from Cape Hatteras, North Carolina, to Cape Cod, Massachusetts. A permanent front at the shelf-break separates relatively fresh and cool waters on the broad (~100 km wide) shelf from saltier, warmer Slope Sea water influenced by Gulf Stream eddies. This shelf-break front is prone to non-linear instabilities with wavelengths of order 40 km that evolve on time scales of a few days, and sustains along-shelf currents that reach the seafloor driving significant flow-bathymetry interactions. Appreciable across-shelf fluxes of heat, freshwater, nutrients, and carbon control water mass characteristics and impact ecosystem processes. The circulation is influenced by winds, tides, buoyancy input from rivers, a steady along-shelf sea level gradient, and mesoscale eddies that impinge upon the shelf edge. This spectrum of forcing mechanisms, and the dynamic shelf edge frontal zone, make the region a challenging laboratory for testing the skill of coastal ocean models and data assimilation methodologies.

The MAB is densely observed compared to coastal oceans globally, with much of the local data acquisition coordinated by the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS; maracoos.org) – one element of a growing national network of regional observatories supported by ad hoc consortia of federal, state, academic and commercial partners. MARACOOS operates an extensive CODAR (Coastal Ocean Dynamics Applications Radar) network observing surface currents from the coast to the shelf edge, and deploys autonomous underwater glider vehicles (AUGV) to acquire subsurface temperature, salinity and biogeochemical data along transects throughout the MAB.

The Rutgers University Ocean Modeling Group (RU OMG!) has operated a real-time forecasting system for the MAB since September 2009, assimilating CODAR velocities, satellite sea surface height (SSH) and satellite surface temperature (SST) from multiple platforms. The assimilation of in situ temperature and salinity data from AUGV and ships of opportunity has been conducted experimentally. Further observations from National Marine Fisheries Ecosystem Monitoring (ECOMON) voyages and in situ data reported via the WMO GTS network are used in skill assessment. Climatological mean data analyses are utilized in a data-assimilative estimate of Mean Dynamic Topography that is combined with altimeter sea level anomalies.
The ocean circulation model is ROMS (Regional Ocean Modeling System; www.myroms.org), which solves the hydrostatic, Boussinesq, primitive equations in terrain-following vertical coordinates. Shchepetkin and McWilliams [2009] give a thorough review of the algorithmic elements that comprise the ROMS computational kernel. Features that make ROMS particularly attractive for continental shelf applications include: a formulation of the depth-integrated mode equations that suppresses aliasing into the slow 3-d baroclinic mode while retaining accuracy in representing barotropic motions due to tides and coastal-trapped waves; minimal pressure-gradient truncation error associated with the terrain following coordinates; a finite-volume, finite-time-step discretization for the tracer equations to improve conservation in shallow water applications where the free surface displacement is a significant fraction of the water depth; wetting and drying; and, optional positive-definite advection for biological tracers and sediment concentration. Companion applications include a sediment transport model and several ecosystem and bio-optical models, sea ice, and coupling to the SWAN wave model and WRF atmospheric model.

ROMS is unique in that three variants of 4-dimensional Variational (4DVar) data assimilation are supported in the code [Moore et al., 2011a]: a primal formulation of incremental strong constraint 4DVar (I4DVAR), a dual formulation based on a physical-space statistical analysis system (4D-PSAS), and a dual formulation representer-based variant of 4DVar (R4DVar). In its general form, I4DVAR seeks adjustments to the initial conditions, boundary conditions, and surface forcing in order to find the best estimate of the circulation in the least-square sense (model error can be also included in 4D-PSAS and R4DVar). In addition to 4DVar, other drivers in the ROMS suite utilize the adjoint and tangent linear models for formal analysis of observation impact and observational sensitivity [Moore et al., 2011b].

The ROMS real-time data assimilative model for the MAB is termed ESPreSSO, for Experimental System for Predicting Shelf and Slope Optics. The horizontal resolution is 5 km, with 36 terrain following vertical levels. Open boundary data are adapted from the HYCOM-NCODA global ocean forecast system, and surface fluxes are derived from 12-km resolution 3-hourly forecast meteorology from the North American Mesoscale (NAM) model operated by NCEP. Observed daily-mean river discharges are applied at 7 sources. Harmonic tidal boundary conditions are taken from a regional model. The vertical turbulence closure is the $k-kl$ option of the Generalized Length Scale (GLS) formulation [Warner et al., 2005].

In ESPreSSO we use the I4DVAR formalism under the assumption that the surface and lateral boundary forcing are error-free and therefore the only control variables adjusted are the initial conditions of each analysis cycle, a procedure often referred to as “strong constraint” 4DVar. Daily, an I4DVAR analysis of 3 days of observations (CODAR, altimetry, SST) is performed to derive a now-cast of the ocean state – the analysis. From this analysis, a 72-hour forecast is launched using forecast meteorology and open boundary conditions, and persisted rivers. The first 24 hours of each forecast is retained as the “best estimate” of the ocean state for that day, with model output at 2 hour intervals added to an open access THREDDS (Thematic Real-time Environmental Distributed Data Services) server conforming to CDM (Common Data Model) standards. This facilitates inter-operability with MARACOOS partners, and ready access for remote users via OPeNDAP (Open-source project for a Network Data Access Protocol).
We perform substantial pre-processing and quality control of the data used for assimilation. For example, judicious application of the Jason-2 altimeter data error flags and revised wet tropospheric radar range correction [Feng and Vandemark, 2011] allows us to use these data in shallow water to within 10 km of the MAB coast. To altimeter SSH data we add Mean Dynamic Topography computed by a single 4DVar assimilation of an MAB region Ocean Climatological Hydrographic Analysis (MOCHA), mean wind stress, mean CODAR surface velocity, and mean currents from a decade of M/V Oleander ADCP data (on a New York to Bermuda transect).

To date, AUGV and ship of opportunity CTD data have largely been withheld for skill assessment, and do not yet enter the real-time data stream. In an inter-comparison of 7 ocean models that run in real-time and cover the MAB (3 global operational models, 3 MARACOOS models including ESPreSSO, and a coupled ROMS-SWAN-WRF model), only 3 of these models typically outperform a “prediction” based solely on climatology (MOCHA). With respect to model bias and centred root mean square error computed for 16 AUVG missions and 4 ECOMON cruises in 2010-2011, ESPreSSO is consistently among the three models with the lowest errors.

References


BLUElink – status, challenges and future

Peter Craig\textsuperscript{1}, Gary Brassington\textsuperscript{2}, Joanne Haynes\textsuperscript{3}, Andreas Schiller\textsuperscript{1}, Tim Pugh\textsuperscript{2}, Paul Sandery\textsuperscript{2}, Peter Oke\textsuperscript{1} and Graham Symonds\textsuperscript{1}

\textsuperscript{1}CAWCR, CSIRO, Hobart Australia
\textsuperscript{2}CAWCR, Australian Bureau of Meteorology, Melbourne, Australia
\textsuperscript{3}HM Branch, Royal Australian Navy, Sydney, Australia

BLUElink represents three successive partnership projects, between the Royal Australian Navy, the Bureau of Meteorology and CSIRO, first established in 2003 with two primary aims:

\begin{itemize}
  \item to implement an operational ocean-forecasting system at the Bureau; and
  \item to provide the RAN with tools to access and interpret the ocean forecasts
\end{itemize}

Ocean forecasts deliver predictions of ocean currents, temperature, salinity, and sea-level using computer models that resolve the mesoscale ocean variability e.g., eddies and fronts. The operational forecasts since 2008 have been based on global models with finer resolution confined to the Australian region. The current BLUElink-3 project (also known as Modelling Ocean Systems in the Tactical Environment, (MOSTE), 2011-2014) will implement a new model to resolve the mesoscale variability of all non-polar ocean basins. Similar to weather forecasting, the modelled state is adjusted toward the observations from satellites and instruments in the water (in a process called data-assimilation) to improve their nowcast accuracy and forecast skill over the forecast period of seven days. The Bureau of Meteorology’s ocean forecasting system offers a range of services including a graphical online service at: \url{http://www.bom.gov.au/oceanography/forecasts/} as well as data product services.

The propagation of sound signals in the ocean can be used to detect the presence of ships and submarines. The speed and direction of sound as it travels through the water is governed primarily by the water temperature to depths \(\sim 1000\) m but is also affected by changes in salinity and pressure. The Relocatable Ocean-Atmosphere Model (ROAM), developed in BLUElink, allows the Navy to run their own high-resolution (\(\sim 2\) km) forecast over areas of operational interest throughout the world downscaled within the Bureau’s ocean forecasts. These high-resolution ocean forecast data are used to determine the vertical structure of the ocean, from which the acoustic propagation of sound (and therefore sonar ray paths) can be predicted. ROAM output plays an integral role in assisting RAN to gain a tactical advantage.

Forecasting systems can also be used to recreate past records (“reanalyses”). This is undertaken regularly by leading weather agencies, to generate archives of the weather history. A reanalysis involves the use of a single model configuration and assimilation procedure to perform an approximately homogeneous reconstruction based on past observations. In BLUElink, we have created an ocean reanalysis (called BRAN, the BLUElink ReANalysis) dating from 1992 that enables researchers and industry to examine past ocean conditions. The archive is used, for example, to compare with fish-stock records or test oil-spill models.
In the second phase of BLUElink, beginning in 2006, the Navy expressed the need to extend its forecasting ability to the littoral zone, with a particular focus on nearshore and beach forecasting in support of amphibious and diving operations. A nearshore forecasting package called LOMS (Littoral Ocean Modelling System) was developed that could work on a laptop. The operator enters the wind and offshore wave forecasts, using a combination of Bureau products, and the system predicts the waves and currents, such as rip currents, close to the beach.

Ocean-forecasting systems are relatively new, and under continuous development. The ocean models are well established, but are being adapted and improved for forecasting. Data-assimilation techniques are also still relatively new and evolving. Furthermore, data availability is generally increasing ocean data but does not yet have the same reliability as atmospheric measurements. We have a high dependency on international satellite and buoy programs. Importantly, computer power is growing, enabling more ambitious implementations of the models. BLUElink now in its third phase is organised into three target zones: global, regional and coupled and the littoral zone. The remainder of this extended abstract will describe each of these areas as well as outline some of the observational requirements.

**Global ocean prediction**

The challenge of large-scale operational oceanography has been to determine whether narrow-swath altimetry observations with cycle periods of ~10 days and 35 days, augmented by satellite SST and *in situ* observations from, e.g., Argo profilers, are sufficient to constrain a mesoscale resolving ocean general circulation model and to define the observing system requirements for skillful ocean forecasting. BLUElink together with other international groups within GODAE and GODAE OceanView has demonstrated that this can be achieved but the field continues to mature.

The BLUElink project established the first Australian near-global operational ocean forecasting system, called the Ocean Modelling Analysis and Prediction System (OceanMAPS, Brassington et al., 2007) and commissioned operational at the Bureau of Meteorology in August 2008. OceanMAPS provides a data service and a graphical service ([http://www.bom.gov.au/oceanography/forecasts](http://www.bom.gov.au/oceanography/forecasts)). OceanMAPS is based on an implementation of MOM4, called the Ocean Forecast Australia Model (OFAM), and an Ensemble Optimal Interpolation (EnOI) scheme called the Bluelink Ocean Data Assimilation System (BODAS; Oke et al., 2008). The development of the prediction system is preceded by the Bluelink ReANalysis (BRAN; Schiller et al., 2008) using reanalysed surface fluxes and delayed mode observations where available. An example of output from BRAN is presented in **Figure 1**, which shows the correspondence of drifting buoy trajectories with the contours of the mean sea level. The mean sea level contours closely align with the ocean currents that are in quasi-geostrophic balance with the normal pressure gradient.
Figure 1 Monthly mean sea-level from BRAN (version 2p2), with surface drifter velocities and trajectories overlaid. (adapted from Oke et al., 2009)

OceanMAPS version 2 included a number of system enhancements to OFAM, BODAS and initialisation (Sandery et al., 2011) and a four-cycle design to deliver a daily forecast (Brassington et al., 2012). An example of the four hindcasts from each cycle for the 14th Feb 2012 is shown in Figure 2. The four independent hindcasts, each lagged by 24 hrs, shows the same pattern of large scale sea level anomalies including the characteristic alternating sign eddies along the NSW coast. However, the four hindcasts demonstrate variability with the magnitude of anomalies and position of frontal boundaries indicating the limits of predictability of the prediction system.

Figure 2: Hindcasts of sea level anomaly in the Tasman Sea for the 14th February 2011 from four independent cycles each with different hindcast periods: (a) 72 hr, (b) 48 hr, (c) 24 hr and (d) 0hr (best estimate). (adapted from Brassington et al., 2012). Note hindcast period is the time since the last assimilation and initialisation step.

In addition to OceanMAPS, BLUElink contributed to the first climate model Australian Climate Ocean Model (AusCOM), and a revised version of CSIRO Atlas for Regional Seas (CARS). A summary of the recent progress for the global component systems is outlined in Table 1.
<table>
<thead>
<tr>
<th>System name</th>
<th>BLUElink Global</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ocean models</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>OGCM</td>
<td>OFAM2 (MOM4p1)</td>
</tr>
<tr>
<td>Domain</td>
<td>Near-Global</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>0.1°×0.1° (90E-180E, 75S-16N)</td>
</tr>
<tr>
<td>Vertical sampling</td>
<td>47 z-levels</td>
</tr>
<tr>
<td>OGCM (forecast mode)</td>
<td>OFAM2 (MOM4p1)</td>
</tr>
<tr>
<td>Atmospheric Forcing (forecast mode)</td>
<td>ACCESS-G (Bureau global NWP based on UKMetOffice UM6)</td>
</tr>
<tr>
<td>Atmospheric Forcing (reanalysis mode)</td>
<td>ERA-40 Interim</td>
</tr>
<tr>
<td><strong>Assimilation characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Assimilation Scheme</td>
<td>3D EnOI, BODAS2</td>
</tr>
<tr>
<td>Initialisation</td>
<td>24hr nudging</td>
</tr>
<tr>
<td>Assimilation Scheme (forecast mode)</td>
<td>3D EnOI, BODAS2</td>
</tr>
<tr>
<td>SST</td>
<td>AMSR-E (RSS) AVHRR (Navocean L2P)</td>
</tr>
<tr>
<td>SSH</td>
<td>Jason1, Jason2 (Envisat (ESA))</td>
</tr>
</tbody>
</table>

Table 1: BLUElink global prediction capability changes and status of the Bureau of Meteorology operational ocean prediction system (BLUElink OceanMAPS) relative to year of operation
Regional and coupled ocean prediction

The Earth’s weather and climate system involve physical feedbacks between the atmosphere and ocean across a range of time and space scales. These feedbacks are governed by turbulent exchanges of heat, mass and momentum across the air-sea interface within the surface boundary layers. It is well understood that seasonal and climate forecasting cannot be done without representing these exchanges in coupled ocean-atmosphere models (Frederiksen et al. 2010). It is also well known that air-sea interaction plays an important role in tropical cyclones (TCs) (Bender and Ginis, 2000). Here, wind-driven ocean cooling of SST has an important effect on storm intensity by reducing energy fluxes and stabilising the marine atmospheric boundary layer. The upper ocean thermal structure has a large influence on the degree to which a storm can induce cooling. Less well understood is the importance of air-sea interaction at synoptic time-scales across the spectrum of weather events, however, it is clear that the ocean and atmosphere are coupled in nature and that climate and weather are inseparable. With the advent of the BLUElink OceanMAPS operational ocean forecasting system and increased computational resources, it is now technically possible for the Bureau of Meteorology to run coupled ocean-atmosphere NWP prediction systems. However, scientific challenges remain such as the understanding of the propagation of error in such systems and incomplete representations of physical processes. Some of the key contemporary issues for coupled atmosphere-ocean NWP are initialisation, data assimilation, uncertainty estimation and representation of the physics of the turbulent air-wave-sea boundary layer.

The BLUElink3-MOSTE project has provided for the continuing development of two regional modelling systems, namely the coupled ocean-atmosphere prediction model (CLAM) and the Relocatable Ocean Atmosphere Model (ROAM). CLAM component models are the UK-Met Office Unified Model (UM) (Rawlins et al. 2007), OASIS4 (Redler et al. 2010) and MOM4p1 (Griffies et al. 2009). CLAM is nested inside ACCESS-G and OceanMAPS and provides a framework for routine validation of coupled forecasts against observations. ROAM, is underpinned by the Regional Atmospheric Modelling System (RAMS), the Sparse Hydrodynamic Ocean Code (SHOC) and the SWAN model. ROAM components are nested inside OceanMAPS and ACCESS-R or ACCESS-G. ROAM is not a coupled modelling system, but instead runs each modelling component in series – the atmospheric model first, then the ocean and wave models. Two main developments set the ROAM system apart from any other in the world. First, the ease of deployment, and second the robust performance. ROAM, is easily deployed, by a non-specialist user through an intuitive graphical user interface (GUI). Through the GUI, a user can graphically prescribe: the domain to be modelled; the models to be run; the model resolution; and the forecast length. Ongoing developments are enabling ROAM to be run for any historical period, with nesting inside BRAN. The ocean component of ROAM has undergone significant developments to ensure robust performance – with constant model checks to avoid numerical instability, with increased diffusion where instabilities appear to be developing. As a result, ROAM almost always executes successfully, even for untested domains.

In BLUElink2, the coupled limited area model was used to study the impact of atmosphere–ocean coupling on predicting the ocean response to tropical cyclones (TC) in the Australian region and the affect of this on intensity change (Sandery et al. 2010). Additionally, it was used to investigate constraints on drag and exchange coefficients at extreme wind speeds (Walsh et al, 2010). We also carried out an ensemble prediction study (EPS) of the East
Australian Current (EAC) and illustrated the role of dynamical instabilities on flow dependent forecast errors (O’Kane et al. 2011). In BLUElink3, CLAM evolved into a regional ocean-atmosphere dynamical ensemble prediction system (Sandery et al. 2012). This system was used to study coupled initialisation and bred cyclic modes in the case of Tropical Cyclone Yasi. Ocean initial perturbations were constructed to identify the fastest growing non-linear modes in the ocean response to the TC and provide a characterization of how initial and evolving perturbations of SST influence the coupled system through surface fluxes under extreme conditions. Results were obtained that quantified the projection of SST perturbations into atmospheric pressure and moisture content within the storm environment. The iterative approach to coupled initialization was shown to generate bred cyclic modes embedded onto the dynamics of regions critical to the coupled ocean-atmosphere TC dynamics. The forecasted ensemble-mean SST and SSHA associated with the ocean response were in better agreement with observations. Both model and observations were used to reveal a twin cold core structure in the ocean wake of TC Yasi.

In Bluelink 2, ROAM was combined with BODAS. Through a series of hindcast experiments, the benefits of local data assimilation. An example, from Oke et al. (2009) is shown in Figure 3, showing the better performance of a data-assimilation version of the ocean component of ROAM off the Bonney Coast during a wind-driven upwelling event. In this example, the 6-day composite SST field is independent (un-assimilated), and is compared to 5-day “forecasts” from BRAN, SHOC without data assimilation and SHOC with data assimilation (SHOC+DA). This figure shows a strong signature of wind-driven upwelling in the observations, with very cold waters upwelled to the surface and becoming advected offshore. The wind stress prior to this period is moderate and upwelling favourable (Figure 2f). Despite the coarse resolution of the ERA40 forcing fields used here (2x2°), BRAN produces an upwelling, but it is weaker than the observed event. Similarly, SHOC produces an upwelling, but is also too weak. The SHOC+DA run produces a stronger upwelling that is in better agreement with the observations.

Figure 3 An example of SST from (a) 6-d composite AVHRR, (b) daily mean BRAN (version 2p1), (d) daily mean SHOC, and (e) daily mean SHOC plus data assimilation. The model fields are valid 5 days after initialisation. The arrow in panel (a) shows the daily mean wind stress along with the magnitude. The region of the SHOC domain is shown in panel (c) and the time series of zonal (bold) and meridional (thin) wind stress is plotted in panel (f). The arrows in panels (b, d, and e) show the daily mean surface velocities (from Oke et al. 2009).
Littoral zone prediction
The littoral zone (depths<10m) forecasting component of BLUElink aims to develop a predictive capability out to several days for waves, currents and beach shape to assist the Navy with amphibious operations and rapid environmental assessment (REA) in the littoral zone. This modeling capability has wider application as coastal communities develop adaptation strategies to rising sea levels and changing wave climates and assess the risks associated with coastal development. The package is based on the numerical model XBeach [Roelvink et al., 2009; McCall et al., 2010] a coupled circulation and morphodynamic model forced by wind and waves including infragravity waves associated with a time varying incident wave field. Model domains are typically only a few kilometers with grid cells of a few metres. Wind and wave forcing can be specified by the user or provided through direct data feeds from the Bureau of Meteorology. The physics of wave propagation are well understood and numerical wave prediction skill is reasonable over forecasts periods of a week, though in depths less than 100m, and through to the surf zone, additional shallow water physics is required, and higher spatial resolution usually necessary to account for complex bathymetry. The spatial scale of this variability is of order 10-1000m and on sandy coasts the nearshore bathymetry can change significantly over time scales of days to months. Through the surf zone depth induced breaking transfers momentum from the incident wave field to higher and lower frequency motion and these processes are less well understood. Finally, the combined effects of waves and nearshore circulation modifies the nearshore bathymetry and these sediment transport processes are arguably the least well understood. The numerical model XBeach contains most of the above processes.

The Morphodynamic Environmental Assessment System (MorphEAS) predicts morphological change on a beach given the offshore wave forcing and initial bathymetry. The morphological evolution is sensitive to the initial bathymetry and the incident wave field, both of which can vary significantly in both space and time. Around Australia most of the standard bathymetric data sets do not have sufficient spatial resolution and observations of the temporal variability in the nearshore are virtually non-existent. The initial bathymetry may be derived from conventional hydrographic surveying methods with cross-shore resolution of a few metres and alongshore of hundreds of metres. The survey area is, typically the size of the model domain and repeat surveys limited by weather and available resources. Remote sensing techniques can also be used such as video, XBand radar and Laser Airborne Depth Sounding (LADS). Video and radar derived depth can be done with spatial resolution of order 5m at daily intervals by estimating the surface wave phase speed and inverting the linear dispersion relationship. LADS is a direct depth measurement usually limited to a one-off survey given the costs. A relatively new data stream is satellite multispectral sensors with the potential to provide shallow water bathymetry with a spatial resolution of 5-10m with repeat times of a few days and can be used in regions where access is denied. Surface or bottom mounted directional wave sensors can provide offshore forcing but there are relatively few permanent stations around Australia. Numerical wave models provide reasonably reliable short term forecasts and satellite derived surface wave fields may provide a useful source of data where direct observations are not available.
Conclusion

Global ocean prediction - At this stage, any detailed plans about the future R&D under a possible BLUElink4 (2015 onwards) are purely speculative. However, the robustness of the forecast system and our ability to respond to changes in the observing system (e.g. altimetry) are likely to be a key focus of the global component of BLUElink (new observational data streams, system failure support). Biogeochemical forecasting (ocean colour), sea-ice and advanced data assimilation methods (tides, Ensemble Kalman Filter) are other options. We note, however, that existing and increasing funding constraints are likely to force BoM and CSIRO to prioritise their R&D efforts, which would impact delivery of BLUElink products to the research community and the public.

Regional and coupled prediction - In order to make progress towards a better understanding of error growth in coupled ocean atmosphere NWP an instance of CLAM called ACCESS-RC (a coupled version of the operational ACCESS-R) has been integrated in parallel to create a large reference dataset. This will be analysed to describe for the first time the impact of coupling on both ocean and weather prediction in the Australian region. This system has been initialised using a cyclic bred vector ensemble approach that provides useful estimates of uncertainty. More recently, Barras and Sandery (2012) have demonstrated that the this system had more accurate accumulated precipitation forecasts for the Brisbane 2011 flooding event at 48-72 hour lead time and improved SSTs in its boundary condition with respect to observations compared to the ACCESS-R, which persisted analysis SSTs (Figure 4).

![Figure 4](image.png)

**Figure 4:** (a) Difference between SST boundary conditions for ACCESS-R and observed SST from AMSR-E for the 24 hour time-average the 48-72h forecast period from the base date 8th January 2011. (b) Same as for (a), but for ACCESS-RC using EBV SST initialization (adapted from Barras and Sandery, 2012)

BLUElink-MOSTE will investigate the impact of ocean dynamical downscaling on predictability and whether the finer scales can be constrained by the observing system to yield skilful information. Investigations will also include explicit modelling of total sea-level through the explicit modelling of atmospheric pressure, tidal and surface wave effects. These areas pose new challenges for prediction, in particular for data assimilation. Future work plans include the research and development of an EnKF based coupled data assimilation system for greater dynamical consistency, to improve forecast initial conditions and provide better estimates of uncertainty for both the ocean and the atmosphere.
**Littoral zone prediction** - In recent years short term wave forecasting has become more reliable though not all models contain the necessary physics or resolution to propagate waves into shallow water. However, wave model validation around Australia requires an expanded network of directional wave observations. Furthermore, predicting nearshore wave conditions is compounded in many regions by poorly resolved bathymetry. Simulating the complete spectrum of spatial and temporal variability in the nearshore circulation is challenging and requires hydrodynamic models with a spatial resolution of 1-10 metres and time steps of 1-10 seconds. Validating these models requires observations of currents in the nearshore, including the surf zone. Apart from in situ current meters video and radar have potential to map surface currents in the nearshore but these methods are still under development. Finally, short term prediction of morphological change is the least well understood. Antecedent bathymetry plays an important role in morphological evolution (Holman et al, 2006) and in regions where access is denied initial bathymetry derived from multispectral satellite data is one of the few options left. Future model development could include assimilating bathymetry observations to constrain the morphological evolution.

**Brief response to IMOS specific questions**

*What and how existing IMOS/Non IMOS data is used?*

The OceanMAPS and BRAN systems are the foundation systems that make use of remote sensing observations for sea surface height and sea surface temperature and in situ profiles for temperature/salinity. The specific platforms and coverage are under continuous change with those used in recent years summarised in *Table 1.*

At present the CLAM and ROAM systems are nested and downscaled within the global systems and do not reuse or introduce new observations. The BLUElink-MOSTE project is investigating the use of a secondary data assimilation step to enhance the initial conditions and forecast skill of both systems. It has not been determined to what spatial scale the existing observing system can continue to constrain the variability and produce skilful forecasts. Similar to the global prediction systems, applications in regions with rapid error growth (e.g., turbulent boundary layers, geostrophic turbulence) have greater demands for higher spatial and temporal observations. The demands increase for the regional and coupled systems if the high-resolutions resolve additional physical processes. A specific paper will be presented that discusses the requirements for the littoral zone.

**Potential to use new data streams in the future**

Observations that observe the five prognostic variables (sea level, temperature, salinity and currents) can be assimilated into the global and regional prediction systems provided the observation error can be estimated and the observations successfully quality controlled. The impact of new data streams will depend on the accuracy of the observations and the spatial and temporal coverage. Assimilation of coastal and regional observations within the global prediction systems provides the best strategy to improve the initial and boundary conditions for downsampling for coastal and regional predictions.

**Barriers to using new data-streams; including data packaging and delivery requirements**

The introduction of new data streams into the prediction systems has a number of scientific and technical requirements. The technical requirements include:

- Product specification (data format, meta data standards)
- Robust communications
- Quality control procedure (automatic and delayed mode)
- Calibration/Validation and error estimation
- Monitoring and fault alert system
- Change management alert system
Model error/uncertainties and how/what observation could help

The ocean remains under observed, particularly below the surface layer, therefore each “quality controlled” observation has a measurable positive impact. The impact of each individual observation for the BLUElink systems varies according to: (a) the magnitude of the error of the model background estimate (which frequently scales with the ocean variability); (b) the accuracy of the observation (not only instrument error but also the representation of the modelled scales); (c) the availability of other observations; and (d) the covariance length scales of the data assimilation scheme. For the BLUElink system the covariance length scales are determined by the scales of the modelled ocean dynamics and in many regions is of the order of the internal Rossby radius of deformation.

Satellite remote sensing observations have a dominant impact on the global systems due to their relatively high spatial and temporal coverage compared with in situ observations. Therefore, in situ observations that support the calibration/validation for remote sensing platforms can have a high impact for these systems. This includes not only the rapid replacement satellites data streams but also the introduction of new platforms (e.g., HF radar, AltiKa, HY2A, SMOS, Aquarius).

BLUElink global systems assimilate near real-time and delayed mode Argo, mooring and XBT observations, which are obtained from the GTS and the two global data assembly centres. The relatively low spatial and temporal coverage of profile observations compared with remote sensing limits their impact on global statistics. However, each quality controlled profile observation has a measurable positive impact local to the observation. Quality control for profile observations is a critical activity as “bad” profiles can introduce convective instabilities and in exceptional cases numerical failure.

Variables that are the least constrained or validated in the BLUElink systems are ocean currents and salinity.

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Biogeochemical modelling and data assimilation: status in Australia and internationally

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1. Introduction

Marine biogeochemical (BGC) modelling is a key approach to helping us understand the biochemical processes responsible for the transfer of nutrients and carbon between inorganic and organic pools (Matear and Jones, 2010). Quantifying these biochemical processes is essential to understanding carbon cycling in the ocean, the air-sea exchange of carbon, the impact of climate variability and change on marine ecosystems, and the link between ocean physics and ocean biology.

Data assimilation represents a new and exciting tool to advance ocean biogeochemical studies. The coupling of physical and biogeochemical data assimilation is a natural evolution of the Global Ocean Data Assimilation Experiment (GODAE). Data assimilation fuses models with a diverse set of observations to provide a more consistent view of the physical and biological state of the ocean. Extending the GODAE effort to include BGC data assimilation presents an exciting opportunity to expand the researchers interested in using ocean data assimilation products and Brasseur et al. (2009) provides a summary of BGC applications of data assimilation. However, delivering these new BGC data assimilation products is not a trivial task. In this presentation, we discuss the challenges of utilizing the existing physical ocean data assimilation systems to include BGC data assimilation. To help set the context of this discussion, we will first briefly discuss previous BGC data assimilation effort. Then, we will discuss both international and Australian BGC data assimilation activities.

2. Biogeochemical Data Assimilation

The application of data assimilation separates into two types of problems: 1) parameter estimation and 2) state estimation. The two approaches reflected different philosophies on how to fuse the BGC model with the observations with both delivering useful but different information. In both approaches, data is used to constrain the evolution of the state variables but with parameter estimation it is the model parameters that are modified to fit the data constraints while in the state estimation the state variables are modified to fit the observations. The state estimation approach generally forms the foundation of GODAE physical data assimilation with such effort delivering either ocean forecast or reanalysis products of the time evolving 3-D ocean physical state. However, BGC data assimilation studies have tended to focus on data assimilation for parameter estimation. Although a complete description of the two approaches is beyond the scope of this presentation, the following is a brief summary of the application of these two data assimilation approaches.

2.1 Parameter Estimation

An obvious feature BGC models are the large number of model parameters that must be specified to simulated the BGC cycles. The setting of these parameters can be partially accomplished from observations but for many parameters no direct observational estimate is available. Further, even for the more observable parameters like the phytoplankton
growth parameters much uncertainty still exists in setting the parameter values because either the parameter values change with time or the values determined from the individual phytoplankton species may not be applicable to the entire ecosystem. The inability to directly specify all the model parameters forces one to determine the parameters values by tuning the model to reproduce the observations. This is a tedious and time consuming approach. The attraction of data assimilation is that it provides a means to generate a set of model parameters that reflects the observations, determines the values of the poorly known parameters, and provides insight into which parameters are constrained by the model (Kidston et al., 2011; Schartau and Oschlies, 2003).

There is now a long list of studies which have used data assimilation methods to estimate model parameters of ecosystem models (see Gregg et al. (2009) for a list of these studies). There is even a webpage setup to explore parameter estimation of a suite of different BGC models at a number of different sites (http://www.ccpo.odu.edu/marjy/Testbed/Workshop1.html).

The uncertainty in the biological model is not just in the model parameters but extends to the choice of equations used to describe the biological system (Franks, 2009). Both parameter and model formulation uncertainty introduce large model error in BGC modelling, which lends itself to parameter estimation studies which explore the parameter space, model complexity and model formulation (e.g. Matear (1995)). The ability to address all three of these issues demonstrates the value in the parameter estimation approach for BGC data assimilation. In addition, parameter estimation can provide insight into what observations are critical to building and constraining more realistic models, and identifying the critical model parameters required to reproduce the observations (Kidston et al., 2011). The latter result provides a convenient way to identify a subset of critical model parameters, which capture the key observed dynamics of the biological system, and then explore how these parameters affect the dynamics of the system (e.g. Friedrichs et al. (2006)).

One important aspect to note with the parameter estimation approach is that unrealistic parameter values may be estimated because important processes are excluded from the model formulation (these are call structural errors in the model). Therefore, the estimated model parameter values must be ecologically assessed and deemed plausible otherwise the formulated model has structural errors.

2.2 Ocean State Estimation

The attraction of state estimation data assimilation is that it provides a way to incorporate both physical and biological observations into the numerical models to obtain the evolution of BGC fields that are dynamically consistent with the observations and provide a tool to extend the observations in both space and time (Lee et al., 2009). The application of state estimation is to overcome limitations in the model by correcting the ocean state to produce a more realistic evolution of the ocean state (Natvik and Evensen, 2003a). The approach provides a way of limiting the impact of model errors (parameter, formulation, initialization and forcing) to better hindcast and forecast the ocean state.
The study of Gregg (2008) provides a nice review of sequential BGC data assimilation studies which I briefly summarize here. Not surprising the focus of these studies is on assimilating ocean colour surface Chlorophyll a concentrations into their BGC models since this data product provides the best spatial and temporal data of the ocean biological system.

The first example of sequential data assimilation directly inserted CZCS chlorophyll into a 3-dimensional model of the southeast US coast (Ishizaka, 1990). They produced immediate improvements in their chlorophyll simulation but these improvements did not last more than a couple of days before the model simulation diverge from the observations. The divergence of the model simulation from the observations reflected a bias in the biological model to overestimate Chlorophyll a. Correcting such a bias would be crucial to obtaining better and longer lasting state estimation results. More recently, the Ensemble Kalman Filter (EnKF) has been used to assimilate SeaWiFS ocean color Chlorophyll a data into a 3D North Atlantic model (Natvik and Evensen, 2003a, 2003b). They showed the EnKF updated ocean state was consistent with both the observed phytoplankton and nitrate concentrations. However, this study did not show any comparison to unassimilated data to enable a quantitative assessment of the impact BGC state estimation (Gregg et al., 2009). Recently, Hemmings et al. (2008) presented a nitrogen balance scheme with the aim of assimilating ocean color Chlorophyll a to improve estimates of the seawater pCO2. They used 1D simulations at two sites in the North Atlantic (30N and 50N) to assess the performance of their scheme. The scheme exploits the covariance between Chlorophyll a and the other biological state variables at a fraction of the computational cost of the multivariate EnKF scheme. To do this Hemmings et al. (2008) use 1D model simulations with varying model parameters to extract the relationship between simulated Chlorophyll a and the other biological variables. This information was then used to project the assimilated Chlorophyll a data on to all biological state variables. They show the nitrogen balancing approach improves the ocean pCO simulation over the case where only phytoplankton and DIC are updated.

At present, the application of state estimation has been confined to utilizing remotely sensed ocean colour Chlorophyll a. To extend this information from the surface into the ocean interior will required coupled biological -physical models. Further, many of the colour images are corrupted by clouds and filling these data gaps is another obvious outcome of state estimation. Finally, it quite possible that the fields that we are most interested in are not sufficiently observed to provide the spatial and temporal coverage desired (e.g. pCO2). For these cases, state estimation data assimilation provides tool to exploit the existing observations to generated the fields of interest.

Data Assimilation Activites

To help articulate existing data assimilation activities both internationally and within Australia we draw from the international of the GODAE Ocean View program, which has set-up a new Task Team called Marine Ecosystem and Prediction (MEP). CSIRO is involved in the MEP- Task Team. The MEP Task Team seeks the integration of new models and assimilation components into operational systems for ocean biogeochemistry and marine ecosystem monitoring, which aims to bridge the gap between the current GODAE OceanView
capabilities and new applications in areas such as fisheries management, marine pollution, water quality and carbon cycle monitoring.

3.1 GODAE (International) Activities

Exploiting Existing GODAE Ocean View Products

Operational Oceanography (OO) products, both hindcasts or reanalyses of the ocean state provide the best representation of the ocean state hence such products should be used by BGC models. However, there is a lack of documented studies explicitly discussing the practical advantages and weaknesses of using constrained versus unconstrained physical forcing to drive biogeochemical models. The key activity here is to provide a more accurate picture on how biogeochemical modellers can benefit from the data products and insight already being generated by GODAE OceanView.

This activity will also investigate how GODAE OceanView products can be improved for BGC simulations. For instance, it is widely recognized that the GODAE systems need to improve their representation of physical variables, such as the vertical fluxes in the upper ocean, which are critically important to biological processes. This activity will require direct inputs and efforts from experts in ocean circulation modelling and data assimilation involved in the development of operational systems to interface with BGC modellers to produce improvements that benefit both physical and BGC simulations.

b) Biogeochemical model development and observing systems

The first aim of this activity will focus on 2 aspects:

(i) the downscaling from global to regional systems, by provision of biogeochemical boundary conditions and the

(ii) further development of 2-way biogeochemical coupling in models to assess bio-physical feedbacks and quantify the impact of biological activity in, for example, heat fluxes.

The second aim is the development of multi-purpose observing systems. Key to this activity will be to identify the essential physical and biogeochemical observations required to constrain the coupled physical and BGC models and to formulate relevant recommendations to further develop the global ocean observing system. The new observations should target of several key biogeochemical applications, such as ocean CO2 flux monitoring, Harmful Algal Blooms and fisheries management.
**Australia Activities**

The Australian activities are closely integrated with the GODAE MEP activities, and the jointly funded CSIRO/BOM/RAN Bluelink 3 project with additional effort focused on the coastal environment.

The Bluelink 3 project will provide the key project for delivering results to GODAE Ocean View activities. With Bluelink 3, several new initiatives were planned. The ocean model is now eddy-resolving in its entire domain (1/10 degree resolution between 75S to 75N). A simple Biogeochemical cycle (BGC) module with phytoplankton, zooplankton, nitrate, detritus, oxygen, and carbon has been added to the ocean model to enable the simulation of phytoplankton and carbon. A re-analysis product with BGC fields will be produced along with an assessment of how physical data assimilation impacts the BGC (GODAE activity a). The Bluelink 3 project will also deliver regional simulations with the global model providing the boundary conditions for the open boundary of the regional (e.g. Great Barrier Reef) and local (e.g. Heron Island) simulations. Both the global and regional models will deliver both forward running and data assimilation products with BGC cycling in the water column and in the sediments. The Bluelink 3 effort intends to exploit the data streams generated by the Integrated Marine Observing System to assimilate into the model and to assess our model simulations. These data streams will include, coastal BGC reference sites, argo drifters, ocean colour products, gliders and moorings.

In addition to the Bluelink project, data assimilation is also occurring in ACCESS-o (the coupled ocean and sea-ice model that Australia is using for its AR5 climate change simulations). With ACCESS-o, a multi-decadal re-analysis product will be generated. Several test re-analysis products have been produced and we expect within the next year to complete a re-analysis simulation with BGC (using the same BGC model that is used in Bluelink 3). The BGC data assimilation will assimilate remote sensed ocean colour Chlorophyll a to constrain the BGC cycle parameters.

The funding of the Wealth from Ocean Carbon Cluster has provided a third data assimilation effort in Australia. The effort requires extending the coastal BGC model to included carbon and the key processes and time-scales required to simulate the carbon cycle in the Australia coastal waters. This new effort will be challenged to exploit limited BGC understanding and observations to develop a realistic representation and simulation of carbon cycling in coastal waters. For this application, BGC data assimilation will be used to assist in parameterising the BGC model, to pursue state estimation of BGC fields and to direct the observing strategy of the both the Carbon Cluster and the IMOS.

**Conclusion**

The field of BGC data assimilation is a relatively new but there are now many examples where the approach has been applied to both parameter estimation and state estimation problems. Data assimilation with BGC models provides a framework to extract information from BGC observations and refine prognostic models of carbon and nutrient cycling in the ocean. The existing GODAE data assimilation systems are an obvious avenue for expanding
data assimilation to include BGC. At present the modifying the GODAE system to include BGC is an important focus of CSIRO data assimilation effort but through the Carbon Cluster the BGC data assimilation effort in the coastal environment will expand.

At present, remotely sensed ocean colour Chlorophyll a is the key data stream to assimilate but we need to evolve the BGC models to actually simulate the observed quantity (e.g. for ocean colour Chlorophyll that is water leaving radiances). Further, better use of other data streams needs to be explored and data assimilation can help identify the optimal observations required to constrain the BGC model for a given problem.

Data assimilation has the potential to improve BGC models, deliver better estimates of BGC ocean state and direct observational strategies. All 3 tasks are important but do them requires continued access to data streams like remotely sensed ocean colour and the allocation of sufficient human and computation resources to tackle these demanding problems.

References


Sea Level and Coastal Impacts from Climate Change, Weather and Seismic Disturbances: a review of research activities and observational requirements.

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1 Introduction

The coastline of Australia’s mainland and islands totals around 60000 km. In this zone around 85% of Australia’s population resides including about 6% of Australian addresses that are situated below 5 m elevation and within 3 km of the coast (DCCEE, 2009). Associated with these coastal settlement patterns are critical services and infrastructure as well as significant economic activity. Information on coastal hazards such as rising sea levels due to anthropogenic climate change and extreme sea levels and waves that are associated with severe storms and tsunamis is much sought after by government and industry to aid in protecting their valuable coastal interests now and into the future.

Analysis of ocean observations and modelling of the coastal ocean underpin efforts to understand the risks posed by marine hazards such as rising sea levels, storm-induced extreme sea levels and tsunamis. Recent research endeavours on these topics in Australia (that are addressed here) can be broadly categorised as (1) those that quantify and understand the causes of past trends in sea level and their impacts, (2) those that quantify extreme sea level risks for current and projected extreme sea level conditions and (3) those that develop improved early warning systems for emergency response to marine hazards. Various linkages and interdependencies exist between the above-mentioned activities both in terms of modelling approaches and data requirements. For example, understanding the causes of past trends in sea level is necessary to refine projections of future sea level rise and reduce uncertainties associated with them. Inundation modelling has similar modelling and data requirements whether applied to tsunami or storm-induced inundation. This paper therefore provides an overview of recent Australian research activities in these areas. Observations on a range of time and space scales are essential to support these activities and so particular attention is given to the observational requirements needed to support these efforts now and into the future.

2 Sea Level Change

Understanding past and future changes to sea level is essential for developing strategies for the management of coastlines and adaptation to projected sea level rise. Tide gauges are a major source of sea level information from which changes in relative sea level (sea levels relative to land-based benchmarks) can be estimated. However, rates of rise differ between coastal and global sea levels due to the interaction of factors such as climate variability (e.g.
ENSO), coastline geometry and the density of coastal observations (White et al, 2005). To
develop a more complete understanding of past sea level change, Church and White (2004,
2006) used principal component analysis to develop spatial functions from the satellite
altimetry, which represent the large-scale patterns of sea level variability. This allows coastal
sea levels measured by tide gauges to be interpolated spatially between tide gauge locations
and leads to more reliable values of Global Mean Sea Level (GMSL).

This research has relied upon a global network of tide gauges sourced from the Permanent
Service for Mean Sea Level (PSMSL; Woodworth PL and Player R, 2003) and includes
Australian baseline sea level data as well as data from gauges administered by ports and
other local agencies. The sea level reconstruction work has also relied on the sea surface
height (SSH) relative to the centre of mass of the Earth along the satellite tracks from three
satellite altimetry missions; the TOPEX/Poseidon, Jason-1 and OSTM/Jason-2 satellite
altimeter missions. As measurements from these missions span different overlapping time
frames, there is a need to ensure the calibration of data from the various missions. Ongoing
measurements of sea level using both satellite and in situ data are continuing to be used for
calibration of the satellite observations (Watson et al. 2011).

The development of global-averaged time series of mean sea level has also provided the
opportunity to better understand the contributions to sea level increases that have been
observed over recent decades, which provides an important basis for narrowing the
uncertainty in future projections of sea level rise. Church et al (2011) have shown that it is
possible to explain the observed sea-level rise since 1970. Ocean thermal expansion and the
melting of glaciers are the two most important terms and together explain about 80% of the
observed sea-level rise since the 1970s. Additional contributions are from changes in the
Greenland and Antarctic ice sheets and changes in the amount of water stored on the land in
reservoirs and ground water reserves.

Through examination of the global energy budget since the 1990s it has been found that
about 90% of the additional energy stored in the climate system is in the ocean.
Furthermore the contribution of aerosols to the global energy budget over this time frame
has led to a significantly enhanced aerosol forcing (a cooling) over the last 15 years. The
budget for the complete 20th century can be closed, if it is assumed that there is a small
long term ongoing contribution, presumably from the Antarctic ice sheet (Gregory et al.
2012, submitted). Comparison of the observed ocean warming and climate model
simulations has resulted in a further detection and attribution of anthropogenic climate
change (Gleckler et al. 2012).

However, our understanding of past sea level, ocean temperature and planetary energy
budgets is currently limited by poorly quantified biases in historical ocean temperature data
collected by expendable BathyThermographs (XBThs). Some recent research aimed at
quantifying biases in historic ocean temperature profiles has led to the assembly of an
extensive data base of historical temperature profiles reaching back to the 1970’s of XBTs
and high precision research instruments including ARGO floats to support these efforts.
3 Storm Surge Modelling

Storm surge modelling efforts in Australia in recent years have been largely motivated by the need to understand current climate risks from extreme events as well as long term impacts at the coast that may be expected due to rising sea levels and changes to weather patterns arising from climate change.

To facilitate large scale comparative assessments of land at risk of inundation due to extreme sea levels combined with future sea level rise scenarios, spatial maps of extreme sea level return periods were developed for Victoria (McInnes et al; 2009, 2012a) and Tasmania (McInnes et al, 2012b) under late 20th century conditions using hydrodynamic modelling and extreme value statistical modelling. In this region storm surges are commonly caused by the propagation of large-scale, mid-latitude cold frontal systems and can be modelled using atmospheric forcing from reanalysis products such as ERA40 or NCEP or climate models (e.g. Colberg and McInnes, 2012). The modelling has typically been undertaken at spatial resolutions of 5 kms to tens of metres and has employed nesting approaches to incorporate information from more extensive but low-resolution regions to the high resolution regions.

Along the tropical coastlines in Australia, extreme sea levels arising from tropical cyclone-induced storm surges are a significant threat. However, the relatively small scale of tropical cyclones, together with their infrequent occurrence and the limited sampling of these events in the short (typically several decades) and sparse coastal tide gauge network means that alternative methods have been developed and applied to understand storm tide risk in these areas. These typically use an idealised cyclone vortex model (e.g. Holland, 1980; Holland, 2008) to specify the sea level pressures and winds, which in turn are used to force a hydrodynamic model. A large, stochastically generated population of tropical cyclones is modelled using this approach to generate cyclone-induced storm surges (e.g. McInnes et al, 2003; Harper et al 2009).

Recently Haigh et al., (2012) used an unstructured hydrodynamic model grid set up over the entire coastline of Australia up to about 10 km resolution to develop a hindcast of water levels over the period 1949-2009. This was then used to estimate extreme water level return periods. In order to capture the forcing from both large scale weather patterns (important mainly around the mid-latitude coastlines) as well as the forcing from tropical cyclones the two broad modelling approaches described above were employed. Modelling of storm surges and tides was achieved by forcing the hydrodynamic model with meteorology from the NCEP reanalyses. The modelled sea levels were shown to validate well against 30 tide gauge locations. To then capture sea level extremes due to tropical cyclones that typically are not well represented in the reanalyses a stochastic cyclone modelling approach was also employed. The modelled values provide a consistently developed dataset of sea levels and their extremes around Australia for a range of coastal applications.

To investigate areas subject to potential inundation in the future sea level rise scenarios have typically been added to values derived from the above-discussed studies and GIS approaches have then been used to map areas likely to be affected by extreme sea levels in conjunction with projected higher mean sea levels at various times in the future (e.g.
McInnes et al, 2012a) Essential to this endeavour is an accurate representation of the nearshore topography (typically obtained from LiDAR at resolutions of 1-2 m). While efforts have increased to collect LiDAR data around many parts of the particularly highly populous regions of the coast to facilitate such efforts, it can be difficult to source relevant data sets as they reside with different organisations at state and local level.

4 Tsunami Modelling

Tsunami modelling efforts in Australia can be broadly divided into two main areas: modelling for early warning systems and modelling for tsunami hazard assessment. Both of these applications use a similar modelling approach in which an initial condition is generated by an undersea seismic disturbance, the tsunami is propagated across the deep ocean and then the coastal inundation is modelled. Typically, the priorities and emphasis for early warning have been on the open ocean modelling, while the priorities for hazard assessment have been on coastal impacts. Tsunamis are long waves (in relation to the ocean depth) and can be readily described with the shallow water wave equations. Boussinesq long wave models are also used (Dalrymple et al., 2006).

In the context of tsunami warnings for Australia, the non-linear shallow water wave model, MOST (Method of Splitting Tsunamis; Titov and Synolakis, 1998) has been used to develop a tsunami scenario database which is used to provide warning guidance for the Joint Australian Tsunami Warning Centre (Greenslade et al., 2009; Greenslade et al, 2011) The database, termed T2, consists of 2069 tsunami scenarios (wave amplitudes and depth-averaged velocities) describing tsunamis resulting from earthquakes occurring along subduction zones in the Indian, Pacific and South Atlantic Oceans. With appropriate scaling, T2 can provide guidance for any subductive earthquake with moment magnitudes ranging from $M_w = 6.8$ to $M_w = 9.3$.

Burbidge et al, (2008) developed a probabilistic tsunami hazard assessment for Western Australia (WA). Their analysis concludes that large earthquakes originating from the Java and Sumba region are likely to be a greater threat than those from Sumatra or elsewhere in Indonesia. The coastline from Carnarvon to Dampier was found to be most vulnerable to tsunamis.

The most effective observing instruments for early warning are tsunameters. These are typically located in deep (~5000 m) water and use Bottom Pressure Recorders to detect the passage of tsunamis. The main advantage of tsunameters is their flexible deep ocean location – they can be installed relatively close to a subduction zone and provide an early indication of the generation of a tsunami. This however, makes them expensive to install and maintain.

Tide gauges, on the other hand, are a more cost-effective way of observing sea level. They are vital for detecting the coastal impact of a tsunami. Given the typical period of a tsunami as it arrives at the coast, existing climate-quality tide gauges typically need to be upgraded to approximately one-minute frequency in order to be useful for tsunami observing. Tide gauges can potentially be useful for early warning if they are located strategically, for example, on offshore islands. One of the issues with tide gauge observations is that since
they are typically located in ports and harbours, the sea-level record contains a number of other components of coastal sea-level variability, and isolation of the tsunami signal can be challenging. Greenslade and Warne (2012) provide more information on the Bureau of Meteorology’s operational tsunameter and tide gauge sea-level network and its effectiveness for tsunami warning.

As for sea level impact assessments discussed in the previous section, accurate representation of the nearshore topography and bathymetry is required in order to model the coastal impact of a tsunami. For verification purposes, post-event surveys documenting the tsunami run-up and inundation extents are vital. Other observing techniques that have been used with some success to observe tsunamis are satellite altimeters (e.g. Titov et al., 2005) and land-based HF radar (e.g. Heron et al 2008).

5 Summary and Discussion

This paper has discussed the analysis, modelling and data requirements of research into twentieth Century sea level change. Coastal tide gauge data over the twentieth Century as well as more recently available satellite altimetry data are essential for this work. In addition, temperature and salinity data collected from sources such as XBT’s and ARGO profilers are important for quantifying the component of sea level rise that is due to changes in ocean density (i.e. thermosteric and halosteric components). This paper also summarised recent coastal modelling aimed at quantifying the risk of coastal inundation from storm surges and tsunamis as well as understanding the future changes to extreme sea level. Tide gauge data is also key to these activities for the purposes of validating models as well as providing measurements of coastal sea levels resulting from tsunamis. While tide gauge data has been collected at around 350 locations around the coastline of Australia and its territories, much of this data is from short term tide gauge deployments. Only 2 tide gauges contain relatively complete records dating back to the 19th Century although paper records of some additional gauges exist but await digitising. Increasing the length of tide gauge records would be of value to the research community to better quantify the changes in mean and extreme sea levels, to support not only modelling and mean sea level trend analysis but also for analysing changes in extreme sea level events. Therefore efforts to digitise such data would be of considerable value.

With regards to coastal storm surge modelling, increasing demands for higher resolution modelling that encompasses not just storm surge but also wave generated contributions to extreme sea levels through processes such as wave run-up and setup are challenging currently available data sources. Challenges for the inclusion of wave effects are the lack of a comprehensive wave buoy network around Australia. Such data is needed to support wave modelling efforts through the provision of model boundary conditions or independent model validation. While some coastlines, such as NSW are well instrumented, other coastlines, such as the south coast are not and in some parts of the coast such as the northwest shelf, wave buoys managed by private industry are not easily accessible to the research community. The second issue is around detailed nearshore bathymetric data sets to allow high resolution modelling of wave setup and runup. In a recent study of extreme sea level inundation in Sydney in which storm surge and wave setup were modelled under
different sea level rise scenarios to support inundation mapping, the sourcing of bathymetric data from different agencies and combining these into a single data set for wave and storm surge modelling became a significant component of the study (McInnes et al, 2012c). As such modelling efforts are increasingly required for climate change adaptation studies, high resolution terrestrial LiDAR as well as bathymetry obtained from Laser Airborne Depth Sounders (LADS) will be increasingly required to support such modelling efforts. Finally, data for the nearshore validation of wave and hydrodynamic models such as currents, depths and extent of inundation during will also required for the validation of high resolution coastal models where for modelling efforts for tsunami or weather-related extreme sea level impacts are required.

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Key Bluewater observing systems and datasets; and their use in modelling

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1. Introduction

In this paper the main in situ Bluewater data systems are summarized and their application to ocean modelling is described. Observations are collected for characterizing aspects of the ocean. These include, determining the spatial structure of mean properties through the water column, resolving temporal changes at seasonal, interannual, and multi-decadal, capturing global parameters such as sea level, heat content, and to track fluxes of heat, salt and carbon through the atmosphere and ocean. Observation systems need to be designed to resolve both high-frequency changes for operational requirements as well as high-quality long-term time series for climate studies. High-quality datasets are used to initialise and to provide model forcing fields, to assimilate into models and to provide reference fields for model validation. To ensure full integration of observations with models, a systematic and long-term strategy incorporating development of metadata standards and automated data analysis, implementation of large-scale observatory programmes, improvement of observation-model links, and efficient sampling strategies. Finally, these elements should be tied together in an observation-modelling framework, coordinated by international organizations, to improve our understanding and quantification of open-ocean dynamics.

2. Observing Systems

Argo Array

A global array of profiling floats that measure temperature and salinity down to 2000m every 10 days in real time (www.argo.net). The array has proven to be very robust with many floats surpassing their projected lifespan- it has now reached a design coverage of more than 3000 floats with a spatial resolution of 3°x3°. This is the first time that the oceans have been sampled with a full global coverage and Argo is now the essential and dominant in situ data stream for ocean and climate research and prediction/reanalyses

Australian deployments of 60 floats/year are required to maintain the 50% contribution in the Australian region which will sustain an array of 210-230 floats. In the medium term there is no prospect of “operational” funding and support must remain in research sector. The Argo core mission does not measure BGC parameters, nor in marginal seas or under ice.
**XBT network**

Repeat temperature sections through regional flow systems to monitor variability of regional circulation and temperature structure. Two modes of operation are maintained: frequently repeated (FRX - fortnightly with low spatial resolution) and high density (HD - typically once per season but at eddy resolving spatial sampling). There are nearly 20 years of sustained sampling on some lines giving insight into decadal flow variability. These lines are the only existing means of monitoring regional current transport and heat flux variability. However, they are an imperfect tool for WBC monitoring – they are shallow (700m); provide no velocity data; or no corresponding salinity, biogeochemical or ecosystem information.

Australia is a major international contributor to this network (Figure 2) and has a solid longterm partnership with the US program (dominant global contributor). We have proven technical capability and strong relationships with shipping industry and operators.

The quality control (QC) system is well bedded down, as is data dissemination via the Global Temperature Salinity Profile Program (GTSPP) and to the USA’s National Ocean Data Centre (NODC) in delayed mode.

**Ship of Opportunity Network**

Available vessels, both commercial and research are used as platforms to collect a range of observations including SST, surface flux, biogeochemical, carbon and plankton measurements. Within the IMOS SOOP Facility there is a relatively sparse set of lines measuring different parameters due to ship requirements and availability.

Gaps: coverage not national - limited BGC/ecosystem coverage off east and west coast; no lower trophic information on most lines; no consistent data treatment or dissemination to broader community apart from CO2 data; marine meteorological information poor and insufficient for air/sea flux estimates.

High accuracy sea surface temperature data are collected to extend coverage in the Australian region and calibrate surface temperature products from satellites (via the Global High Resolution Sea Surface Temperature Project GHRSST [http://ghrsst-pp.metoffice.com/pages/GHRSST-PO/index.htm](http://ghrsst-pp.metoffice.com/pages/GHRSST-PO/index.htm)). IMOS funding has allowed several new vessels to be instrumented with hull-mounted sensors and real-time transmission capability.

High-quality meteorological measurements have been set up to enable the calculation of accurate air-sea flux estimates. Through IMOS meteorological measurements on several research vessels of opportunity were upgraded. The data streams will be contributed to the global Shipboard Automated Meteorological and Oceanographic System (SAMOS) project ([http://samos.coaps.fsu.edu/html/](http://samos.coaps.fsu.edu/html/))

Several research vessels have been instrumented with an underway pCO2 system. This data stream is aimed primarily at filling regional and seasonal gaps in an effort to improve the seasonal climatology of air-sea carbon fluxes, particularly on the Australian shelves and offshore regional seas. The instrumentation of a repeat SOOP line on l’ Astrolabe which provides repeat transects in October to March to track the variability in carbon fluxes over
the poorly sampled Southern Oceans. The observational programs on these ships for CO₂ is integrated with international efforts to establish the ocean uptake of CO₂ (http://www.iocccp.org/) and contribute to the Surface Ocean Carbon Atlas project (SOCAT), developing gridded CO₂ products for flux estimates and model testing.

Overall, SOOP is a highly cost effective platform. There are many biogeochemical (BGC) and ecosystem parameters that could not be measured without the SOOP program. The ideal platform is one that has combined BGC, ecosystem and physical measurements on the same ship, but that is not always possible due to ship limitations and not all issues require a complete set of measurements.

**Deep Ocean Time Series Sections**

These sections provide the only means of collecting high-quality, high-resolution (vertically and horizontally) observations of the main properties over the full ocean depth. They are therefore the only method of tracking water mass changes in the deep ocean (below the reach of Argo) and tracking the global carbon and biogeochemical inventories (e.g. oxygen and major nutrients). These data also provide the highest standard for calibration of Argo salinity and temperatures. The high cost of implementing these sections is balanced by the fact that they provide many parameters at high accuracy that cannot be measured in any other way. Unfortunately the high cost means that the lines are relatively sparse and are only repeated every 5-10 years. Australia takes responsibility for the re-occupation of key sections in ocean surrounding Australia - Southern Ocean (south of Perth, and Tasmania and western Pacific at 170°W). The sections are a component of the International Repeat Hydrography and Carbon Program.

Gaps: National lack of ability to measure chlorofluorocarbons (CFCs) or tritium/helium. Ship time and operational costs are subject to individual applications to the Marine National Facility and annual research funding.

**Drifting Buoys**

For several years satellite-tracked drifting buoys have been deployed as Lagrangian drifters which follow the path of water parcels at a selected depth. The most recent version is the Surface-Velocity Programme Barometer (SVP-B) drifter which provides both SST and air pressure and surface currents (resultant current arising from Ekman and geostrophic components). The buoys are battery powered and last for up to 2 years and are easily deployed by ships crews. They provide the primary source of air pressure over the ocean (vital for NWP) and the SST data they collect are important climate datasets. The surface current observations provide large scale current patterns and are central validation product for model and satellite derived currents.

**Tropical Moored Buoy Arrays**

A globally coordinated network of moored buoys that collect both atmospheric (winds, pressure, temperature) and oceanic information (temperature, velocity) in real-time has been implemented in the equatorial oceans. This array is the core of the ENSO observing
network. Australia is a heavy user of this data stream, both for research and operational purposes, but currently plays no current role in operating this infrastructure.

Gaps: Indian Ocean array (RAMA) is only partly completed. There is a ‘hole’ in the array over the maritime continent and north of Australia.

**Bluewater Glider**

This may be thought of as a ‘smart’ Argo float. That is their depth is controlled by changing buoyancy but unlike floats they also have a horizontal velocity component. This means their paths may be controlled by externally rather than being a passive drifter. However, they only achieve forward speeds of 20-25 cm/s which limits their ability to negotiate strong currents. Temperature, salinity, dissolved oxygen, turbidity, chlorophyll and CDOM data are collected. As for floats, average velocities between surface fixes can be estimated.

The glider deployments are designed to capture the behaviour of the major boundary currents around Australia (EAC, Leeuwin Current). While the deployments have been very much in pilot mode, where the strengths and limitations of the instruments are being determined, the aim is to generate sustained time series of these current systems. At present glider deployments have been made off eastern Tasmania (EAC Extension), southern Australia (Leeuwin Current Extension), NSW (EAC eddy), and Western Australia (Leeuwin Current). Further deployments to ‘transects from the SOTS site to Hobart’ and north Queensland outside the GBR’ have been included.

**Deepwater Mooring Arrays**

Bottom-anchored moorings supporting instruments that span the water column are required for observing the time-varying ocean currents and water properties over sustained periods of a year or longer. These systems are deployed at strategic locations to capture boundary currents (Gulf Stream, EAC), flow through ‘chokepoints’ (Drake Passage), and other dynamic features. The state of the art for mooring deployment duration is around 1 year for surface moorings and 2-2.5 years for subsurface systems. While discrete conductivity-temperature-pressure sensors and some other devices can easily accommodate a 15-minute sample rate for 2 or more years, many of the other instruments now available exceed their battery or memory capacities after about a year at this sample rate. The extended durations cited above require sampling at reduced frequency, risking aliasing error. The current systems are very energetic and an extremely robust and expensive array is necessary. Another design requirement is that a transport array fully span the current being studied. Apart from those regions where a current is confined bathymetrically and it is feasible for the array to extend that full distance, the point where a particular current ends can be quite difficult to determine. New IMOS deployments include the ITF array across Timor Strait and the new EAC array east of Brisbane.
Biological Data Streams -

In general observing systems for biological data have lagged well behind those of physical properties. This is mainly due to the difficulty of actually measuring biological processes and the fact that appropriate and robust technology is not yet available. However, it must be said that a further constraint is that few international sampling collaborations have been developed to coordinate a global observation program. Two areas in which some progress has been made and which offer the potential to generate long-term biological time series are presented below.

Bioacoustics are collected by deep water echosounders at single and multiple frequencies to understand pelagic ecosystems. Instruments are operated on research vessels, merchant ships and many fishing vessels on transit over regions of high regional, ecological and oceanic importance to provide sustained repeatable basin scale observations of micronekton communities. This is the only means of sampling species distribution at this mid-trophic level. Mid-trophic level organisms regulate the primary production involved in biogeochemical cycles and are forage for top predators. Despite the enormous pelagic realm these organisms occupy and their pivotal role in the functioning of ecosystems linking biogeochemistry to the distribution and abundance of predators, they remain one of the least known components of the ecosystem. Research us underway to fully utilise these data, to quantify and interpret the acoustic output and to assimilate data into ecosystem models.

Continuous Plankton Recorders - The AusCPR survey deploys Continuous Plankton Recorders (CPRs) behind ships of opportunity (SOOPs) and on research vessels in the Southern Ocean in collaboration with the international Scientific Committee for Antarctic Research (SCAR). CPR tows collect plankton samples for subsequent identification in the laboratory. The device can carry instrumentation (e.g., CTD-F, multispectral fluorescence) onboard. Data products from AusCPR are abundances and species composition of phytoplankton and zooplankton communities, as well as the physical data (temperature, salinity, fluorescence) simultaneously. Plankton produce half the primary production on Earth, contribute to the biological pump drawing-down CO₂ into the deep ocean, support most marine life in the oceans, and are extremely sensitive sentinels of climate change. A critical gap limiting the predictive capability of our ecosystem models is our lack of knowledge on how the plankton community will respond to climate change.

3. Data Quality Control

Observations may both be used to characterize an aspect of the ocean, or for input to an ocean model. In each case we must ensure that erroneous data are removed by applying appropriate data quality control methods. These includes both the more real-time techniques applied in operational systems as well as delayed mode procedures to produce high quality data for climate research. The most successful and efficient QC procedures are coordinated by international data science teams (eg. Argo SWT). Such teams include representatives from all of the data operators, and user groups to ensure that development of metadata standards and automated data analysis
4. Model Applications

**Initialization and surface fluxes**

*Overview* - Ocean model forecasts rely on external forcing to alter the model state once initial conditions are implemented. An important external forcing is air-sea fluxes (the other is side boundary conditions), which represents the interaction of the atmosphere and ocean. The physical fluxes are momentum (wind), heat and mass (evaporation and precipitation) that act on the surface of the ocean to mix, inject momentum, heat and cool, add and subtract mass, thereby changing density, currents and water mass formation.

The momentum flux is fairly well observed thanks to a succession of satellites carrying scatterometers (Seasat-A, ERS-1, ERS-2, NSCAT, QuickSCAT, ASCAT, OceanSAT2) and providing global, high-resolution (~25km) coverage on a daily basis. While the importance of air-sea fluxes is widely recognized for understanding processes from waves generation up to inter-annual variability, there is only a handful of heat and mass flux products available for ocean modelling and forecasting. The flux products have large uncertainty due, in part, to the limited observations available for development and validation. The lack of suitably accurate satellite observations is a major hindrance to developing high spatio/temporal flux products.

*Products available* - Flux products can be categorized as in situ-based, satellite-based, reanalysis, and hybrid. Readily available turbulent heat flux products (excluding the radiation components) include: FSU3 (Florida State University fluxes); NOC version 2 (National Oceanography Centre); HOAPS2 (Hamburg Ocean-Atmosphere Parameters from Satellite data); IFREMER fluxes (French Research Institute for Exploitation of the Sea); J-OFURO (Japanese Ocean Flux Data Sets with Use of Remote Sensing Observations); GSSTF2 (Goddard Satellite-based Surface Turbulent Fluxes); OAFLUX (objectively analysed fluxes); NCEPR2 (National Centers for Environmental Prediction) JRA (Japanese 25-year reanalysis); ERA-40 (European Centre for Medium Range Weather Forecasts reanalysis).

*Gaps* - The range of flux products suffer from various deficiencies for the coastal ocean modelling community such as coarse temporal (monthly) and spatial (1 degree) resolution, incomplete coverage (some are regional) and poor resolution towards the coast (due to satellite footprint, or coarse NWP grids). The uncertainty of the flux magnitude can also be high with poor agreement between the various products and even disagreement on the sign of the heat flux in some regions.

Efforts are being made to obtain the necessary high quality observations across the range of variables required to estimate bulk fluxes. Programs such as OceanSITES and SAMOS (Shipboard Automated Meteorological and Oceanographic System) aim to consolidate and unify the collection of mooring and ship observations although the networks are sparse and not necessarily optimized for coastal applications.

The Australian IMOS project has undertaken the collection of ship-based fluxes from three research vessels since 2008. This operates in a “ships of opportunity” mode, collecting observations wherever the vessel goes. Bulk flux observations are also collected on a
mooring in the Southern Ocean, which while not in a coastal setting, can be used to verify the flux uncertainty in various flux products. These bulk flux observations can be used directly when collected in the coastal region, but also to improve the flux products listed here.

**Data Assimilation**

**Overview** - While advances in methods and computing power have produced major improvements in ocean models there are still limits on model resolution which means that there are unresolved ocean processes. Observations and ocean dynamics are brought together in the large range of data assimilation techniques. Data assimilation (DA) is used to estimate initial or boundary values data, and to provide model hindcasts, nowcasts and forecasts. DA may be thought of as a means of interpolating sparse observations and smoothing noisy data or correcting model trajectories back to realistic targets. Many of the techniques have come from meteorological forecasting where significant advances have been made in the past decades. Ocean applications have been mainly in the assimilation of physical data although there is increasing development of methods to assimilate biogeochemical data.

Since the assimilation of data into a model adds a further potentially extensive computing overhead, when the system is applied to a large domain (such as a global model) compromises need to be made. For a high resolution model only a relatively simple DA scheme may be used – if a more sophisticated system is employed then the model resolution would need to be much coarser. DA may be used to provide model hindcasts, nowcasts and forecasts. Long model runs in hindcast mode provide ocean re-analyses that are a valuable tool for climate studies such as SODA and GECCO. Nowcasts and forecasts are the focus of more operational prediction systems.

**Data** The central in situ dataset used in all DA systems is Argo. It provides global coverage, has both real-time and delayed mode inputs and includes both T and S profiles. Further XBT, CTD and fixed buoy observations are also used. The temperature and salinity profile data are assimilated at all depths. In the operational system the data are obtained from BATHY, TESAC and BUOY messages distributed by the Global Telecommunications System (GTS). These message formats are used to report expendable bathythermograph (XBT) data reported by Voluntary Observing Ships (VOS), and data from the Argo profiling floats and TAO/Triton equatorial moorings respectively. Quality control checks on these data include track, stability, background and buddy checks

Assessment of open-ocean ecosystems relies on understanding ecosystem dynamics, and development of end-to-end ecosystem models represents an approach that addresses these challenges. These models incorporate the population structure and dynamics of marine organisms at all trophic levels. Satellite remote sensing of ocean colour and direct at-sea measurements provide information on the lower trophic levels of the models, and fisheries studies provide information on top predator species. However, these models suffer from a lack of observations for the so-called mid-trophic levels, which are poorly sampled by conventional methods. This restricts further development, and acoustic observations can be linked to the ecosystem models to provide much-needed information on these trophic
levels. To achieve this, the models need to be tailored to incorporate the available acoustic data, and the link from acoustic backscatter to biologically relevant variables (biomass, carbon, etc.).

**Validation**

Another major application of observations is the validation of model outputs. We will only have confidence in a model estimate if it is verified by comparison with an equivalent observational value. We also note that such reference data should also be independent of the model estimate. For example, only data withheld from the assimilation are used to validate a DA forecast. In general, to make model validation more systematic comparisons are made between model and observation for a set of standard reference parameters or ‘metrics’. These consist of ocean properties that represent an important physical process, that capture the behaviour of a region, where observations are available and which can be easily extracted from a model. Examples include, the mean property on a surface, the meridional overturning circulation, an ENSO SST index, the ITF strength, the timeseries of flow at specific chokepoints or XBT transects. Observations from ocean climatologies (CARS, WOA), high-density XBT sections, long-term mooring arrays provide important data metrics. This validation exercise aims to test the ability of a model to capture the mean and time-varying nature of ocean properties, the structure of currents, fronts and eddies, the changes through the water column.

5. **Observing System Design and Assessment**

While the previous aspects generally have involved the input of observations into models; to initialise, force, adjust or validate. However, models are increasingly being used as tool to inform the design, deployment and assessment of ocean observing systems. This is both a process of looking back, to evaluate the relative importance of existing or past observational components (Observing System Experiments, OSE), or looking forward (Observing System Simulation Experiments, OSSEs) to evaluate the potential impact of future observational programs. These methods generally are based on DA approaches and a suite of ensemble-based and adjoint-based tools have been developed. Model output may also be used to design the configuration of observing systems such as mooring arrays.
6. Figures

Figure 1: Location of active Argo floats by operator country. Source: Argo Information Centre.

Figure 2: XBT drops collected in a single year as part of the global Ship-of-Opportunity network coordinated by JCOMM-OPS.
Figure 3: Locations and state of implementation of the Tropical Moored Buoy Array. From http://www.pmel.noaa.gov/tao/global/global.html

Figure 4: Locations of the CLIVAR/Carbon Repeat Hydrographic lines by country. Australia via CSIRO, the ACE CRC and the Australian Climate Change Science Program (ACCSP) occupies 3 meridional lines in our region.
IMOS/AODN Ocean Portal: tools for data delivery

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Introduction

Established in 2007, Australia’s Integrated Marine Observing System (IMOS) has set out to build a collaborative research infrastructure for ocean observations. Over the last 4 years a robust information infrastructure has been developed to make all IMOS data discoverable, accessible and reusable. A broader definition of an information infrastructure could encompass the people, processes, procedures, tools, facilities, and technology which support the creation, use, and transport of information. However, the goal of an information infrastructure in the context of a regional ocean observing system should be to deliver the critical information required by society to meet multiple challenges. These range from government policy (supporting policy formulation, the monitoring of policy compliance and the assessment of policy effectiveness) to underpinning commercial decisions, and from science to public use. Important though it is, an information system needs to move beyond harmonized data exchange to promote a streamlined and efficient mechanism for meeting societal needs. IMOS is research infrastructure supporting the marine and climate research community and the IMOS Ocean portal (http://imos.aodn.org.au) aims to fulfil this function. However, Australia’s need for marine information extends beyond this community and encompasses Commonwealth agencies, State governments, private industry and the public. This paper describes the IMOS Ocean portal and how this information infrastructure has grown to support the wider community through the establishment of the Australian Ocean Data Network (AODN, http://portal.aodn.org.au), to make all marine and ocean climate data discoverable and accessible through a national ocean data commons.

IMOS Ocean portal

The intention in setting up the IMOS portal was to provide an intuitive, easy to use point of access for IMOS data. The approach developed a map-based display where all IMOS data could be located and easily accessed underpinned by rich metadata which could be interrogated through a refined search capability. The features of the information infrastructure, with the discovery portal as the outlet, are simple. The guiding principles are to use Open source tools which are standards based (examples are Open Geospatial Consortium Web Map Service, Web Feature Service, Sensor Observation Service, Catalog Service for the Web, OPeNDAP, NetCDF, Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH) with metadata conforming to the ISO19115 Marine Community Profile, with the vocabulary service linked to NASA’s Global Change Master Directory (GCMD)); its Governance is provided through information on usage policies and licence agreements, all of which are available on the IMOS website (www.imos.org.au) – it should be noted that all IMOS data is offered freely and unencumbered subject to an acknowledgement of use; it is a distributed data network connected through machine
interfaces, employing (mostly) web services delivered through Geoserver, GeoNetwork, RAMADDA, and THREDDS.

The IMOS distributed data network utilises the Data Fabric, Australia’s national data storage system. It enables groups and communities to easily store, maintain and share their data. The system is available to all Australian researchers and free within stated limits. The storage system, accessed through the iRODS middleware (www.irods.org), sits on top of the Australian Academic and Research Network (AARNET), the high-capacity internet service (Fig. 1). The Data Fabric is currently managed by iVEC in Western Australia on behalf of the Research Data Storage Initiative (RDSI, http://www.rdsi.uq.edu.au/). IMOS data is distributed about this network (Fig. 2), to some extent mirroring the structure of the IMOS nodes. Data and metadata catalogs (locally known as the MEST (Metadata Entry and Search tool), the IMOS version of Geonetwork) are located around the country, and these catalogs are harvested to a master catalog maintained in Tasmania, home of the IMOS eMarine Information Infrastructure facility. The network provides IMOS with publicly available data directories, with much of the data stored in CF-compliant netCDF data structures utilising OPeDAP and THREDDS servers, and a private archive for raw data. Delivering large datasets through THREDDS allows the utilisation of sub-setting and aggregation services server-side, thus reducing the data download traffic to the user.

The Australian Ocean Data Network (AODN)

The vision of the AODN was articulated in 2005 by the Australian Ocean Data Centre Joint Facility (AODCJF), a joint venture between the six Commonwealth Agencies1 with primary responsibility for marine data. This was “to put in place, by June 2011, an interoperable, online network of marine and coastal data resources, including data from the six AODCJF partner agencies, supported by standards-based metadata, which will serve data to support

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1 Australian Antarctic Division, Australian Institute of Marine Science, Bureau of Meteorology, Commonwealth Science and Industrial Research Organisation, Geoscience Australia, Royal Australian Navy.
Australia's science, education, environmental management and policy needs: Australia's digital ocean commons.”

In 2010 the AODCF looked to IMOS to turn this vision into a practical reality, utilising the IMOS information infrastructure to establish an AODN (http://portal.aodn.org.au). It became clear quite early on in this process that extending the infrastructure set up for IMOS, which had full control in specifying data formats and metadata descriptions, needed to be more flexible to cope with more diverse data, metadata, and delivery mechanisms. In particular, extending the distributed network to include web servers not part of the Data Fabric, and to include metadata not strictly adhering to ISO standards, caused a re-think of the portal architecture, moving away from a Java ZK framework to a Groovy-Grails-extJS structure. This move also allowed us to incorporate the full Geonetwork searching capability, including faceted searches, and to set up regional views of the AODN. The first regional view is the Western Australian view, created in August 2012 (http://wa.aodn.org.au/portal/), which presents IMOS, Western Australian Marine Science Institution (WAMSI), University, large collaborative programs and State Government data in a regional context. The infrastructure (fig. 3) is now common to both IMOS and AODN.

![Image](https://via.placeholder.com/150)

**Fig. 3** – Overview of IMOS/AODN information infrastructure

The list of contributors to the AODN now includes a wide range of institutions, regions and data types. Institutions now delivering data and / or metadata include Commonwealth agencies, Commonwealth government departments, State government, Universities; national-scale programs include IMOS and CERF (Commonwealth Environmental Research
Facilities) and the new National Environment Research Program’s Marine Biodiversity Hub has included AODN in its data management plan. AODN data now spans from ocean through to coastal regions and estuaries of Australia, and will soon link with the coastal program of the Terrestrial Ecosystem Research Network (TERN). Through an Australian-New Zealand government agreement to enhance collaboration in marine research, AODN has worked with the New Zealand National Institute of Water and Atmospheric Research (NIWA) to make NIWA a node of the AODN. Data is available across a wide range of disciplines – physical, biogeochemical, biological, ecological, and, some initial socio-economic data – in a range of digital formats, including imagery and documents. The intention over time is to provide access to model datasets (simulation and climatology) as well as observations, and AODN has started this collection with CSIRO products CARS (CSIRO Atlas of Regional Seas), SETAS (Southeast Tasmanian pre-operational model) and RIBBON (sample output from the whole-Australia Coastal Ocean model). The recent establishment of a Marine and Climate node of the RDSI offers potential storage for a large collection of modelled products, which would be linked into AODN and provide resource datasets for MARVL, the Marine Virtual Laboratory funded through the National eResearch Collaboration Tools and Resources program (www.nectar.org).

The functional diagram of user interaction with the AODN portal is shown in Fig. 4. A user either selects a ‘search’ query to discover what data is available, or uses the map to display data sources directly from a menu of contributing organisations/programs. The portal features an option to save searches and map displays for future use.

![AODN Functional Diagram](image)

**Fig. 4 – Interacting with AODN**

An organisation wishing to become a node of the AODN, and make their data publicly available, is encouraged to follow a protocol involving recognised standards for both their
datasets and the metadata, with delivery through a web service. To aid this process we have produced ‘the AODN Cookbook’.

As an example of model / observation interaction Fig. 5 shows a simple overlay of different data sources highlighted in the layer panel.

![Fig. 5 – snapshot from AODN portal with data layers](image)

This brings together surface currents from the RIBBON model, sea surface temperatures from satellites, tracks from ships of opportunity showing phytoplankton abundance, tracks of glider deployments, locations of acoustic curtains for tagged fish detection and fixed mooring platforms. Further clicking on a map feature will bring up additional information about the feature and, frequently, direct access to the data. At the time of writing, the AODN contains more than 10,000 metadata references and more than half these have data or data products attached.

References

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Remote Sensing: Observing a Big Country

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Remote Sensing provides Consistency at Scale

The ability to automatically record large areas rapidly with a daily (or better) repeat frequency gives sensors on satellite platforms orbiting the Earth a unique advantage when observing ocean dynamics. Phenomena with characteristic sizes of 10s to 100s of km that change continuously over that scale cannot be practically sampled with either the spatial or temporal density necessary by any other means (Fig. 1a). For a large country in a big ocean, remote sensing is an essential component in Australia’s marine observing system. While remote sensing is a powerful measurement tool, it is only able to provide direct observations of the surface (or very near-surface) of the ocean. This nevertheless is an important boundary condition for 3D models and, in addition, provides a record of the part of the ocean with which most human interaction occurs and which is also arguably the most important interface in the Earth’s climate system.

Figure 1: Contrasting remote sensing observations (a) Eddies in the East Australian current from a single surface temperature image and (b) a twenty year record of global mean sea level from satellite altimetry (CSIRO).

Although a technologically complex measurement technique, the high stability of satellite orbits enables the accurate calculation of observation conditions so that factors affecting the signal (such as illumination and view conditions and atmospheric effects) can be consistently accounted for. This enables automation of the measurement process, leading to a high degree of confidence in the repeatability of observations. Satellite remote sensing is thus able to fulfill a role as a tool for long-term monitoring as well as short term dynamics. Nowhere is this better demonstrated than in the satellite altimetry record of global sea level (Fig. 1b). Another benefit of observational consistency is that in-situ observations at relatively few locations can be used to calibrate and monitor each sensor for widespread use, leading to highly efficient operations.
Thermal, Optical and Temporal Observations

Satellite sensors can make measurements of the ocean wherever the atmosphere is transparent to electromagnetic radiation. This includes microwave, infrared and optical wavelengths, providing a window on a rich variety of phenomena. Direct passive observations can be of radiation intensity, or the spectral variability of intensity, while active observations (where an illuminating signal is transmitted from the sensor) include using signal transit time and phase to measure distances (altimetry) or form images (radar). Three of the most commonly used data types are described here.

Sea Surface Temperature

Sea surface temperature images based on thermal infrared imagery, and more recently microwave bands, have been a mainstay of ocean remote sensing since the inception of satellite sensors over 30 years ago. Predominantly these data have come from the operational meteorological satellites with constellations, at times, providing as many as six or eight observations globally every 24 hours. Since the radiation observed is emitted directly from the target object, these observations can be made by both day and night. The data have been key to discovering and investigating a whole range of current, eddy and upwelling phenomena (Fig. 1a, Fig 2a). They are also critical in understanding not only the diurnal heat dynamics within the ocean, but also the energy transfer between the atmosphere and the ocean globally over the longer term (Fig. 2b).

Ocean Colour

Sunlight reflected from within the surface layer of the ocean is modified by its interaction with the in-water constituents. Ocean colour is the technique of measuring the resulting spectrum to deduce the nature and quantity of those constituents. One approach to analysis is to form so-called “true-colour” imagery by combining spectral bands in such a way as to mimic human vision and to examine colour differences (Fig. 3a). A more quantitative approach, based on either empirical relationships or an understanding of the physics of in-water radiative transfer, can be used to derive a whole range of indices of water content, including abundance of chlorophyll (eg. Fig. 3b), suspended solids, dissolved organic matter, and properties such as light penetration depth.

Figure 2: Satellite sea surface temperature images of (a) the Bonney Coast upwelling (IMOS) and (b) the global SST anomaly (present – historical average) synthesised from multiple sensors (GHRSST: https://www.ghrsst.org/data/todays-global-sst/).
Ocean colour measurements are an inherently difficult observation because the amount of sunlight reflected from the ocean is only a few percent of that which is scattered in the atmosphere, so satellite observations are burdened by the requirement to compensate accurately for a significant atmospheric contribution. Consequently it was only relatively recently, with the launch of the SeaWiFS sensor in 1997, that data products began to become routinely available. Nevertheless ocean colour data are realising their potential to improve our understanding of ocean biology in the same way that SST observations have for ocean thermodynamics.

Figure 3: (a) True colour imagery shows coccolithophore blooms off NE Tasmania (CSIRO), while specialised derived products, such as Chlorophyll abundance (b), can be used to quantify the biological productivity (NASA).

Sea Surface Height
The transit time for a radio pulse transmitted from a spacecraft and reflected from the ocean surface can be used to provide a very precise measurement of the distance between the spacecraft and the ocean. If the spacecraft orbit is known with precision, then the deviation of the sea surface height relative to the geoid, due to tides and geostrophic currents, can be determined. Additionally, measurement of the return pulse shape and its magnitude can also be used to infer significant wave height and surface wind speed. The launch of Topex/Poseidon mission in 1992 signalled the beginning of satellite altimetry and the series of breakthroughs in understanding the data from it, and subsequent instruments, has led to a revolution in ocean observing.

Figure 4: An altimetry-derived map of sea surface height anomaly (LHS) and geostrophic current vectors overlaid on an SST image off Sydney in 2011 (IMOS).
Future Development
There are several other ocean parameters that can be derived from remote sensing, including sea surface salinity, roughness, the presence of slicks, and, in shallow waters, bathymetry. Many of these are far from routine observations that are still undergoing research and development using experimental sensors. As measurement understanding and analysis techniques continue to progress, the most valuable of these new data will undoubtedly become more widely available and used.

Increasingly remote sensing data is becoming ubiquitous to provide spatial and temporal context for surface and sub-surface measurements. The IMOS Ocean Current web site (http://oceancurrent.imos.org.au) provides numerous examples where multiple satellite and in-situ data are integrated to complement one another (Fig. 6).

Figure 6: Images from the IMOS Ocean Current web site showing merging of complementary data sets. (a) Satellite SST data provides context and meaning for surface current vectors derived from an IMOS coastal radar at Coffs Harbour. (b) & (c) Contemporaneous Chlorophyll and SST maps off Perth, together with coastal radar, Argo floats and drifter buoys reveal the dynamics and relationship between temperature and biology.

The ultimate expression of data merging is in ocean model-data assimilation. Modelling captures process understanding, while observations record an expression of the state of the system. Remote sensing data, with their broad coverage and high repeat frequency, have proven to be the most valuable input to ocean modelling (eg. in Bluelink) because, in assimilation, every data point, together with an estimate of its uncertainty, contributes to helping the model reflect reality. As remote sensing technologies and techniques mature and become more routine and widespread, parallel advances in understanding the ocean environment will result in progressively more and more accurate models.

IMOS has played a key role in harnessing the power of remote sensing for marine observation, through support of production of national SST and ocean colour data sets, and of in-situ measurements for calibration and validation of both those and altimetry data streams. The remote sensing data provides essential context for many of the other observations that IMOS produces. It informs the interpretation of those data enabling the pursuit of an integrated research program leading to more holistic understanding of the marine environment and ecosystem.
ROMS Modelling in Australia: current status, plans and aspirations

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1. Introduction

We describe current and near future applications of the Regional Ocean Modelling System (ROMS; http://www.myroms.org/). In addition, we make reference to the use of data streams used to force and validate these models including those from the Integrated Marine Observing System (IMOS; imos.org.au). The problems associated with forcing fields (e.g., meteorology) are identified along with the fields needed for model initialisation (e.g., CARS). The range of data products that can be accessed for model validation are outlined. Future areas of development are identified. One recommendation is that an annual workshop be held of ROMS oceanographers to facilitate model development, our understanding of the physics and data uptake. A recent (successful) MARine Virtual Laboratory (MARVL) proposal seeks to provide Australian modellers with a semi – automated process for downloading much of the needed data and software to expedite the implementation of regional models. We comment below. Observation uptake (Stenberg) and the use of assimilated models to evaluate the importance of data (Oke) will be addressed in other presentations at the workshop.

2. The Applications, set-up, domain and forcing.

The applications and aims of ROMS vary for each modelling group and region.

Figure. The domains of ROMS models. The numbers shown indicate the models:

1) South-East ROMS - NSW,
2) Southern Australian Regional Ocean Model - SARDI,
3) High Resolution Spencer Gulf Model (hydrodynamic, waves, particles, NPZD - SARDI)
4) Kimberley (internal tides) – Ivey
5) Pilbara (internal tides) – Ivey
6) Cyclone impacts – Ivey
7) Ningaloo upwelling – Lowe
8), 9) and 10) – Pattiaratchi.
11) WA/SA very large scale model (dashed) – Pattiaratchi
**U.W.A.:** ROMS is used by UWA researchers through the whole state: from the Kimberley region to the north extending into south-Australia. Within this domain there are a number of applications focussing on specific regions and processes.

The larger scale model extends from the Kimberley to Bass Strait, *(11 in the Figure)* and uses curvilinear-orthogonal grids with 2-4 km horizontal resolution for the entire region with 1-2 km resolution in the sub-domains (north-west, central-west and south-west) with 30 sigma layers in the vertical water column. The model was forced with daily atmospheric (wind and air pressure) and air sea fluxes (heat and freshwater). The model open boundaries were specified with monthly salinity and temperature climatology. The model forcing included tides and monthly mean sea levels. The model initial and forcing data (2000-2010) were extracted from various global and Australian oceanographic/meteorological data sources and interpolated in to surface horizontal mesh and open boundary vertical sections.

In north-west Australia, ROMS is used in a number of coastal and shelf process-studies *(4-11 in the Figure)*. A nested ROMS model has been developed to examine the regional circulation and transient upwelling along the coast of Ningaloo Reef validated with extensive shelf mooring datasets *(7 in the Figure)*. A coarse ROMS model extends ~1000 km with ~2 km grid resolution along the north-west coast from south of Shark Bay to north of Port Hedland. It is initialised and forced at its open boundaries with surface elevations, velocities, salinity and temperature fields from the 1/12° resolution global HYCOM model. A fine-scale ROMS model surrounding Ningaloo Reef, with grid resolution ~ 200-500 m, is nested within the coarse ROMS model. Both models are driven by hourly wind vector fields (0.3° resolution) available from the UCAR Climate Forecast System Reanalysis, with additional atmospheric properties for surface heat flux terms provided by the NCEP/NCAR Reanalysis at 2.5° resolution. Barotropic tidal forcing is provided by the Oregon State University (OSU) TPXO Indian Ocean Atlas (1/12° degree regional model). The model is being applied to a number of projects focused on ocean processes along the Ningaloo coast, with recent results reported in Xu et al.,(2012).

Using ROMS, UWA have also developed a series of shelf scale models for the Australian North West Shelf *(Rayson et al., 2011, van Gastel et al., 2009)*. The primary focus has been on describing the tidally driven flows and internal tides that dominate the local circulation *(4 and 5 in the Figure)*. Typical of these is the modelling described by Rayson et al., (2011) who used the ROMS in the Kimberely with a domain which extended approximately 500 km offshore and 300 km alongshore. The horizontal resolution of the model varied from 1 to 3 km, with higher resolution used in areas of internal wave generation, and 50 vertical sigma layers, stretched to increase the resolution near the seabed and sea surface. Topography was derived from Geoscience Australia datasets. The initial and boundary conditions for (T, S, u, v, SSH) were taken from the Bluelink Reanalysis (v2.1) hind-cast output and augmented by measured density fields from local moorings. Tidal forcing with 8 tidal constituents was supplied from the TPXO Indian Ocean Atlas (1/12th degree regional model) and described by Rayson et al., (2011).

Future work is focussing on incorporating cyclone forcing into these tidal forced models *(including 6 in the Figure)* by blending high-resolution cyclonically-driven atmospheric forcing with background surface forcing from the UCAR and NCEP/NCAR Reanalysis data.
S.A.: The ROMS applications in Southern Australia have two foci. The first is to describe the shelf/slope circulation and cross-shelf exchange between the head of the GAB and Portland (Victoria). This S.A. Regional Ocean Model (SAROM) model has a grid size of 2 km, with 30 sigma layers in the vertical (2 in the Figure). It is initialised using the CARS data for winter and surface forcing provided by the BoM’s LAPS and ACCESS models (The LAPS data ends, and the ACCESS data starts, in 2010). It has been run for several years between June 2004 and June 2011. At present the upstream boundary condition adopted is a CTW paddle using data from the mid Bight. Tidal velocities are also modelled through application along open boundaries of the 13 constituents of the OSU TPXO model. SAROM is currently being re-configured with open boundaries specified from the global HYCOM model.

A second High Resolution Spencer Gulf Model (HRSGM; 3 in the Figure) is embedded in SAROM so as to a) model the ocean circulation at a scale of the aquaculture lease regions (~ 500 m), and b) to drive coupled models for larval dispersal (LTRANS), waves (SWAN) and biogeochemistry (NPZD). The open gulf mouth of the HRSGM is forced using SAROM. SWAN is forced at the gulf mouth using the Wave Watch 3 data and local winds used in the interior. The NPZD model is forced at the gulf mouth using nutrient data collected through SAIMOS with anthropogenic nutrient inputs specified from data collected in the interior (e.g., aquaculture farms, sewage outfalls, steel factories).

A third application of ROMS will very likely be for the circulation in the Great Australian Bight with a domain that extends from Cape Leeuwin to Kangaroo Is. Funding for this study is pending.

UNSW: Using ROMS, UNSW have developed SEAROMS (South East Australian ROMS) for the region (30 - 37.5 °S, 150 – 159 °E; 1 in the Figure). It has 50 sigma levels in the vertical and a grid resolution of approximately 3.5 - 4.3 km. A second configuration has been developed at higher resolution (1.75 x 2.15km, from 29.9°S to 37.33°S). SynTS products (temperature, salinity and geostrophic currents) are presently used for model initialization and time-varying boundary forcing. For areas of the model below 2000 m the initial temperature and salinity conditions come from CSIRO’s CARS climatology. We have previously used BRAN Zp1 (downscaled in POM) and will be implementing this in ROMS by July 2013. Recent ROMS work (Macdonald et al., 2011a, b) has focussed on understanding eddy formation and other processes such as over-flooding of Tasman Sea Eddies. Present work is focussed on adding a biogeochemical module.

A new project funded to commence in 2013 involves downscaling climate change scenarios for the East Australian Current region – to force the SEAROMS model in order to investigate climate change impacts on circulation, eddy variability, stratification and biological connectivity.

3. Generic Problems with the Models and Forcing.

The Models: ROMS is well supported through various web sites, and is our first choice based on a) previous use of POM and other models and b) the wide variety of “bolt-on” models including SWAN, NPZD and LTRANS. The model is quite complex with an enormous number
of options. The complexity has grown to the point where implementing new features, such as online nesting, can be very challenging for ROMS programmers. The bolt on models can be adopted, although with the exception of SWAN, some effort is required.

**Meteorological Forcing:** The first issue relates to the meteorological products used for surface forcing. The products provided by the BoM include LAPS and more recently ACCESS output. The data are generally of high quality and with a good spatial resolution of 0.1$^\circ$ and thus able to resolve frontal features. However, issues here include a) lack of geographical coverage, since these products do not generally cover all of the regional model domains b) temporal gaps whereby several months of ACCESS/LAPS output may not be available, c) quality, where freshwater fluxes are unrealistically identically zero, and d) accessibility: some data are not easily accessible via the web. Surface meteorological data is also available from the NCAR/NCEP and ECMRF web sites. These data are easily accessible and provided 4 times per day so that the sea breeze is represented. However, the (assimilated) data are presented on quite coarse grids (1.9$^\circ$ X 1.9$^\circ$ and 0.75$^\circ$ X 0.75$^\circ$ respectively) and sharp fronts and the sea breeze not well resolved. Alternatively NOAA/NCDC provides a blended 6-hourly 0.25 $^\circ$ Sea Surface Wind product.

**Boundary Forcing:** ROMS can be embedded in global models such as Bluelink and HYCOM although care is needed to ensure exact balances of mass transports result. Errors in the global models can of course lead to errors in the embedded models. Further comment is made below.

**Initial Conditions:** CARS provides temperature and salinity data interpolated onto a (1/4$^\circ$ X 1/4$^\circ$) grid, at a year of weekly interval averages. The data set was last updated in 2008 and needs to be updated using the IMOS data collected since then and allowance made for ENSO and non-ENSO years which can be important on the western and southern shelves. Alternatively SynTS can be used for model initialisation and for time-varying boundary forcing from the surface to 2000m depth.

**Model Grids:** Bathymetry is available from US Naval Research Lab (DBDB2 V3) at 2 x 2 minute resolution. Smoothing must be considered when interpolating onto a higher resolution grid to minimise the pressure gradient error associated with terrain following models. **MARVL:** A proposal has been successfully submitted (Proctor et al., 2012) to the National eResearch Collaboration Tools and Resources (NeCTAR) for the development of a MARine Virtual Laboratory, MARVL). The purpose of MARVL is to develop infrastructure to enable a more rapid implementation of Ocean Models (including ROMS) by users around Australia. MARVL will seek to provide the user with the requested model set up for the required domain, and with initial conditions and boundary forcing chosen from a menu of data and modelling resources available – many of them those described above. In addition, as a one stop shop, MARVL will seek to provide the data streams needed for model validation.
4. Model Validation and Observations.

ADCP and CTD data: The regions of ROMS studies outlined above are quite diverse but each generally coincides with one of the coastal IMOS Nodes including SAIMOS, WAIMOS and NSWIMOS. Each of these nodes have maintained several moorings and the data here has been used (e.g., S.A.) for model/data comparisons of along-isobath transport in the spectral domain so as to determine in what frequency bands significant variance is (or is not) explained. Comparisons have also been made between temperature and salinity fields and S.A. have used CTD sections obtained in winter 2008 to improve initial conditions for SAROM. Many of the Nodes have now collected 3-4 years of data (a number of shelf arrays were deployed in 2008) so that these comparisons can now extend to seasonal and inter-annual variability.

RADAR Data: Uptake of HF RADAR surface current data is beginning now that the data can be more easily accessed. Comparisons of estimates of RADAR and ADCP currents are being made in order to interpret the former in terms of surface boundary layers and ultimately near surface current of ocean models. The use of daily averaged current data as presented by David Griffin through OceanMaps is a logical place to start. The WERA HF RADAR wave data might also be used to validate and/or complement the Wave Watch 3 output for applications of SWAN. ACORN has indicated that better algorithms for processing wave data will be adopted.

ARGO float opportunistic profile data can provide good model validation in typically undersampled regions, particularly in deep waters off the continental shelf where sub-surface observations are sparse (such as Tasman Sea Eddies).

GLIDERS provide observations of temperature and salinity on the shelf and slope and have been used (WAIMOS; NSWIMOS) to provide data on meso-scale eddies.

Satellite Remote Sensing is one of the most used tools for assessing model performance, particularly Sea surface temperature and elevation. Alternatively they can be used for model assessment.

Data assimilating models are a next step where non-assimilating models have been thoroughly validated against data. A number of proposals are being planned to improve on this area.

Community visualisation tools will also be useful for displaying and comparing data/model output. An example is the MATLAB script developed in S.A. that allows current vectors to be interpolated in time and space so as to provide curved current vectors that will highlight flow around headlands and eddies. WAIMOS has developed software that enables RADAR and SST data to be overlaid providing excellent resolution of meso-scale features including fronts and eddies.
The Teams: SARDI - C. James, J. Luick, M. Doubell; WA – G. Ivey, R. Lowe, N. Jones, M. Rayson, T. Xu; UNSW - : H. Macdonald, M. Baird, J. Wilkin (Rutgers)

ROMS Publications


The data assimilation component of the real-time coastal ocean forecast system implemented off Oregon (US West coast)

Alexander Kurapov, Peng Yu

The real-time coastal ocean circulation forecast model has been developed and implemented off Oregon (the US West Coast). It has provided daily updates of 3-day forecasts of surface currents, SST, and other oceanic variables of interest. The forecast model is based on the Regional Ocean Modeling System (www.myroms.org), a three-dimensional, free-surface, fully nonlinear model featuring terrain-following coordinates, a comprehensive sub-grid turbulence parameterization scheme and advanced numerical algorithms (Shchepetkin and McWilliams, 2005). Our model domain is approximately 400×800 km (Figure 1). The forecasts are obtained at the 3-km horizontal resolution.

To improve quality of predictions, the system assimilates observations of SSH (alongtrack altimetry), hourly SST from the geostationary GEOS satellite, and surface currents from a network of high-frequency (HF) radars installed along the Oregon coast (Kosro, OSU). Assimilation proceeds using the variational representer-based method (Kurapov et al., 2011, Yu et al., 2012). To implement the variational algorithm, we have developed and utilized our own tangent linear (TL) and adjoint (ADJ) codes AVRORA (the Advanced Variational Regional Ocean Representer Analyzer). These are stand-alone codes that numerically and dynamically consistent with ROMS. Using AVRORA, instead of the TL&ADJ components embedded in ROMS, gives us greater flexibility incorporating new data types and designing the most appropriate model error covariance formulations. The AVRORA codes can be utilized not only with ROMS, but also with other forecast models. In our ongoing research, in collaboration with Dr. P. Oke (CSIRO), we are using AVRORA to provide improved initial conditions for the SHOC model, implemented along Australian coastal regions.

Variational assimilation is performed in a specified finite-length time window, in which dynamically consistent time- and space-interpolation of sparse data sets is obtained. In our forecast system, assimilation proceeds in a series of 3-day time windows (Figure 2). On the assimilation day, data for the previous 3 days are collected. The correction to the initial conditions at the beginning of the assimilation window is obtained iteratively. At each iteration, the ADJ and TL models are run once. With effective preconditioning, about 20 iterations are needed to find the optimum correction to the initial conditions, satisfying a specific optimization criterion. After the correction to the initial conditions (and in general forcing) is obtained, the ROMS is run for a period of 6 days,
providing the 3-day analysis (improved solution in the given assimilation window) and 3-day forecast. The forecast becomes the background solution for linearization in the next window.

4DVAR = dynamically based time- and space- interpolation of data

At every iteration step, the result of the ADJ model is convolved with the initial condition error covariance, which provides smoothing of the adjoint sensitivity field and may also introduce dynamical constraints in the correction. We have used the covariance based on the balance operator (Weaver et al., 2005), with modifications for the shallow water case (see Kurapov et al., 2011). Using this approach, the corrections to velocities, temperature, salinity, and SSH are in approximate balance (including geostrophic and thermal wind balances, as well as the linear T-S relation and the equation of state).

Our forecast fields have been distributed to the public via the visualization system of the regional ocean observing system association (www.nanoos.org). They have been popular among the local fishermen who used the forecasts to help planning their trips. In addition, the forecast fields have been provided via the OpenDAP server to our colleagues at the National Oceanic and Atmospheric Agency (NOAA) laboratory in charge of oil spill and other environmental hazard responses. In particular, they have been using our forecasts to track large pieces of marine debris originating from the 2011 Japanese tsunami and approaching Oregon and Washington coasts.

Our ongoing efforts include development of the model in the extended domain (41-50N), in which the Columbia River fresh water discharge is included. The Columbia River buoyant plume influences near-surface velocity and SST fields. Inclusion of the Columbia River makes
the model more consistent with observations and may potentially improve the impact of assimilated data on forecasts. In winter, the Columbia River waters are deflected to the north. The velocity associated with the plume can be as large as 30 cm/s along the plume edge. The plume waters are colder than the ambient ocean in winter. In summer, the dynamics in our area are dominated by wind-driven upwelling, with the plume deflected toward south and offshore. The presence of the plume over the continental slope influences upwelling of near-bottom waters on the shelf, resulting in stronger cross-shore density gradients and near-surface currents.

Assimilation in presence of the river plume presents challenges. In particular, we may need to provide a new error covariance, which accounts for anomalous T-S properties in the thin near-surface layer associated with the buoyant plume. Such a covariance may include the modified T-S relation. Alternatively, the covariance may be built using an ensemble of ocean forecasts.

References.


Australian coastal modelling and information systems: assisting management decision making.

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1 Introduction:
Over the last two decades, there has been a move towards adopting adaptive management strategies for coastal environments. A key step towards this vision is a sound scientific understanding of the dominant processes that drive the dynamics of these systems. As process knowledge is gained, it is encapsulated into mechanistic numerical models that can be used for a variety of tasks including multiyear hindcasts, short-term forecasting and investigating alternative management scenarios. In this extended abstract, we present the modelling framework, associated observing systems and our vision of an integrated coastal information system (Figure 1) that can feed into science based coastal management system.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{coastal_info_system.png}
\caption{A schematic of the components that form a coastal information system based on a combined observational and modelling approach.}
\end{figure}
1.1 The Modelling Framework:
The CSIRO Marine & Atmospheric Research Environmental Modelling Suite (EMS) includes a core hydrodynamic model, a multi-layer sediment model, a biogeochemical model, a statistical toolbox and data assimilation capabilities (Figure 1). The software can be implemented in a wide range of configurations with options to link the sediment and biogeochemical models to a hydrodynamic box model, an off-line transport model or a fully coupled hydrodynamic model in 1, 2 or 3D. Similarly, the sediment and biogeochemical models can be implemented across a range of process complexity with the flexibility to target specific science and management questions.

The EMS has evolved through a series of case studies including the Port Phillip Bay Environmental Study (Harris et al 1996; Murray & Parslow 1997), the National Land and Water Audit Estuaries Theme, the Gippsland Lakes Environmental Study (Parslow, et al., 2001), the Derwent Estuary ERA (Parslow et al., 2001), and the Ord-Bonaparte Study (Parslow et al., 2003). Each study addressed specific environments and ecological questions resulting in the development, implementation and testing of a diverse range of model components. In these previous studies the sediment and biogeochemical models were linked to a box model which represented physical transport with relatively low vertical and horizontal resolution (Walker, 1997).

Traditionally, modeling case studies were approached by nominating a hindcast timeframe, assembling forcing and calibration data available within that timeframe, and then producing a number of model simulations that allowed the model to be calibrated, analysed for sensitivity and then used to characterize the system and identify dominant processes. The resulting system understanding was then usually conveyed to stakeholders in the form of a report. However, this approach has limitations for regulatory authorities (who are usually the stakeholders) in practically transforming that understanding into useful management strategies. The products more frequently requested by stakeholders to assist in sound management practice are numerous model scenarios of alternative futures resulting from perturbing the model forcing (e.g. increasing or decreasing pollutant loads). Although these scenario products can inform management practice, they do not address how compliant those strategies are with ecological targets; this is typically left to observation programs. A shift from hind-casting to now-casting is required to address the issue of the provision of relevant model outputs, and increasingly near real-time models are being implemented in case studies (see Figure 2) to provide up-to-date products. The advantage of this approach is that current products can be supplied indefinitely to stakeholders, on call, after the lifespan of a particular project, without the arduous task of resurrecting models that may have been ‘put on the shelf’ and are no longer compatible with current modeling methodologies or code bases. The near real-time delivery of system information also provides an additional avenue for stakeholders to address compliance issues in their area of interest.

In more recent studies, the sediment and biogeochemical models have been restructured in modular form, with a software core linked to a central library of ecological processes. With this structure the code has been fully incorporated into the CMAR Environmental Modelling Suite (EMS) and dynamically linked/coupled to a high resolution 3D hydrodynamic model ‘SHOC’ (Herzfeld et al., 2005) and a multilayer sediment model (MECOSED Margvelashvili
The sediment transport and biogeochemical models have been directly coupled to a 3-D hydrodynamic model at continental shelf scales in the North-west Shelf Environmental Study (Herzfeld, et al., 2003; Condie et al, 2009), the Strategic Research Fund for the Marine Environment study off WA (Koslow et al., 2006), CRC Reef Torres Strait Program (Margvelashvili et al., 2008), and in estuarine applications in the Huon Estuary and D’Entrecasteaux Channel (Wild-Allen et al., 2005), the Fitzroy Estuary (Douglas et al., 2005; Wild-Allen et al., 2005; Robson, et al 2006; Ryan et al., 2007), and the Derwent Estuary (Wild-Allen et al., 2010). Biogeochemical dissolved tracers are advected and diffused in an identical fashion to physical tracers such as temperature and salinity and ecological particulate tracers sink and are resuspended by the same formulation as sediment particles. At each ecological time step, non-conservative ecological rate processes such as growth, nutrient uptake, grazing and mortality are integrated within the ecological module which returns updated tracer concentrations to the hydrodynamic model via an interface routine.

The fully-coupled hydrodynamic-biogeochemical-sediment transport modelling suite is computationally expensive to run. To alleviate this, the sediment transport and biogeochemical models have recently been coupled to a transport model, which facilitates simulations of ecosystem dynamics over fine-scale and computationally large model grids (Wild-Allen 2008, Herzfeld, et al., 2012) The transport model consists of velocity and diffusion fields from the hydrodynamic model, saved to file at high spatial and temporal coverage (e.g. hourly), which are used to drive the downstream models. Whilst expensive in terms of disk storage and IO operations, the transport model, by avoiding the time step limitations of the hydrodynamic model, can operate with much longer time steps for tracer advection and diffusion (e.g. 1 hour), thus allowing more efficient solution of ecological processes and enabling practical run-times for large domains and/or finer-scale resolution.

Figure 2. Case studies, including near real-time implementations undertaken by the Coastal Environmental Modelling Team.
1.2 Observing systems

Traditional approaches to marine observing, focus on high quality observations but often with minimal spatial coverage, such as those deployed by the Integrated Marine Observing System (IMOS). These traditional approaches include mooring deployments, ship-based observations and, more recently, deployment of AUVs and gliders. In traditional hindcast modelling approaches, models were calibrated and evaluated against these spatially-limited data. Although these observations remain valuable for detailed model evaluation, the timelines of the data return and the requirement for quality control are not always adequate for near-real-time modelling, and need to be complemented by real-time, telemetered observations.

Low-cost sensors and platforms do not provide the high quality observations and diversity of phenomena, but by sacrificing some accuracy at one geographic point it is possible to achieve improved representation of a larger but local area using a low-cost wireless sensor network.

The TasMAN (Hugo et al., 2011) low-cost nodes were designed to be inexpensive, modular, and scalable to high-volume manufacturing (Figure 3). The integrated design avoids the range limitation and brittleness of mesh networking by instead making 3G cellular communications affordable on every sensor node, and significantly improves data throughput. As well as the Fleck-based electronics board, each node features a string of temperature, conductivity, pressure and (optional) dissolved oxygen sensors that communicated with the board via a 1-Wire bus.

![Figure 3: (Left) TasMAN sensor & telemetry expansion board mounted on Fleck WSN platform; (Right): 70cm polyethylene surface buoy from above.](image)

The explosion of real-time data from sensors embedded in the environment provides the opportunity to study the environment at a higher spatio-temporal resolution than was previously possible. However, to ensure that these measurements are fit for purpose, their quality needs to be assessed; this becomes increasingly challenging as the size and heterogeneity of data sets used in scientific studies continue to expand. Automated approaches to assess the quality of data are important as the number of observations being generated make human-based assessment too unwieldy and costly (Dietterich, 2007).
A number of automated processes have been developed in recent years that consider the time series data from a sensor, sensor metadata and data from nearby sensors to automatically assign data quality flags or error bars to measured data (Doonga et al., 2007; Koziana et al., 2008; Timms et al., 2011 and Smith et al., 2012).

2 Current Projects:
No other system within Australia’s coastal margins is in greater need of relevant, accurate information to assist the formulation of sound management strategies than the Great Barrier Reef (GBR). Although the GBR is recognised as one of the best managed reefs in the world, coral cover has continued to decline over the last decades at rates similar to less well managed reefs, and research based management and policy is recognised as a pathway for mitigating this trend. Model development to guide management actions is considered a criterion for the effective integration of science and management, and a modelling framework which links the management of agricultural activities in catchments that drain into the 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. To this end, the eReefs project has been implemented to provide an information system spanning the catchment to open ocean for all of Queensland, delivering hydrodynamics through to biogeochemical outputs that will assist regulatory authorities with issues relating to reef management. The modelling package will operate routinely in near real-time, delivering up-to-date information on the state of the GBR. These products will be archived so that events can be revisited in hindcast, or alternative management scenarios simulated. The development methodology of the proposed eReefs information system builds upon work undertaken within the INFORMD (Inshore Network For Observation and Regional Management: Derwent-Huon) project in south-east Tasmania, where a similar system was developed (at a smaller scale) and used as a test-bed for many of the technologies required of a near real-time, data-assimilating system (e.g. Jones et al., 2012). The work done within INFORMD was always undertaken with the view of portability, and eReefs can therefore leverage on the significant advances made in SE Tasmania and proceed with a framework for the required modelling system in place. Additionally, access to data from numerous observational platforms trialled within INFORMD have allowed model-data fusion technologies to be explored that can be similarly ported, and be of benefit to eReefs.

3 Models and Observations:

3.1 Review of observations to support Coastal Information Systems

3.1.1 Observations in the GBR
Australia’s Integrated Marine Observing System (IMOS) was established in 2007 under the National Collaborative Research Infrastructure Strategy (NCRIS), with initial funding from Australian Government and co-investment from partners. It comprises a range of deployed observing equipment in the oceans around Australia. Data is made freely and openly available through the IMOS ocean data portal. The Queensland node of IMOS (Q-IMOS)
provides real time and delayed mode observations from weather stations, oceanographic moorings, underway ship observations, gliders, ocean surface radar, satellite remote sensing and reef based sensor networks, with a geographical focus on the Great Barrier Reef. However, the majority of the ocean observation infrastructure on the GBR relevant for use in eReefs delivers information in delayed mode, and are therefore of limited use in the delivery of routinely operating near real-time models. Some near real-time data streams exist, including the GBR National Reference Station, some reef based temperature observations (FAIMMS), coastal radar (ACORN), ships of opportunity underway thermosalinographs and occasional glider deployments, but these are strongly geographically constrained or, in the case of the underway systems and gliders, provide enhanced spatial coverage but with sparse temporal resolution at repeat stations.

3.1.2 ICT: TasMAN
The Tasmanian Marine Analysis Network (TasMAN) project has developed a sustainable coastal observation system including a low-cost sensor network platform, tools for deployment, real-time quality control frameworks, flexible real-time processing, data storage, web services, and web based visualisation tools. The TasMAN architecture is reusable, relocatable and scalable. Marine observation systems are costly in many aspects, including: design and construction of sensor platforms, network layout design and deployment, maintenance, communications, data storage, analysis and presentation. A low-cost system must consider all these aspects. TasMAN has deployed low-cost sensor platforms in coastal and estuarine regions in multiple locations including South East Tasmania (43°S, 147°E), Sydney Harbour (33°S, 151.2°E), and the Brisbane River (33.8°S, 151.4°E), and for different applications with industry partners, such as environmental monitoring and aquaculture. The TasMAN approach to marine observing systems is to focus on high spatial resolution, temporal resolution and coverage, sacrificing some accuracy on a per observation basis. TasMAN has also developed information architecture to provide data services. The capabilities of these data services are demonstrated by the TasMAN portal web interface which provides exploration and visualization tools. INFORMD models are integrated into the TasMAN portal allowing quick and easy comparisons between modeled and observed data.

3.1.3 BGC Observations
Biogeochemical observations to support coastal information systems include observations of plankton species and biomass, particulates, nutrient concentrations and rate processes which control the cycling of nutrients through dissolved and particulate organic and inorganic phases. In shelf waters these observations are required throughout the water column and surface sediments.

In most studies biogeochemical observations are highly constrained across spatial, temporal and parameter (state variable) scales due to limited resourcing and the complex nature of many of the analyses (e.g. C14 primary production, microscope plankton species identification, sediment core incubations). Systematic under-sampling of biogeochemical variables further confounds interpretation of data and processes that often fluctuate widely over daily cycles, vertical profiles and patchy spatial scales. For these reasons biogeochemical models continue to be poorly constrained by observations in the context
of model parameterization, initialization, boundary forcing, specification of point source loads and model validation.

In many studies coastal biogeochemical observations are limited to <10 state variables and proxies (e.g. nitrate, silicate, phosphate, chlorophyll, oxygen) at 1 or 2 depths in the water column and a few key monitoring locations (e.g. Derwent Estuary Program monthly sampling at 12 sites).

To address the systematic under-sampling and aliasing of biogeochemical data across spatial and temporal scales, **continuously recording biogeochemical sensors need to be deployed on a range of mobile and profiling platforms.** Optical sensors show significant promise and fluorometers, optodes and ISUS (in situ ultra violet spectrophotometer for detection of nitrate) have been deployed on benthic landers, moorings and profiling AUV’s. Multi-spectral sensors and a pulsed fluorometer (proxy for primary production) have also been deployed on a glider. At low nutrient concentrations (typical of Australian surface waters) wet chemistry nutrient analysis is required for accurate determination of concentration. An automated Systea Wiz probe has been trialed on a coastal mooring and is now returning head of estuary (Derwent) concentrations with 2hrly resolution. A rapid reverse flow injection nutrient analysis system has also been trialed on a coastal vessel and delivered maps of surface nutrient concentrations at similar spatial resolution to coastal models, including the resolution of nutrient plume dispersion.

### 3.2 Cal/Val of Models

#### 3.2.1 Hydrodynamics

Hydrodynamic models are typically calibrated, i.e. model parameters are ‘tuned’, so that correlation of model output with observations is optimum. Obviously the choice of metric used to quantify the ‘goodness’ of the model-data match can influence the quality of the calibration. Once calibrated, models are usually compared to an independent dataset to provide confidence they are accurate under different conditions (model ‘validation’). Both of these processes rely heavily on quality observations, and given issues with temporal and spatial variability often inherent within systems, dedicated observational programs need to be conducted to support model cal/val. Moored instruments collecting temperature and salinity at various depths supported by sea level and velocity profiles are considered the most useful information, as snapshots delivered by in-situ profiles may be subject to temporal aliasing. Recently, gliders deliver vast amounts of data that may be suitable for calibration, although it’s fair to say that methodologies to best capitalize on these data are yet to be perfected.

Calibration of model physics remains a difficult task that is largely heuristic and relies strongly on the experience of the model operator. There are actually relatively few hydrodynamic parameters available to ‘tune’; if a satisfactory model-observation comparison cannot be achieved by perturbing these, then a key process is either inappropriately represented or absent altogether. The key process is usually identified from the outcome of a literature review of the regional dynamics, or application of expert judgement (to generic ocean dynamics or the observations). If the key process is inappropriately represented, expert judgement is required to identify its numerical
representation in the model and substitute one more appropriate. If the process is missing, judgement is required to discern whether the process is absent due to no numerical representation or due to omissions in the forcing data. In the case of the latter, judgement is similarly required to identify the element of the forcing responsible for the absence of the process. Therefore, the calibration process is a decision tree, but decision points rely heavily on the user’s judgement. This implies that different model operators attempting the calibration process are likely to provide outcomes of different quality.

3.2.2 BGC
For quantitative validation of biogeochemical models, data streams with high/known QC are required across a wide range of state variables and rate processes in the water column and sediment. The application of most biogeochemical models is limited in scope due to the constraints in validation; all un-validated biogeochemical models, and process rates across all un-validated spatial and temporal scales remain a hypothesis.

3.3 DA and parameter estimation
Given the time-space scales of the dominant dynamics in the coastal ocean, most observing systems can be considered quite sparse. Also, acknowledging that coastal models contain errors that stem from multiple sources, data assimilation and parameter estimation are attractive options to try and get the best estimate of the state and parameters of a particular system. Presently, two approaches are being trialed:

1.) An Ensemble Optimal Interpolation (EnOI) algorithm (Jones at al., 2012) similar to BODAS (Oke et al., 2008) for pure state estimation; and,
2.) An Ensemble Kalman Filter (EnKF) with an augmented state vector for joint state-parameter estimation (still in development).

Due to the nature of coastal models, errors associated with meso-scale chaotic behavior are not present in shallow water depths. Rather, chaotic behaviors occur on time and length scales that are almost impossible to observe with a sparse observing system. Therefore the goal of a coastal assimilation system is to correct for persistent errors in the forcing, boundary or model parameterisations that may lead to persistent bias in the model state. The EnKF for joint state-parameter estimation is particularly attractive as it corrects for persistent errors, rather than just correcting the symptomatic effects in the model state. An example of this approach has been used in the high resolution Moreton Bay model to estimate the shortwave parameters in the hydrodynamic model (Figure 4).
Where do we need more observations

4.1 Hydrodynamics

Provision of accurate data to hydrodynamic models is twofold; firstly they underpin the cal/val process and secondly they can be used with data assimilation techniques to improve the accuracy of predictions. Given that the water bodies typically modelled are vast in comparison with the observational footprint, it follows that the domain is usually severely under-sampled. In particular, sub-surface observations on time and space scales that resolve dominant phenomena are often lacking, particularly around the location and movement of the pycnocline. The move towards quasi-operational ocean modelling practices requires system-wide observations telemetered in near-real-time, particularly for data assimilation. Currently, these observations are extremely scarce. The routine deployment of gliders may help to fill this gap; however to test the effectiveness of these data streams, we need robust repeat transects for case studies and refinement of methodologies on how to best use these data within the models. In shallow water depths (<30m) and within 3G coverage areas, the low-cost TasMAN sensor nodes could provide a very complimentary dataset for use in model cal/val or for DA purposes. The eReefs project provides an opportunity to address both these issues; an IMOS co-funded project will deliver repeat glider transects in the Capricorn
Channel. Building on work initiated in the INFORMD project, these data will be assimilated into the hydrodynamic model in near real-time.

Enhanced observations are also required to help resolve and parameterize processes that occur at spatial scales unresolved by the model grid, or that at temporal scales not captured by the model physics. For the case of sub-grid processes, the GBR presents an extreme example where processes at various spatial scales interact and provide strong feedback from, for example, reef-scale processes to meso-scale circulation. Large reef complexes steer the prevailing currents toward areas of low reef density, and flow through the reef the matrix produces wakes and tidal jets which in-turn deflect the mesoscale circulation further. The strength of the tidal jets and wakes, and there interaction with the mesoscale circulation are modulated by the spring-neap cycle. The difficulty lies in identifying the small-scale processes that are relevant at larger scales, and undertaking an observational program that sufficiently captures the range of spatial scales in order to parameterize these processes in the larger scale models. Ocean radar systems show some promise through their broad spatial coverage, although they are constrained by their resolution.

Large volumes of sediments, nutrients and pollutants are carried and redistributed in coastal environments during extreme events, such as floods, cyclones, severe storms, tsunamis. Strong currents and high waves, typically accompanying such events, are instrumental in reshaping seabed morphology and influencing benthic and pelagic habitat processes. An adequate observing system must be sufficiently robust to withstand rough weather conditions that develop during such events. It must also be capable of delivering high-frequency observations on at least hourly time-scales during the impact time. On the other hand, the duration of the observational record needs to be sufficiently long to capture long-term (seasonal, annual and beyond) variability in the characteristics of the extreme events (e.g. frequency, intensity, spectral characteristics, etc.). In the Near Real Time (NRT) context, having such a system in place would be critical for NRT now-casting and forecasting of the extreme events.

5 Use of models to support observing systems
With the dual purpose of using observations for process understanding and also to support modeling, the use of models to aid in the design of observing systems is a growing field. Using ensemble and/or variational methods, it is possible to identify the spatio-temporal ‘footprints’ of current and proposed observing systems.

Within the Machine Learning community, Gaussian process regression (Rasmussen, 2005) has recently received much attention for tasks such as sensor placement (Guestrin, 2005) and sampling design (Rigby, 2010). These techniques can be readily applied to the placement of sensors on a mooring. However their use is dependent on the availability of ‘training data’, from which the algorithm can learn the covariance structure of the process under study. For a new site, where no measurements have yet been taken, a hydrodynamic model (even if relatively coarse and uncalibrated), can be used for this purpose. These methods can show a quantitative comparison between proposed mooring designs in terms of the expected information that will be gathered. This can then facilitate the cost-benefit analysis.
of various scenarios, for example adding or removing sensors to a mooring, or substituting a sensor for another with a different accuracy.

Alternative approaches include more traditional Observing System Experiments (OSE’s) (e.g. Oke and Sakov 2012) and Observing System Simulation Experiments, where the former is used to evaluate a current observing system and the latter is used to evaluate a proposed observing system. To date, these approaches have been widely used in designing observing systems to constrain the hydrodynamics, however, there is an increasing need to apply similar techniques to the biogeochemistry. A relevant example of this approach was given in Wild-Allen et al., (2011), where a calibrated coastal BGC model was used to select environmental monitoring sites in SE Tasmania. Ultimately, these approaches yield a quantitative (or possibly qualitative) assessment of the value of the observing system and give a metric on the information gained.

6. Conclusion:
In the last two decades, there has been a strong focus on increasing our process knowledge in the marine coastal environment. This process knowledge has then been captured in mechanistic models that can be used in science based management. Furthermore, technological advances in observing systems along with national observing infrastructure have led to a substantial improvement in observational coverage in Australia’s coastal ocean. However, there is still a need to increase the number of BGC observations in the coastal (and global) oceans. The eReefs project is an example of an upscaling of the INFORMD and TasMAN style projects, aiming to deliver a near real time environmental information system for the Great Barrier Reef Region. The combined modeling and observation developments see us poised to deploy end to end catchment to blue water modeling systems that can be used for a number of purposes:

- A modeling based approach to water quality ‘report Card’ systems, rather than just observations alone.
- The development of fast approximate models for use in management strategy evaluations (e.g. Scott Condie’s project INFORMD2 in the D’Entrecasteaux Channel).
- Real time receiving water quality models of the Great Barrier Reef.
- NRT and forecast models that can be used for adaptive sampling/observing systems and water quality compliance.
- Model scenarios that can be used to determine sustainable loads for catchment management practices so as to deliver optimum environmental outcomes for the receiving environment.

Our future vision is of a national coastal information system that will require a combination of a national coastal model (e.g. the Ribbon Model) with a national coastal observing system. We see the continued funding support for IMOS infrastructure to be absolutely critical for delivering such a system. Ultimately, a national coastal information system will have a two fold impact:
1.) It will assist in closing the loop on a full adaptive management approach to making management and policy decisions in the coastal environment; and,

2.) As Australia transitions to a “low-carbon” economy, a national coastal information system will form the foundation to estimating carbon stores and fluxes in coastal marine ecosystems (Blue Carbon).

We see the continued and combined modeling and observation of Australia’s coastal waters to be paramount to informing smart management decisions that affect 95% of Australia population.

7. References


The National Plan for Environmental Information initiative: Pilot Projects

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Introduction
The National Plan for Environmental Information (NPEI) initiative is an Australian Government program established in 2010 intended to address the environmental information needs of the nation. This paper outlines two of the major activities currently underway within the Bureau of Meteorology (BoM) and other partners to deliver on the goals of the NPEI initiative.

The National Environmental Information Infrastructure (NEII) Project is a core activity under the initiative that aims to improve access and discovery to fundamental environmental data across Australian Government. eReefs is another activity within the initiative that provides a detailed case study of how the NEII principles can be applied to a particular issue, i.e. water quality within the Great Barrier Reef.

NEII

NEII principles
The NEII project will inform the development of environmental information standards, and build the first stage of a national, integrated environmental information system. A number of foundational principles have been adopted for the NEII, outlined below.

Feasible and sustainable. This argues for an approach that adopts existing best-practice international standards, following the ‘Spatial Data Infrastructure’ (SDI) pattern as far as possible. In addition, it implies maintaining data at source in a distributed architecture wherever possible (though retaining the option to centralise or cache information elements centrally where required). While standards minimise implementation risk, they do not necessarily guarantee longevity – the infrastructure must also evolve with new technical paradigms for online information sharing.

Data re-usability. In order to support multiple use-cases and innovative applications, the infrastructure should support re-purposing of data. While it is not meaningful a-priori to determine fitness-for-purpose in an objective sense for arbitrary applications, it is possible to assign quality indicators to enable evaluation of fitness by users for specific applications. Likewise, attaching provenance metadata to datasets provides users with a measure of reliability. Frameworks for data provenance and quality exist, and will need to be supported in NEII at an appropriate time. A related issue is that of data licensing – a common framework ultimately will be required in order to enable seamless access without requiring users to navigate complex agreements before retrieving data.

Environmental intelligence. NEII aims to provide more than mere data download. The value proposition for an integrated environmental information infrastructure is enhanced if the network supports analysis and correlation of diverse datasets, assimilation of data with models, etc. In order to achieve this, a framework is required to manage (model and implement) the ‘behaviour’ afforded by different information types – calculating ‘monthly mean’ is appropriate for a temperature time series, but not a marine species survey. This is a longer-term aim, but early architectural decisions are laying a suitable foundation.
NEII roadmap
Adopting an SDI architectural pattern for NEII reduces the technical risk of the project. It implies a number of core elements within the infrastructure:

- a metadata catalogue to describe datasets and services in a standardised way for discovery,
- standard web services for providing a common network access and query interface for distributed data sources, and
- conformance to agreed community information models to ensure common understanding of the logical structure and semantic content of datasets.

On the other hand, the SDI pattern is usually applied to geographic (often cartographic) data, and has limited ability to support specific capability for environmental information. NEII, therefore, is supplementing the architecture with additional components providing specific environmental benefit:

- a register of environmental monitoring sites to enable a natural access key for related observational data,
- online vocabulary services to enable re-use of, and conformance to, standard terms for environmental parameters,
- web services for a range of ‘environmental geographies’ (e.g. bio-regions, soil zones, catchments, water courses, hydro-geological formations, etc.) that provide domain context to observational data.

Figure 5 shows the roadmap of NEII projects to support development of these architectural components, while Figure 6 shows the alignment of these components with potential targets of information standardisation.

![Figure 5: NEII project roadmap](image)
**NEII Phase One**

The first phase of NEII projects worked with providers and representative datasets across the four broad target domains of land, air, water, and ocean:

- ‘Level 7’ soil samples from the Australian Soil Resource Information System (ASRIS) developed through the joint CSIRO/DAFF Australian Collaborative Land Evaluation Program (ACLEP)
- Marine mooring data from the NCRIS Integrated Marine Observing System (IMOS)
- High-quality streamflow data from the Murray-Darling Basin from the BoM, and
- Long-term temperature timeseries’ from the BoM’s Australian Climate Observations Reference Network

These data were used first to harmonise and populate sites metadata into a National Environmental Monitoring Sites Register (NEMSR). Second, common information models were developed and standardised data web services deployed for the respective data streams, in partnership with the data custodians. In addition, a production discovery metadata catalogue was deployed. By combining the sites metadata with data web services, for the first time uniform access was established to these diverse datasets within a single interface (Figure 7).

Current work in NEII is extending these components to additional providers and datasets. As well, new components are being developed, including an online vocabulary service, and web services for ‘environmental geographies’.
eReefs

The eReefs project signals the start of a new generation of critical intelligence products and services offered under the framework of the Australian Government’s NPEI initiative.

eReefs Principles

A number of foundational principles have been adopted for eReefs, outlined below.

Collaboration. eReefs brings together corporate Australia (through the Great Barrier Reef Foundation and its partner BHP Billiton Mitsubishi Alliance), Australia’s leading operational and research agencies (the BoM, CSIRO, and the Australian Institute of Marine Science), Government (the Australian and Queensland Governments), the Science and Industry Endowment Fund and reef managers (Great Barrier Reef Marine Park Authority).

Innovation. eReefs will use the latest technologies to collect data, develop new and integrated modelling and provide powerful visualisation, communication and reporting tools. The eReefs system will be compatible with the NEII.

End-user driven. eReefs products and services are developed with specific users and use cases in mind. Regular interactions between technical teams and end users provide formal avenues to incorporate user needs.

Phased delivery. eReefs is being delivered in three phases over a five year period. This project phasing allows for the delivery of prototype products and services based on mature research while further research and validation occurs where needed. This iterative approach to product development and delivery supports the ongoing integration of user needs into product delivery.
**eReefs Roadmap**

Over the next five years, the eReefs project will deliver:

1. Expanded and improved monitoring data through the application of the latest measurement technologies such as mobile and internet tools
2. A suite of new and integrated models tailored for connectivity between land and ocean that can represent how land use practices in the catchment may be affecting the adjacent reef
3. A framework to analyse the status of indicators such as water temperature, nutrient levels, turbidity and pH and gauge the resulting impact on the health of Reef ecosystems and the marine environment
4. An interactive visual picture of the Reef and its component parts, accessible to all
5. Citizen Science Initiatives to engage the broader community in the health of the Reef. Targeted communication products, including smart phone applications and customised web portals will be developed to allow the public to interact with the Reef – contributing monitoring information and learning about the Reef.

**eReefs Phase 1**

Phase 1 officially began in January 2012 and will run until December 2013. The focus of this first phase is to build the basic capability to deliver the eReefs vision. Specific outputs to be delivered in Phase 1 include:

1. A marine water quality dashboard that provides access to a range satellite derived water quality parameters (e.g. sea surface temperature, chlorophyll, coloured dissolved organic matter);
2. Calibrated and validated hydrodynamic models at varying scales for the GBR with further validation of transport and bio-geo-chemical models in future phases;
3. The overall architecture of the system will be designed and documented in line with NEII and eReefs;
4. Production of the current Reef Report Card will be automated; and
5. A range of scoping studies to investigate catchment monitoring and modelling as well as citizen science.

**Conclusion**

Significant investment is currently underway as part of the NPEI initiative to inform the development of environmental information standards, and build the first stage of a national, integrated environmental information system. The NEII and eReefs are two transformative projects that provide a concrete framework through which environmental information will be managed in the future.

The NEII project will inform the development of environmental information standards, and build the first stage of a national, integrated environmental information system. NEII is founded on a distributed architecture with data stored at the source using shared standards to transfer data between users.

Building on the NEII framework and using the latest technologies to collate data, and new and integrated modelling, eReefs will produce powerful visualisation, communication and reporting tools. This five year project, which commenced in January 2012, is the first step in building comprehensive coastal information systems for Australia.
eReefs will be used by many Reef stakeholders including: Reef managers and government policy makers, local stakeholders and the general public and the research community including universities and government agencies. It will be useful in undertaking strategic assessments of the Reef’s health, the outlook for its future and planning for potential natural and economic changes such as climate change and coastal development.
Ocean Observation uptake: Present status and the way forward

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1. Introduction

Australia’s Integrated Marine Observing Network (IMOS) was established in 2007 and is designed to be a fully-integrated, national system, observing at ocean-basin and regional scales, and covering physical, chemical and biological variables. Regional workshops were held to decide what infrastructure was needed and this has resulted in detailed science plans reviewed internationally. The state based nodes representing the marine research community were then formed. This was to partly acknowledge the significant co-investment from State Governments. The core NCRIS and EIF federal government funding was also increased with contributions by the facility operating agencies. Ten institutions within the National Innovation system operate the twelve facilities. They are responsible to deploy the equipment and deliver quality data streams for use by the Australian marine and climate science community and its international collaborators (source: www.imos.org.au). In 2012 a trans-Tasman symposium between IMOS and NIWA was held to include New Zealand as a data node expanding the Australian Ocean Data Network.

The observing system has been rapidly rolled out with aims to provide robust, reliable, sustainable and quality observations. The observing system was therefore conservative from the outset however investment in relatively new systems (to Australia) were still achieved such as ocean surface radar, gliders and sensor networks.

Mature systems here are defined as having a long history of providing real time data to the modelling community. They lean heavily on the infrastructure developed by the global weather observing network by having clear pathways of disseminating the data, usually via satellite or internet to the World Meteorological Organisation (WMO) Global Telecommunication System (GTS). Here satellite remote sensing data, comprising ocean colour, temperature, Altimetry and most recently Sea Surface Salinity in open ocean waters are routinely distributed to operational weather forecasters, as are ARGO profilers. For oceanographic applications the assimilation into OceanMAPS modelling (Brassington et al,
2012) and OceanCurrent (Griffin and King, 2012) are examples of recent Australian initiatives dealt with in accompanying ACOMO papers.

This paper focuses with the less mature observational streams that have yet to reach their full potential in uptake e.g. HF radars, gliders and moorings. Radar and gliders are relatively new commercial systems whereas the majority of the moorings array was planned to be delayed mode. These were a compromise by the research community to invest in a spatial array rather than bear the added expense of delivering in near-real time.

2. Examples of Regional Observation Uptake
The node science plans have been the driver for how the observational arrays have been designed and prioritised. These outlined what processes would be observed and how they can be used to support the research community to understand the seas around us. In the following sections recent examples of how IMOS infrastructure has been utilised to observe in detail the shelves around us and how they are being used in modelling. Increasingly the range of platforms available to modern oceanographers is yielding a growth in collaborative studies that are also attracting international participation.

2.1 Queensland’s Great Barrier Reef
The Great Barrier Reef (GBR) component of Q-IMOS is focussed on the island based research stations at lizard, Orpheus, Heron and One Tree. Their existing long term research projects meant demand for improved ocean observations would have a ready client base. The sensor networks provide data kiosks for local users to see what is happening now on the reef, whereas the deeper water moorings are concentrated on the outer continental shelf and slope requiring a six monthly service to download the logged data. The data has been used to help understand and validate models of extreme events such as tropical cyclones (TC) Harry (Woolsey et al 2012) and Yasi (Rigby et al, 2012). A near-real time 4 km resolution three-dimensional hydrodynamic model covering the entire GBR and western Coral Sea is being developed under the multi-agency eReefs project. It provides framework to explore the impact of multiple factors such as currents, temperature, nutrients, turbidity and pH on the GBR and from the Coral Sea and up into the catchments. eReefs has partnered with IMOS to upgrade the Palm Passage mooring to near real time in early 2012 complementing the Yongala National Reference Station that will resume real-time communications post TC Yasi.

By far the largest concentration of infrastructure in the GBR is in the Capricorn-Bunker Group. Here satellite remote sensing, HF radar, open ocean moorings and reef based sensor networks are advancing coral reef research (Heron et al 2010). Long term studies of coral bleaching by NOAA UQ ARC Linkage and more recent focus on ocean acidification is driving the higher resolution hydrodynamic and biogeochemical modelling. These efforts are nesting down from Bluelink Reanalysis and OceanMAPS, to eReefs whole of GBR scale and then to sub-reef scale models. At these finer scales wind (ACCESS) and wave (SWAN) models are being coupled with 3D hydrodynamic models (SHOC) to look at across reef flows (Gillibrand et al., 2012). They provide a platform for the biogeochemical modelling necessary to understand the large diurnal changes in chemistry observed on coral reef systems.
Observations of cold water intrusions at depth are yielding hither to unexplainable effects at higher trophic levels such as seabirds.

The QLD HF radar, covering the Capricorn Bunker group of the southern Great Barrier Reef, was the first system of its kind to be deployed in Australia and much of the uptake of data from this system has been within projects closely associated with the ACORN group. These include a study of the relationship between current speed and susceptibility to coral bleaching (Heron et al., 2012) a near real time evaluation of the track of a potential oil spillage from the grounding of the Shen Neng 1 container ship on the Douglas Shoal in April 2010; tracking of particles after a coral spawning event in 2009 (Mantovanelli and Heron, 2012) showing that the large scale circulation can sometimes be important in determining the dispersion of corals.

2.2 New South Wales
The glider deployments off the NSW coast have uncovered a number of new ocean processes and phenomena that are a challenging both our understanding and numerical models. The first Slocum glider deployment off NSW showed a deep chlorophyll maximum (DCM) in a warm-core eddy (WCE) (Baird et al., 2011). Previous studies of WCEs in the western Tasman Sea had suggested that deep surface mixed layers would prevent the formation of DCMs. During the deployment an arm of the East Australian Current wrapped around the eddy and flooded over the top of it, creating a shallow mixed layer. The DCM form at the interface of the flooding layer and the existing eddy below.

Further glider deployments along the northern NSW shelf on the coastal side of the East Australian Current demonstrated strong northward flows which 10 km resolution models do not resolve well. While these coastal currents were well known, the glider provided a new set of observations particularly of the biooptical properties of the coastal waters and the response to various forcing mechanisms.

Analysis of NSW and Tasmanian glider deployments found a lens of Bass Strait Water (BSW) formed at the centre of the larger warm-core mesoscale eddies (Baird and Ridgway, 2012). The southward advection of BSW in the larger WCE was unexpected. Preliminary analysis of output from the Blueline reanalysis (BRAN, Oke et al., 2008) showed some BSW does move south, although distinct eddy events were difficult to isolate (pers. comm. Ken Ridgway).

The above mentioned ‘new’ discoveries all have characteristic spatial scales similar to the vertical profiling glider with a spatial resolution of a few kilometres. While models remain courser than the observing platforms, observations will lead the discovery of new oceanic phenomena. The NSW –IMOS mooring array consists of 2 moorings upstream of the EAC separation point (off Coffs Harbour in Northern NSW), 4 moorings off Sydney and 2 moorings well down stream of the separation point off Narooma in Southern NSW. The high spatial (8m vertically) and temporal (5 min) resolution of the temperature and velocity records as well as the significant length of the time series (more than 2 years of data at most locations) has provided great insight into the temperature and velocity field upstream and downstream of the EAC separation point.
One application of these data is to understand the cross-shelf momentum budget and the importance of the secondary terms upstream and downstream of the separation point. Schaeffer et al (2012) show that while the dominant balance is geostrophic, upstream of the EAC separation point, bottoms stress influence is far greater than off Sydney, where wind stress dominates. Through an analysis of the relationship between temperature and current velocities, they show that the bottom cross-shelf temperature gradient is proportional to the magnitude of the encroaching alongshore current. Cross shelf sections show the upwelled water is subducted below the EAC, potentially driving biological productivity along the EAC separation front.

Wood et al (2012b) used the same mooring data to understand the seasonal variability in temperature and velocity along the NSW continental shelf. Using two different harmonic regression models they showed that temperature exhibited the strongest seasonal effect explaining up to 80% of the variability at the surface. Along-shelf currents at the shelf-break upstream of separation show a weak seasonal cycle, explaining just 5% of the variability with an amplitude of greater than 0.15 m s⁻¹ sub-surface. This is low when compared to other current systems e.g. the Californian current where seasonality explains up to 50% of the variability in shelf break currents.

Presently ACORN are conducting trials of the real time Ocean Reference Station mooring (ORS065) and hope to launch the website in the next few months. This will facilitate vastly greater data uptake both by the extended community and by modelling systems.

2.3 New Zealand
Coastal/shelf seas observation activity in New Zealand (NZ) is typically focused around broad questions directly driven by stakeholders as well as aspects relating to climate and Southern ocean processes. Shellfish aquaculture is NZ's equal second fishery whilst fish aquaculture is viewed as a growth area. Rocklobster is NZ's number one export $ fishery, yet we know little about provenance of juveniles (Chiswell and Booth, 1999). Marine energy does not have a high profile in New Zealand but the resources are good and there are some initiatives that have resulted in coastal observations (Stevens et al. 2008; 2012).

At the large EEZ scale, past work has looked at long-term variability in the Tasman Sea (Sutton et al. 2005; Waugh et al. 2006; Chiswell et al. 2007; Sutton and Bowen 20011), the dominant coastal currents (Chiswell 2000b) and mixing over the productive fishing areas of the Chatham Rise (Chiswell 2000a). There has been a focus on climate variability and response as well as large-scale connectivity. Work at this scale has been informed mainly by remotely sensed products, XBT and Argo data as well as models like BlueLink. Wave climates in both deepwater and inshore have been assessed through hindcast techniques but remain challenged by having modest data sets with which to validate (Gorman et al. 2000).

Regional studies have focused on the Hauraki Gulf onshore-offshore exchange, Cook Strait, and the Marlborough Sounds region. The Hauraki especially has been the subject of a significant period of mooring and repeat voyages (Zeldis et al. 2004). The Marlborough Sounds (Pelorus and Queen Charlotte) too has seen a number of studies but these have not always been Sound-wide and there is a great deal of variability throughout the system. A Lagrangian connectivity theme operates at this scale also (Chiswell and Stevens 2010). This
scale of work has typically been related to ROMS modelling efforts informed by the EEZ scales (e.g. Hadfield et al. 2007).

Small-scale work has ranged from internal wave processes observed through vessel and moored observations (Stevens et al 2005; 2012b), flow and mixing in aquaculture facilities (Plew et al. 2005) and more recently river plume mechanics. This has involved focused experiments often incorporating microstructure sampling. This scale of observation has connected with ROMS modelling and adaptive mesh modelling using Gerris (Popinet and Rickard 2007).

2.4 Southern Australia

The SAIMOS primary region of observing consists of the shelf and slope region between Kangaroo Island and the Eyre Peninsula. A WERA HF RADAR system is returning good data for ocean currents over the shelf and slope and these are being validated using data from 3-4 moorings including that from the Kangaroo Island reference station. The eight annual field surveys are continuing that each include 40 CTD survey casts and extensive biogeochemical data at four sites: three of which include moorings that are maintained all year round. The biogeochemical data is being used to drive a high resolution Nutrient, Phytoplankton, Zooplankton and Detritus NPZD model of Spencer Gulf. The physical data has been used to validate a hydrodynamic model of the shelf waters (and indirectly that of Spencer Gulf.

Leases for the exploration of gas and oil have been granted for the SAIMOS region as well as the Great Australian Bight (GAB). The SAIMOS observing system is expected to be extended into the GAB in 2013-2016 through new baseline studies of oceanography and the benthos and pelagic ecosystems.

2.5 Western Australia

WAIMOS was initially rolled out in the south-west and focussed on the seasonal Leeuwin and Capes currents and circulation associated with the Perth Canyon. Sustained cross-shelf sclocum glider missions over 13 months have tracked the formation of inshore dense water inshore, cascading across the shelf as a near bed gravity current (Pattiaratchi et al, 2011). The HF radar data are being used to look at the Leeuwin current and the small eddies that are associated with its interactions with the Rottnest shelf (Mihanovic and Pattiaratchi, 2012) as well as by swimmers who take part in the annual Rottnest island race.

In contrast the north-west shelf had only been occupied by the Ningaloo National Reference Station up until the Pilbara and Kimberley moorings array were rolled out in early 2012. Glider transects have also commenced along these lines. The arrays have however attracted significant interest by the research community on the NW Cape with several process based studies by WAMSI utilising the WAIMOS moorings as part of their observing strategy. A significant interest has been the low frequency circulation (Lowe et al 2012) and a number of internal wave studies that are seeking to improve numerical models. The importance of internal waves in the stimulation of primary productivity at Ningaloo Reef was the focus of an Australian National Network in Marine Science grant in 2011. Of particular note is the U.S. Naval Research Laboratory international collaboration of AUV Data Analysis for Predictability in Time-Evolving Regimes (ADAPTER) (Book et al, 2012). The experiment seeks to improve the assimilation of data into operational numerical models from gliders by
reducing aliasing caused by internal waves. The Ningaloo NRS and Pilbara moorings arrays provided two of the four observing nodes that comprised up to seven moorings at each node together with a dedicated Slocum glider.

2.6 Northern Australia
A National Reference Station was established in the coastal water off Darwin in 2009. It utilises an existing channel marker to allow the 3G transmission of data and as a platform for weather observations. Current profiles and wave data from a bottom mounted frame are transmitted to the buoy using acoustic modems. In 2012 the Darwin Port Corporation and the Northern Territory Government are so-investing to allow another mooring destined for Beagle Gulf. The data will be used to improve shipping operations and as boundary conditions for a real-time model of Darwin Harbour to assist with water quality, sea level, tide, wave and current prediction.

In 2010 a shelf array comprising 4 moorings were deployed from Joseph Bonaparte Gulf to the Timor Slope. This was complemented by 3 deep water moorings designed to monitor the Indonesian Through Flow by the Australian Bluewater Observing System. These moorings will be recovered for the first time later this year. Early uptake of the shelf data by UWA has focussed on modelling studies of Internal waves (Nash et al, 2012)

3 The Future of sensing platforms

3.1 HF RADAR from the Australian Coastal Ocean RADAR Network (ACORN)
ACORN is currently providing measurements of surface current from 6 radar systems, each comprising two separate sites, in real time and in delayed mode, the latter incorporating more quality control. Two of these systems are in WA, two in SA, one in NSW and one in QLD. The radar data are now being included in the integrated coastal ocean dynamics presentations of the IMOS Oceancurrent web pages [http://oceancurrent.imos.org.au/](http://oceancurrent.imos.org.au/).

The location of these radar systems were selected to meet prioritized needs of the regional IMOS nodes and limited budgets. New interests have emerged and there is also interest in developing sites at some locations which did not make the first priority list. For example it is likely that IMOS will receive data from an industry-funded radar system on the NW shelf and there is continuing interest in monitoring the region of NSW where the East Australian current separates from the coast.

ACORN chose to deploy two different radar systems within the network, the CODAR SeaSonde and the Helzel WERA system. Both these radar system require constant monitoring, much of which can be done remotely and automatically, and frequent maintenance and trouble-shooting visits. Until more robust radar systems are available their operation will continue to require highly trained technical support. The SeaSonde is the most commonly used system in the world, is relatively easy to deploy and is good for measuring large scale, slow current systems. The WERA has the capability to map waves and winds as well as currents on shorter time scales so was the choice where such measurements were required e.g. in South Australia and Coffs Harbour. ACORN will be providing wind and wave
products in the future. One factor that may limit the extent of this provision is the need for more (and cheaper) data transmission bandwidth from the radar sites some of which operate in rather remote and difficult environments. Most of the radar systems operate with mains power but at one site in SA we use a combination of diesel and solar power. This is a site that could also take advantage of wind power and an Alaskan project, where a SeaSonde system has been run using just wind and solar power (Statscewich & Weingartner, 2012), is an encouraging development which may make it easier to deploy more systems in remote locations.

Each radar site provides radial current data, i.e. the component of the surface current along the radar look direction, over an area and with a resolution determined by the operation frequency and licensed bandwidth. For the Capricorn Bunker radar this gives a maximum range of about 150km with a grid spacing of 4.5km. The actual spatial coverage for all systems varies with time due to interference and other environmental factors. These data are delivered to the data archive within minutes of the end of the data collection period which is 5 minutes for a WERA measurement and 1.3 hours for a SeaSonde measurement. Data from two sites is needed to obtain full vector currents. For WERA these are calculated from hourly averaged radials, for SeaSonde the timescale is the same as the radials and in both cases hourly values are delivered to the archive.

3.2 Gliders
Autonomous gliders have been developed recently with major advances in computing and robotic technology. They can be seen to have evolved from the ARGO profilers that are subject to current drift in the deep oceans. By changing its buoyancy and moving its weight, vertical motion is converted to horizontal motion through its wing orientation. This control allows the vehicles to be controlled to perform controlled missions in shallow (Slocum) and deep waters (Seaglider). The Seaglider is especially useful as it can last months on a mission allowing it to get to remote regions such as the Northern Coral Sea and Southern Ocean that are rarely visited by conventional research vessels.

Assimilating the data in near real time is a possibility and techniques can build on those developed for the ARGO profilers. To date the gliders have been used mainly for hindcast modelling however now that regular missions are being planned the data transmitted via satellite can join other near-real time datastreams. Reliability and quality control however remains an issue as long missions of a few months can take their toll on the robotics, communications and bio-fouling of sensors. Additional value could be gained from additional sensors including improved current estimates or direct current measurements.

New technologies such as wave gliders that remain on the surface using solar cells to power the electronics and sensors and harvesting power from ocean swells look promising developments for future applications. They could be used for surveys of repeated transects or even in station keeping mode to transfer data from in-line moorings via acoustic data transmission.
3.3 Moorings
The spatial and temporal coverage of oceanographic observations around Australia is still lacking. Wood et al (2012a) compares a unique wind-data series from an ocean mooring (now part of IMOS) with two re-analysis products as well as data from six over-land sites in the Sydney region to determine whether these data can infer over-ocean wind conditions. Despite the ‘mooring mania’ in IMOS, over-ocean meteorological observations are sparse around the Australian coastline. Correlations between wind stress at the over-ocean and over-land sites were 0.8, whereas for reanalysis products, correlations ranged from 0.28 to 0.72. Re-analysis products were unable to resolve variability at the over-ocean site with periods shorter than 2 days, indicating that they are not appropriate wind proxies for the coastal ocean – Particularly when trying to estimate short temporal scale processes such as wind driven upwelling.

Real time delivery of data is restricted to a subset of the 9 National Reference stations in Australian coastal waters and the SOTS deep water mooring. Keeping data streams live remains a significant challenge due mainly to the exposure of surface buoys to extreme weather events. Upgrades to real time moorings remain expensive as instruments require additional electronics and acoustic modems or inductive cable modems.

Currently the surface buoys remain large to carry the weight of batteries and surface instrumentation. Developments are needed to continue to miniaturise components and reduce power consumption. This may allow for smaller surface buoys that could also be winched below the surface when not transmitting and could include instrumentation to give detailed profiles. Such a system has been developed over the last decade and recently deployed on the north-west shelf by the aforementioned ADAPTER project. The shallow-water environmental profiler in trawl-safe real-time configuration (SEPTR) winches out an instrumented buoy to transmit the data via satellite. It should be noted though that these systems are very complex and require significant expertise in setting them up and maintaining them especially over the longer term deployments.

In early 2013 a real time upgrade will be made to the Palm Passage mooring (GBRPPS) off Townsville due to co-investment from CSIRO Wealth from Oceans for the eReefs project and Darwin Port Corp will fund a real time mooring in Beagle Gulf.

3.4 Sensor Networks
This IMOS facility is currently based wholly within the GBR together but together with TASMan is showing the future of delivering real time data (Jones et al, ACOMO). Sensor networks aim to be inexpensive and real-time however in the marine environment the need for robustness has meant the initial roll out in the GBR at island based research stations has incorporated more traditional and expensive instrumentation. The area is rapidly developing as are standards for data. There is a push for smart instruments that are interrogable via the network in real time allowing for adaptive sampling and that deliver machine readable data. This will hasten uptake to the modelling community by making the data more easily discoverable however in practice this is limited by availability of these capabilities by marine instrument manufacturers. Over time these developments are expected to transfer over to other facilities’ instrumentation.
4. Use of observations to support modeling

Numerical modelling has experienced significant advances in computing over the last decade and the norm last century was to provide hindcasts of local regions. The runs ideally incorporated the use of actual observed boundary conditions with perhaps a number within the model domain used for validation. Nowcast/forecast ocean modelling is now being increasingly considered a routine application and this is partly due to the timely availability of global scale operational models that provide the open boundaries and initial conditions. This has resulted in an increased demand and expectation for the timely provision of observational data for assimilation into the models.

Delayed mode observations however remain valuable to the research community, as hindcast modelling benefits from the availability of significantly more observations for assimilation or validation. This can include a reanalysis of the real time data that has with more rigorous quality control applied. This is where most of the advances in understanding processes and climate change occur.

Models have been used to inform experimental design in many short term process based studies and recent efforts assessing current, temperature and sealevels from Bluelink against the IMOS existing moorings array reveals the value of the existing design and identifies gaps in the array (Oke and Sakov, 2012).

Assimilation of IMOS HF radar data into hydrodynamic models has not yet begun but there have been many such studies in the US and Europe (e.g. Gopalakrishnan, 2012; Barth et al, 2008; Andreu-Burillo, 2008). Although the US has the advantage of very dense HF radar coverage along its coasts, so assimilation into large scale models should be of great value, most studies to date have been with local coastal modelling. Assimilation into wave models has also been a subject of study in the UK (Siddons, Wyatt and Wolf, 2012).

Sustained biogeochemical observations remain limited to monthly observations at the nine National Reference Stations and some opportunistic observations. These are clearly too sparse and infrequent. The development of cheaper and more stable sensors are critical if there is to be any improvement in spatial and temporal coverage to better inform and test the models.

It is also fair to say that IMOS has necessarily restricted itself to a core subset of key ocean variables. For example sea levels and wave measurements were initially not included as other agencies had existing coastal networks. However open ocean observations of these variables in situ are needed to improve satellite algorithms and numerical models and especially in extreme events (Cahill et al, 2012).

5. Conclusions

Whilst IMOS represents the most significant investment for Australian Ocean Observing the sparseness of the array is readily apparent given the large size of our marine territories. The challenge remains to increase the array in strategic and considered locations that are not
already represented well enough with the existing array. IMOS was launched only 5 years ago in 2007 and has matured rapidly in the short 5 years of life so far.

Australian State and Federal government investment in ocean observing has in the short term most likely to have peaked though significant gaps remain in coverage around our neighbouring oceans. Future expansion will rely on proven success and reliability of the systems already deployed and attracting partnerships with industry in coastal and offshore regions. Plans with industry are well advanced in the North-west Shelf, Great Australian Bight and the growing port developments across Australia.

Technological Innovations are expected to bring the costs per observation down. This will be done by increasing miniaturisation of computing and sensor developments that are key to any expansion of the existing array.

Novel approaches to transmitting data from remote locations are also needed as they are currently a major burden on operating costs. This can be delivered by reduced satellite communications costs and an increasing range of telecommunications coverage across continental shelves as recently experienced by expanding 3G networks.

Uptake by oceanographic modellers will be enhanced through the improved near real time delivery of data to the WMO GTS and an oceanographic equivalent through eMII/AODN. In parallel higher level products and visualisation are required for the general public, industry partners and researchers that are less familiar with oceanographic data. For example a recurring request from marine biologists and stakeholders is for daily averages rather than the higher frequency sampling currently made available.

6. References


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Ocean Observing Systems: recent progress, opportunities and future plans

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1 Introduction
Many methods have been used to undertake observing system design and assessment studies for oceanic and atmospheric applications - most of which borrow tools from data assimilation [14, 4, 9]. To date, only a limited number of model-based studies have been undertaken to specifically assess the design and assessment of the Integrated Marine Observing System (IMOS) [11, 8]. These studies have used a limited set of models, observations, and analysis techniques. The conclusions of those studies need to be rigorously tested by employing different methods, models, and approaches to assess the design of IMOS. The methods that have already been applied to assess IMOS are fairly generic, broadly relevant, but sub-optimal. These methods could easily be extended to address known limitations of past studies, and could be applied using different models, as input, to test the validity of conclusions. Also, different approaches could be readily applied to contribute to the assessment and design of IMOS, include Observing System Experiments (OSEs) [12], Observing System Simulation Experiments (OSSEs) [13], adaptive sampling [1, 6], or adjoint-based approaches [5, 2, 3]. A summary of past studies, designed to assess different components of IMOS, is presented in section 2, followed by a description of future opportunities in section 3.

2 Recent Progress
New South Wales IMOS: An assessment of the likely benefits of assimilating in situ temperature and salinity observations from repeat glider transects and surface velocity observations from high-frequency radar arrays into an eddy-resolving ocean model was presented by Oke et al. [11]. In their study, various options for an observing system along the coast of New South Wales were assessed for their benefits to an ocean forecast/reanalysis system. The forecast/reanalysis system considered in their study was the BlueLink system, and was underpinned by an ensemble optimal interpolation (EnOI) data assimilation scheme [10]. Using error estimates from the EnOI scheme, estimates of the theoretical analysis errors were calculated for different hypothetical observing systems that included a range of remotely sensed and in situ observations. The results demonstrated that if high-frequency radar observations were assimilated along with the standard components of the global ocean observing system (i.e., satellite altimetry, sea surface temperature (SST), Argo, and XBT), the analysis errors reduced by as much as 80% for velocity and 60% for temperature, salinity and sea-level in the vicinity of the observations. Owing to the relatively short along-shore decorrelation length-scales for temperature and salinity near the shelf, the glider observations provided the forecast/reanalysis system with a more modest gain.

National Reference Station (NRS) and Mooring arrays: The footprint of an observation provides an indication of the region that is effectively monitored by that observation. Oke and Sakov [8] defined the footprint of an observation as the region that is well correlated to the observed variable at zero time lag. Examination of the footprint of an observation and the combined footprint of an array of observations provides an indication of the region that is effectively monitored by that observation or array. Oke and Sakov [8] examined characteristics of the shelf circulation around Australia, including the footprint of individual moorings and mooring networks that underpin IMOS. Their analysis was based on a 17-year
time series of modelled SSH, SST, and near-surface velocity, on intraseasonal (<60 days) and interannual (>14 months) time-scales. Examples of the combined footprint of SSH and SST, on interannual time-scales, at the NRSs are presented in Figure 1. The regions of high correlation were deemed to be well-monitored by the observing system. Table 1 shows the percentage of area over the continental shelf (defined as shallower than 200 m depth) and for the entire model domain they considered (within 400 km of the coast) that has a combined correlation of greater than 0.8 for different variables. These results indicate that the NRSs effectively monitor (with a correlation of over 0.8) 81% and 68% of the shelf region for interannual SSH and SST, respectively. The result that nine NRSs provided such good coverage for interannual variability over the shelf was unexpected. However, as indicated in Table 1, the NRSs only effectively monitor 28% and 12% of the shelf region for intraseasonal SSH and SST, respectively. Oke and Sakov [8] found that the 28 additional IMOS moorings that were planned for the regional nodes at the time of their study expands the combined footprint for intraseasonal variability to cover by up to 70% (covering about 50% of the shelf regions). Several gaps in the observing system were identified that could be filled by additional observations. Examples of gaps include the East Australian Current separation zone, central eastern Australia, the central Great Barrier Reef, the Great Australian Bight, parts of the northwest shelf, and the Gulf of Carpentaria. There are several known limitations of the study described here, namely that only the spatial correlations were used - not the temporal correlations; and only surface fields (SSH, SST, and surface velocity) were analysed. That study was meant to be a first step in this process. Options for a continued effort are presented below.

![Figure 8: Combined correlation maps for interannual SSH (left) and inter-annual SST (right) from OFAM2. The location of each NRS is marked with a green bullet [8].](image-url)
Table 2: Percentage of area with a combined correlation of greater than 0.8, for the NRS and the NRS plus the IMOS moorings (in parentheses), based on estimates from the OFAM model [8].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Percentage area</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shelf (&lt; 200 m)</td>
<td>Full domain</td>
</tr>
<tr>
<td>Intraseasonal SST</td>
<td>12 (15)</td>
<td>7 (8)</td>
</tr>
<tr>
<td>Interannual SST</td>
<td>68 (87)</td>
<td>55 (70)</td>
</tr>
<tr>
<td>Intraseasonal SSH</td>
<td>28 (37)</td>
<td>16 (24)</td>
</tr>
<tr>
<td>Interannual SSH</td>
<td>81 (83)</td>
<td>60 (64)</td>
</tr>
<tr>
<td>Intraseasonal surface velocity</td>
<td>21 (36)</td>
<td>17 (27)</td>
</tr>
<tr>
<td>Interannual surface velocity</td>
<td>19 (34)</td>
<td>11 (21)</td>
</tr>
</tbody>
</table>

3 Opportunities and Future Plans

Extension of past work: The studies referred to in this abstract that were designed to help evaluate different components of IMOS [11, 8] were underpinned by elements of the Bluelink model and data assimilation system [16, 10]. As stated above, these studies were also based on correlations or covariances in space, not time; and were limited to only a few variables. The extension of the methods used [11, 8] to include other models is straightforward. Similarly, the extension of these studies to include temporal correlations is achievable, as demonstrated in Figure 2 showing an example of a four-dimensional ensemble-based correlation field. Moreover, a model-based design or assessment of IMOS could be based on multiple models [15]. The model runs used to evaluate IMOS to date have been relatively short (< 20 years) and coarse-resolution (~10 km). A 50-year model run of OFAM3, the new Bluelink global model, is planned. This could underpin future observing system design and evaluation studies and would include longer-period variability. Similarly, high-resolution nested models could be performed to better resolve the coastal and shelf-scale processes that are of interest to IMOS. A key challenge with such studies is running the regional model for a long enough period to adequately represent the variability of interest - including the climate-relevant variability. Perhaps a regional model, or a suite of regional models, could be nested within a long reanalysis.

Figure 9: An example of four-dimensional ensemble-based correlation fields showing the spatio-temporal influence of a sea-level observation in the open ocean, south-west of New Caledonia. Each panel shows the ensemble-based correlations between sea-level at t = 0 days and sea-level in the surrounding region for time-lags of (a) -4 days, (b) 0 days, and (c) +4 days [7].
Different methods: The model-based observing system evaluation studies referred to in this abstract were both based on ensemble data assimilation methodology. Alternative methods are available [7]. These include analysis self-sensitivities [14], and a range of more advanced ensemble-based [15] and adjoint-based techniques, including breeding [6], adjoint sensitivity [2], and singular vectors [5]. Of these methods, adjoint-based techniques, forecast sensitivities, and singular vectors require a tangent linear model (TLM) and its adjoint. These tools are available - but a phase of training would probably be required if the Australian research community were to embark on their application for coastal observing system design studies. All of the tools needed for ensemble-based studies are readily available.

Observing System Experiments (OSEs): With the development of maturing modelling and data assimilation capabilities, the opportunity to perform OSEs to assess IMOS is readily achievable. OSEs generally involve the systematic denial, or with-holding, of different observation types from a data assimilating model in order to assess the degradation in quality of the model when that observation type is not used. Importantly, the impact of each observation type may strongly depend on the details of the model into which they are assimilated, the method of assimilation, and the errors assumed at the assimilation step. It is therefore instructive to consider results from a range of different models and applications in an attempt to identify the robust results that are common to a number of different systems. A series of OSEs, relevant to IMOS, could assimilate IMOS data into a high-resolution regional model, for example, and then systematically withhold different elements of the observing system. Another approach is to run a Bluelink-style reanalysis under IMOS - synthesising all available IMOS observations using a global or Australia-wide regional ocean model (e.g., ribbon model) - and then subsequently performing a series of OSEs for each component of IMOS. The tools needed for such a study are readily available.

Observing System Simulation Experiments (OSSEs): OSSEs are useful for looking forward, to evaluate the potential impact of future observational components. OSSEs often involve some sort of twin experiment, where synthetic observations, usually extracted from a model, are assimilated into an alternative model or gridded using an observation-based analysis system. OSSEs are commonly used to assess the impact of some hypothetical array of observations that may not exist yet. This means that these methods can be used to contribute to the design of future observing systems, quantifying their possible impacts and limitations. A series of OSSEs could be performed at the planning stage, to help weight up different options for future IMOS deployments. The tools for performing OSSEs are the same as those needed to perform OSEs - and these tools are readily available to the Australian research community.

References


Wave and near-shore modelling: status and observation requirements in Australia

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1. Significance and Scope

Australia is the largest nation that is completely surrounded by water, with an estimated total coastline (mainland plus islands) approaching 60,000 km. Approximately 85 per cent of the Australian population now live in the coastal region and it is of immense economic, social and environmental importance to the nation. All Australian state capital cities are located within the coastal zone. Australian territorial waters are twice the size of its land area. About 8% of Australia’s GDP is derived from its oceans and the potential exists to expand this significantly.

Reliable prediction of near shore waves and currents modelling is crucial to many the economic, environmental and recreational activities that take place in Australian coastal waters. This contribution summarises the present state of near shore wave and current modelling as well as future prospects with the associated observation requirements in the Australian context. It is structured as follows. It commences with an overview of the specific present applications followed by a brief summary of the primary professional Australian groups who are direct users of near shore current and wave models. The types of models used to predict waves and currents in the near-shore zone at present are described preceding speculation of possible future applications and developments. The primary roles of oceanographic data, both now and into the future are discussed, concluding with recommendations for future Australian near shore wave and current data collection.

This contribution has been prepared from a marine perspective. While its scope includes modelling waves and currents in coastal embayments, more enclosed waters, such as estuaries and tidal inlets, are not discussed. Waves and near shore currents assume particular importance in the littoral zone. While the modelling and measurement of waves and currents impacting the littoral zone will be discussed, littoral processes will not be described as these are the subject of a sister article (Turner et al., 2012).

2. Present Needs

The specific needs associated with near shore wave and current measurement and prediction fall into three board categories:

1. climatological (what is the general nature of wave and current patterns and how do these vary in time?);
2. operational (what impact will present or forecast waves and currents have on specific activities?);
3. design (what is the character and probability of extreme waves and currents and how might these impact structures in the coastal ocean?).
Weisse (2009) presents an incomplete list of the specific applications for within coastal waters. In Table 1 a more comprehensive list of applications of near shore wave and current models in Australian coastal waters with examples. Note that active wave breaking remains poorly characterised by numerical modelling and reference is made to physical studies in the table below where this is the primary consideration.

Table 1. Present applications of near shore wave and circulation modelling, the specific aspects under consideration and some example applications.

<table>
<thead>
<tr>
<th>Application</th>
<th>Specific Consideration</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure design and coastal inundation</td>
<td>wave loadings</td>
<td>McCowan and Lawry (2011)</td>
</tr>
<tr>
<td></td>
<td>current loadings</td>
<td>Tian <em>et al.</em> (2011)</td>
</tr>
<tr>
<td></td>
<td>elevated water levels</td>
<td>Harper <em>et al.</em> (2011)</td>
</tr>
<tr>
<td></td>
<td>wave energy</td>
<td>Hemer and Griffin, 2011</td>
</tr>
<tr>
<td>Contaminant dispersion</td>
<td>oil spills</td>
<td>Zigic <em>et al.</em> (2011)</td>
</tr>
<tr>
<td></td>
<td>sewage discharges</td>
<td>Cathers and Peirson (1992)</td>
</tr>
<tr>
<td></td>
<td>desalination plumes</td>
<td>Miller <em>et al.</em> (2007)</td>
</tr>
<tr>
<td></td>
<td>dredging operations</td>
<td>Bettington and Miles (2009)</td>
</tr>
<tr>
<td></td>
<td>ballast discharges</td>
<td>Murphy <em>et al.</em> (2009)</td>
</tr>
<tr>
<td>Marine and port operations</td>
<td>Navigation</td>
<td>Youdale and Priestley (2005)</td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td>Banner and Morison (2010)</td>
</tr>
<tr>
<td></td>
<td>military operations</td>
<td></td>
</tr>
<tr>
<td>Recreational and tourist safety</td>
<td>Vessels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>rock fishing</td>
<td>Shand <em>et al.</em>, 2009</td>
</tr>
<tr>
<td></td>
<td>Surfing</td>
<td>Lane <em>et al.</em> (2010)</td>
</tr>
<tr>
<td></td>
<td>Swimming</td>
<td></td>
</tr>
<tr>
<td>Extractive industries</td>
<td>sediment transport</td>
<td>Orpin <em>et al.</em> (2009)</td>
</tr>
<tr>
<td>Research activities</td>
<td>biotic behaviour</td>
<td>Baird <em>et al.</em> (2006)</td>
</tr>
<tr>
<td></td>
<td>Forensics</td>
<td>²Cox and Wang (1995)</td>
</tr>
</tbody>
</table>

²D.N. Foster also assisted police in identifying the dumping location of a body found in the Tamar River, Tasmania in the 1980s.
3. Management and Development of Coastal Waters

Due to the generally impenetrable nature of Australia’s interior (e.g. Cathcart, 2009, p. 89ff), Australia’s coastal ocean has provided the major historical bulk transport route around the nation. In spite of the significance of activity, much of the history of the management and development of coastal activities remains poorly documented although notable contributions by Gourlay (1996); Coltheart (1997) and Callaghan and Helman (2008) are noted.

Apart from the Australian Federal Government (with primary responsibility for managing Australia’s Economic Exclusion Zone, Figure 1) and the State Governments (who have primary responsibility for economic and environmental management of coastal activities), there are a number of key groups who represent Australia’s principal interests in the coastal zone and who rely on modelling of waves and currents in the near shore region.

Local government has primary responsibility for the management of the infrastructure that serves coastal communities. In Australia, these are represented by the National Sea Change Taskforce (http://www.seachangetaskforce.org.au/). The taskforce was established in 2004 as a national body to represent the interests of coastal councils and communities. The Taskforce promotes the adoption of a coordinated national approach to managing sea change growth involving all three levels of government with a focus on sustainability of coastal communities and the coastal environment.

The Australian Meterological and Oceanographic Society (AMOS, http://www.amos.org.au/) is an independent Australian society that supports and fosters interest in meteorology, oceanography and other related sciences. It provides support and fosters interest in meteorology and oceanography through its publications, meetings, courses, grants and prizes, and represents the views of its members to Government, institutes and the public.

Figure 10: Australia’s Economic Exclusion Zone showing established long term monitoring stations relevant to wave and near shore circulation modelling. Wave buoys are shown as red dots while the other instruments deployed under IMOS programmes are shown by the other symbols in the legend. The only long term near shore current and temperature monitoring station, the Sydney Water Ocean Reference Station is located as indicated.
The Australian Coastal Society (ACS, www.australiancoastalsociety.org) promotes knowledge and understanding of the environmental, social and economic value of the Australian coast via providing debate and communication relating to management, planning and development of the Australian coast. It supports a suite of national, state and local coastal conferences including Coast to Coast and the NSW Coastal Conference.

The National Committee on Coastal and Ocean Engineering (NCCOE) is a specialist sub-committee of the Civil College within Engineers Australia (http://www.engineersaustralia.org.au/coastal-ocean-engineering). NCCOE organises the biennial Australasian Coastal and Ocean Engineering Conference which is the premier technical forum for engineers in the Australasian region interested in the coastal and ocean zone. This conference series started in 1973. NCCOE is active in providing professional guidelines in relation to coastal issues (e.g. NCCOE, 1993; NCCOE, 2004; Gourlay et al., 2004)

PIANC Australia (http://pianc.org.au/) is one of the larger of the 21 recognised national sections within PIANC internationally. PIANC is the global non-political and non-profit organisation providing guidance for sustainable waterborne transport infrastructure and operations of ports and waterways.

Occasional specialist meetings occur outside the auspices of these organisations (e.g. Day, 2010).

4. Categories of near shore wave and circulation models

An enigmatic aspect of the numerical modelling of waves and currents is that they are almost always undertaken independently even though wind is a primary forcing generating both (e.g. Pond and Pickard, 1983 Chs. 9 and 12). This is principally because the characteristic time scales of storm waves is much shorter than most other processes generating near-shore circulations (winds, tides, internal waves, coastal trapped waves, tsunamis, large-scale ocean currents; Middleton and Griffin, 1991; Cathers and Peirson, 1992, Figure 3.22). In near-shore regions, direct interactions between currents and breaking waves are well established (Phillips, 1977, p. 54) and modelled (Peirson and Roizenblit, 1993; Taebi et al., 2012).

The characteristically short time scales of storm waves (0.5 to 20s, say) means that very small time steps (and therefore substantial computation effort) are required to represent waves on a wave-by-wave basis (so-called phase resolved models). Consequently, spectral models are used to increase the computational time step to the order of the temporal change in the forcing wind field or the evolving wave groups.

A contrast can be drawn between wave and circulation models in terms of their treatment of turbulence. The diffusion of momentum is a fundamental aspect of circulation models which must incorporate some representation of the Reynolds stresses (with appropriate boundary conditions) in their formulation (e.g. Mellor, 2003; Craig and Banner, 1994). The success of the irrotational approximation In the characterisation of ocean waves has led to wave models being formulated with any Reynolds stresses being neglected except implicitly in terms of energy losses due to breaking (e.g. Banner and Morison, 2010) or interactions with the bed during shoaling (e.g. Smith et al., 2010).

Spectral models have had long acceptance in coastal design (Resio, 1988) and phase-resolved models have been slowly gaining acceptance although their most computationally efficient forms (Boussinesq models, e.g. Kirby et al., 1998) struggle to adequately represent waves in deeper water (e.g. Peirson et al., 2011). Phase-resolved modelling of wind-forced seas to date has remained a research activity (Xue et al., 2001).
Circulation models have been applied in Australian coastal waters for approximately 20 years principally with applications to navigation (Youdale and Priestley, 2005), water quality (Cathers and Peirson, 1991) and the determination of the impacts of cyclone landfall (e.g. Harper et al., 2011). The models normally solve stratified 3D forms of the Reynolds equations employing the shallow water approximation. If the flows are shallow and resolution of the wind drift layer is not required, depth-averaged forms may be used.

Other specific applications include military, structural and naval architecture applications. Such model conventionally draw on information provided by wave and circulation models and are not discussed further here.

5. Use of data in near shore modelling

The collection of data within the coastal ocean is an expensive activity. Consequently, alternative means of obtaining wave and current information have been developed. Altimeter is a satellite-based product capable of measuring surface waves in the open ocean, and has been used to assess climatological variability of the historical wave climate over the last 25-30 years (Hemer et al., 2010, Young et al., 2011, 2012). While altimeters provide regular samples of waves over most of the globe, the sampling frequency is low (≡ 10 - 35 days) and statistics of storm events, which have a duration of a few days, are compromised. Capturing long records of individual storm events are essential to determining design storms (Carley and Cox, 2003; Shand et al., 2011).

Notionally, coastal currents can be derived from recorded water level (tidal) data along the coastal margins. This has not met with great success in Australasia due to the very open ocean boundaries (Cox, 2003) and direct measurements of the coastal currents have been essential.

Near shore wave and circulation models are forced by (generally) decoupled atmospheric models. Consequently, assimilation, as frequently used in atmospheric models, is particularly challenging when applied to the ocean surface as the principal errors may lie in the (spatially-distributed and uncoupled) wind forcing (Gorman and Stephens, 2003). Present practice is to use recorded data for validation purposes only. The specific example cited by Holman (2009) is a highly data rich form of research assimilation. Alternative operational techniques of deriving near-shore waves and bathymetry using optical techniques are available (e.g. Lane et al., 2010).

An exceptional application of assimilative techniques within a model of coastal circulation was undertaken by Wang and Tate (1998). In the Sydney region, which is very weakly forced by the barotropic tide, an inverse analysis technique was developed which enabled the circulation model to derive its boundary conditions from the recorded currents.

Without long term data sets, coastal design and planning of coastal operations must adopt conservative approaches when assimilating the limited information available. In general, coastal development is expensive due to the significant loads imposed by storm waves and the approximately cubic dependence of protection mass on the design wave height (Figure 2 in NCCOE, 1991). The high probability of failing to capturing storm waves during short (≤ 3 year) deployments, makes ongoing monitoring in the coastal ocean essential (particularly for waves) and the cost of monitoring will be recovered many times over due to the optimisation that will be possible prior to construction.

Long-term non-IMOS near shore wave and current data continue to be gathered at the locations shown in Figure 1, principally gathered by State Government or large State-owned corporations.
Presently, IMOS data streams that principally relate to near shore waves and circulation (Figure 1) are poorly integrated into mainstream activities beyond the research community for three reasons:

1. Monitoring locations are too far from the coast to provide information that can be applied in near shore regions.

2. The data is obtained from a sequence of deployments and therefore cannot be used operationally.

3. The instruments have been deployed to develop research techniques which do not yield sufficiently reliable data.

6. The Future

There is little doubt that numerical model capability will continue to improve substantially over the coming decades primarily due to improved capabilities in computational power, improved physics and model integration. Although Australia is very active in the development of improved techniques to determine waves and coastal circulation, it has very limited facilities from which concerted field research campaigns can be deployed. Those that may be available (e.g. the bypassing jetties near the Queensland-NSW borders) have significant limitations from a research point of view.

Where specific project-based coastal developments are to occur, short term (≥ 2 year) deployments of current monitoring for determining the fate of contaminant discharges will probably be adequate, provided the data gathering programmes are appropriately designed.

However, Australia will continue to incur unwarranted expenditure on infrastructure that must be designed to be overly conservative in the absence of reliable long-term data. The importance of long-term data collection programmes has assumed increased significance in the context of climate change. Not only are changes in coastal behaviour anticipated due to changes in atmospheric and oceanic circulation but ongoing monitoring is fundamental to determining whether and when expensive coastal settlement and infrastructure adaptation becomes necessary. Existing (<40 year) data collection programmes must continue if factual information with regard to changes in coastal storm behaviour is to be determined (NCCOE, 1991). The current situation where long-term wave observations are being collected by several State Government and large State-owned corporations independently is not ideal. Data processing and archiving is inconsistent between the data custodians, which may limit the application of the data for determining long term historical variability and change on a National scale. Centralisation of these on-going observations (e.g., via IMOS eMii) may significantly broaden their present utility.

These ongoing wave data collection programmes provide a critical dataset for ongoing validation of Australia’s national operational wave model carried out at the Bureau of Meteorology (Durrant et al., 2011).

Future coastal planning activities, undertaken at all tiers of Government, are dependent on sea-level rise projections, but also understanding of potential changes in storm wave activity. To establish confidence in wave climate projection models (e.g., Hemer et al., 2012a,b), they must demonstrate skill in simulating observed historical variability of wave climate under historical climate model forcing. Long-term wave observation records are sparse and require ongoing support.
Further, for both operations and design, defining event extremes is not sufficient – scour and economic loss dictate that event duration and form are both critically important characteristics (Cox and Carley, 2003). The conjunctive probability of both currents and waves is an important aspect of coastal infrastructure design that is presently very poorly understood (e.g. Shand et al., 2012).

Australia’s fundamental research with regard to determining dangerous sea states is amongst the best in the world (e.g. Banner and Morison, 2010) with corresponding implications for improved vessel safety and applications in the near shore region (e.g. Shand et al., 2010).

Improved techniques for more economical and reliable land-based monitoring of near shore waves and circulation are essential and present IMOS-related development of HF Radar applications should continue (Jaffrés et al., 2010). An immediate priority is to move these capabilities to a pilot operational status.

Renewable forms of energy will assume increasing importance over coming decades. Although mapping of mean wave energy impacting the Australian coastline has been undertaken (e.g. Hemer et al., 2010a,b ; Hughes and Heap, 2010; Pattiaratchi and Bosserrele, 2010), design of wave energy facilities will have to include extreme events. The availability of suitable platforms for the field testing of wave energy devices may be a key consideration in the development of future data gathering facilities along the Australian coast.

Although the deeper ocean currents along Australia’s coast have been characterised in some areas, characterisation of currents in the near shore region will assume greater significance as energy extraction from ocean currents is going to be considered as a potential contributor to Australia’s renewable energy mix.

Both waves and currents have a strong influence on the flux of constituents through the air-sea interface. There is a present research shift towards computing these based on the surface sea state (e.g. Suzuki and Toba, 2011), and increasing attention on the potential feedbacks of the wave dependent component of these fluxes on the coupled climate system (Hemer et al., 2012c, Cavaleri et al., 2012). Australia is well-placed to play a strategic role in such developments but they will require appropriate observational facilities. The IMOS supported Southern Ocean Time-Series mooring (Schulz et al., 2012) provides a new platform to support research aimed at increasing the understanding of this unique and critically-important open ocean environment. Similarly, ship-based wave observations (wave radar proposed for the new National Facility) would provide data to support complementary new observations of the sea surface.

Large-scale numerical modelling of near-shore waves and circulation and their impacts on coastal water quality, sediment transport and biogeochemical systems has become commonplace. Assessment of biological impact is generally undertaken in terms of water quality characteristics. However, there is significant scope to better understand biogeochemical systems in terms of a broader physical context (e.g. Baird et al., 2006).

7. Conclusions and Recommendations

Coastal waters will continue to be crucial to the development of Australia and her regional transport systems. As a sparsely-populated continent, the per capita economic cost of data collection in coastal waters is significant yet the benefit in reducing uncertainty with regard to infrastructure construction is potentially several orders of magnitude greater. Access to suitable numerical model verification data for numerical models of waves and circulation will
remain fundamental to any technical assessment. Technologies presently under development hold the prospect of significantly reducing these costs while providing better information regarding near-shore waves and circulations.

Australia has very limited platforms for direct observation of waves and circulation. Present consideration of ocean-based renewable energy sources significantly increases the need for robust and suitable research platforms within the coastal zone.

Waves and coastal circulations are intrinsically coupled but are almost always treated as separable processes within present numerical modelling systems except in the relatively well understood very near shore region. The next 20 years will see significantly better understanding of the couplings between waves and broader near-shore circulations with implications across marine science and engineering.

References:


Littoral zone modelling: status and observational requirements in Australia

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1. Littoral Zone Modelling – who needs it?
Coastal erosion is front-page news across Australia (Figure 1). Over 80% of the Australian population live in the coastal zone and half of Australia’s shoreline comprises sandy beaches. Accelerating beach erosion, damage to existing beach-front infrastructure and loss of coastal amenity, are all identified by the Australian Greenhouse Office [Voice et al., 2006] as likely detrimental impacts of climate variability and change between now and 2100. But the timing, magnitude and extent of these potential impacts to our sandy shorelines are yet to be established.

The climate change impacts of likely greatest significance to Australia’s sandy coastlines are:
• sea-level rise, and
• changing regional-scale weather patterns.

Waves are the driving mechanism that shape sandy shorelines. At the local scale, changing regional weather trends superimposed on a rising sea-level will result in altered exposure to wave energy at the shoreline, causing the erosion and/or redistribution of unconsolidated sediments within and between coastal embayments around Australia’s coastline. Whether wave climate change will exacerbate or partially offset the sea-level rise impacts is presently a key and as yet unanswered knowledge gap.

The ability to model coastline variability and change at a range of time-scales - from operational ‘now-casting’ of nearshore and beach conditions, to forecasting of shoreline variability and evolution in coming decades - offers the potential to inform and guide coastal planning decisions at all levels of government. We provide here a brief overview of present-day littoral zone modelling capabilities in Australia, and highlight the key obstacle to further advancement, namely the critical paucity around Australia of the sustained observation data-streams that are required to underpin and continue this work. We conclude with the recommendation that, complimentary to other national observation programs recently initiated around the Australian continent, there is an immediate and pressing need for the establishment of an Australian National Coastline Observatory.

2. Overview of Littoral Zone Modelling Capabilities around Australia
Littoral zone modelling of present and future conditions around Australia’s diverse coastline, spans time-scales ranging from ‘now-casting’ of nearshore waves-currents and beach morphology, through the engineering-focused modelling of site-specific coastal erosion driven by extreme storm events, extending to multi-decadal forecasting of shoreline variability and change driven by projected future sea-level rise and regional wave climate scenarios. Provided below is a brief overview of the three different modelling frameworks.
that are currently used to model the littoral zone at these contrasting time-scales, and the data-streams that are necessary to underpin the further development and expansion of this work in the Australian context.

2.1 ‘Now-casting’ of surfzone and beach conditions
As waves propagate onshore and through the surf zone momentum is transferred to higher and lower frequency motions as illustrated in Figure 2. Turbulent motions dissipate energy and stir sediment into suspension which is then transported by mean and low frequency, infragravity motion. Some of these processes are not well understood and present considerable research challenges.

Figure 12: Schematic of the nearshore momentum budget (from Holman et al, 1990)
**Modelling Framework (Process-based)**

Now-casting surf-zone and beach conditions requires a dynamics based model that couples the following three types of models:

1. surface waves,
2. hydrodynamics
3. sediment transport

Some wave models include temporally anspatially varying wave groups which force infragravity waves, while the hydrodynamic model must include wave forcing through the radiation stress terms. The model XBeach [Roelvink et al., 2009; McCall et al., 2010] has all of these features and is being used by CSIRO in the Bluelink project to provide littoral zone forecasting capability for the Royal Australian Navy. The wave model in XBeach simulates groupiness in the incident wave field which provides forcing at infragravity frequencies. Analysis of the model output shows the model is capable of simulating mean alongshore and cross-shore flows, far infragravity waves (shear waves) and infragravity waves (edge waves and leaky waves).

**Data Requirements**

At present a lot of coastal monitoring is done on an ad hoc basis, often by local coastal councils and consisting of very infrequent beach and hydrographic surveys. However, significant changes in the coastal zone are driven by short, extreme events followed by relatively prolonged, quieter periods and slower, but still significant, morphological adjustment. A monitoring system must be able to capture the response before, during and after extreme events over periods of months to decades. CSIRO has established a Nearshore Research Facility that combines XBand radar and video to monitor morphological changes on a natural beach. Time exposure radar and video images at two hourly intervals provide a proxy for the nearshore bathymetry while phase velocity estimates can be used to derive actual water depth using the linear dispersion relationship for surface gravity waves. Bathymetric surveys are done monthly using a depth sounder and RTK GPS mounted on a jet ski, and beach surveys done using the RTK GPS mounted on a quad bike. Directional wave spectra are measured every two hours using an AWAC deployed 500m offshore. Monitoring coastal change around Australia would require a network of similar observing stations at selected sites.

**2.2 Engineering time-scales – storm erosion**

Storm erosion modelling for engineering timescales involves events having time scales of the order of 1 day to 1 week for a single storm. Multiple storms are also considered. Storm erosion modelling is commonly undertaken utilising one or more of the following techniques:

- measured data;
- statistics from other sites;
- simple geometric models;
- numerical models based (to varying degrees) on physical processes.

The (partial) process-based models used in engineering practice (eg SBEACH), while numerically based, are simplified and more empirical than full process-based models.
**Modelling Framework (Empirically-based)**

Due to the clear need for estimating storm erosion for coastal setbacks and planning, a range of models have been developed. Statistical models such as Gordon (1987) are well accepted for similar beaches on the NSW coast, but may not be readily transferred to other locations or more sheltered sites. The more portable models (geometric or numerical) consider at least some of the major drivers of storm erosion, such as wave height and elevated water level. Proper consideration of the major drivers of beach erosion led to the development of semi-process based numerical models such as SBEACH during the 1980s and 1990s, which are best utilised with time series input of waves and water levels (Figure 3).

![Figure 3: Time series of May 1997 "Mothers' Day storm" at Narrabeen NSW used for SBEACH modelling, one of the three largest storms measured on NSW wave buoys](image)

Most literature regarding numerical storm erosion models for engineering use has focussed on modelling recorded events (Figure 3), with little emphasis on how to utilise these models for “design” events and coastal planning. Due to this need, Carley and Cox (2003) developed a methodology whereby storm events more extreme than those recently measured can be developed rationally by extrapolating recorded wave and water level data. Suggestions were also made regarding storm clustering.

![Figure 4: Example of SBEACH modelling of May 1997 "Mothers' Day storm" at Narrabeen NSW, one of the three largest storms measured on NSW wave buoys](image)
Data Requirements

Correct utilisation of the more complex empirical engineering models (such as SBEACH) requires:

- Time series (1 to 6 hourly) of waves (height, period and direction);
- Time series (1 hourly) of water level (tide plus storm surge).
- The pre storm beach conditions (sand grain size and pre-storm beach profile – including the subaqueous portion).

Wave data is reasonably available for most of the Australian coast from wave buoys, and where buoys do not exist, through weather models. The transformation of offshore waves to the coast often requires additional modelling effort, as existing studies have rarely been undertaken. The resources to undertake wave transformation modelling as part of routine engineering studies are often unavailable. While wave records can be processed and extrapolated to develop extreme events, very little information is available regarding clustering of storms, which is likely to be associated with extreme erosion events.

Water level data is reasonably available for most of the Australian coast from tide gauges. Basic sand grading can be undertaken relatively simply, however, limited data is available regarding pre-storm beach conditions. With limited exceptions (such as Gold Coast, Narrabeen, Moruya and Adelaide), subaerial surveys are rarely available which cover the likely range of beach conditions, and subaqueous surveys even more rare.

2.3 Long-term prediction and forecasting of shoreline variability and change

Process-based coastal models that attempt to fully describe the physics of waves, currents, sediment transport and resulting morphological changes across a two- or three-dimensional numerical grid, presently require excessive computational effort to be of any real practical value for the purpose of longer-term shoreline prediction. In addition, the numerous complex and non-linear feedback mechanisms inherent within this type of model framework promote instabilities, which when combined with the aggregation of small-scale errors, produce unreliable predictions. In the absence of any real alternative, longer-term trends (>years) in shoreline evolution have most commonly been ‘predicted’ by some form of simple regression analysis derived from past shoreline trends. The inadequacy of this ‘extrapolate from the past’ approach is obvious, in the context of the potential for unprecedented climatic change in coming decades.

Modelling Framework (Behavioural - based)

The emerging development of an alternative and promising approach to shoreline modelling and forecasting at time-scales ranging from seasonal to multi-year is presently being developed within the context of a new ARC-funded collaboration. The computational efficiency of this approach now enables shoreline variability and evolution spanning from a succession of individual storms to potentially several decades to be forecast, it is inherently stable, and by its formulation requires no numerical diffusion or smoothing.

Called the ‘ShoreFor’ (Shoreline Forecasting) model, the modelling framework that has been adopted for this work shifts away from a process-based formulation, and instead employs a behaviour-orientated approach to predict shoreline movement. The present version of the model (Davidson et al, 2010; Davidson et al, submitted) primarily encapsulates shoreline displacement forced by wave-driven cross-shore sediment transport, with developments currently underway to extend this to include alongshore sediment movement. Hysteresis effects are very important within the ShoreFor model framework, whereby future shoreline change is influenced by past hydrodynamic conditions. The magnitude of shoreline change increases with incident wave power and the degree of disequilibrium between the present state of the beach and the prevailing and past wave conditions. This disequilibrium then
dictates the direction of net shoreline movement at each (hourly) time step. A decay rate weighting function used to compute the disequilibrium term as a function of present and past morphodynamic conditions is a model free parameter determined by calibration against measured data, which physically reflects the degree of observed ‘memory’ of the system.

The ShorFor model has been applied and tested using available datasets from Australia and the US, including two multi-year shoreline (weekly) and wave (hourly) data sets from two contrasting energetic coastal sites in SE Australia (Figure 5). The first is the relatively dissipative, straight Gold Coast (QLD) and the second is a more intermediate embayed beach at Narrabeen (NSW). The model shows significant skill at hindcasting shoreline change at both sites, correctly predicting the dominance of a strong seasonal signal at the Gold Coast site, in contrast to a much greater degree of shoreline variability at individual storm frequency at Narrabeen.

![Figure 5: Example applications of the ForShor behavioural model at Gold Coast and Narrabeen](image)

**Data Requirements**

The ShoreFor model has been specifically formulated so as to minimise the observational data necessary to apply it to a wide variety of coastal settings. Compared to the data requirements of the empirical and particularly process-based frameworks outlined above, the information necessary to calibrate and run the model is modest. Fundamentally, this approach necessitates the following data is available:

- beach width (weekly to monthly)
- inshore wave climate H,T and Dir (hourly to daily)

Despite these minimal data-stream requirements, the fundamental limitation that is presently holding back the much wider application of the ShoreFor model is – with just a handful of notable exceptions - the paucity of sustained shoreline and inshore wave monitoring programs around the Australian coastline.

**3. The Elephant in the Corner…. where’s the data??**

The significance to Australia of enhancing our national coastline monitoring and forecasting capabilities is signalled by the CSIRO Wealth from Oceans National Research Flagship (Hemer et al, 2008) and Australian Greenhouse Office (Voice et al, 2006). Both these benchmark reports stress the high priority in Australia for the rapid establishment of a network of long-term coastline observation sites, to be used as a basis for modelling and forecasting the potential coastal impacts of predicted climate variability and trends in coming decades. The Parliament of Australia House of Representatives report ‘Managing Our Coastal Zone in a Changing Climate’ (House of Representatives, 2009), based upon an 18 month inquiry comprising over 100 written submissions and 28 public hearings. Recommendation #5 of this landmark report states the need for further research in Australia to:
“establish the wave climate around the coast so as to identify those locations most at risk from wave erosion [and] examine how the wave climate nationally interacts with varying landform types”.

Meanwhile, the Australian Government is investing $117 million (2008 to 2012) in climate adaptation policies through the Department of Climate Change, coordinated through the National Climate Change Adaptation Research Facility (www.nccarf.edu.au). Yet in the littoral zone, significant and fundamental knowledge gaps persist.

The high priority internationally that is now being placed on efforts to improve baseline and broad-scale shoreline monitoring capabilities, and to improve model forecasting of coastal change, is summed up succinctly in the IPCC AR4 report:

“the level of knowledge is not consistent with the potential severity of the problem of climate change and coastal zones... there remains a strong focus on sea-level, which needs to be broadened to include all the climate drivers in the coastal zone... [A key priority is to establish] better baselines of actual coastal changes... through additional observations and expanded monitoring. This would help to better establish the causal links between climate and coastal change, which tend to remain inferred rather than observed, and to support model development.” [IPCC AR4, pp.345-346]

The above statement places front-and-centre the immediate challenge directed at coastal researchers and practitioners in Australia, to now come up with new infrastructure, enhanced tools and methods to:

(1) expand baseline monitoring of present and future coastline variability and potential change, and

(2) use this new information to develop new and better methods for modelling and assessing the present and potential future drivers of coastline variability and trends.

4. Pre-Planning for an Australian National COASTLINE Observatory

The IMOS and TERN networks are providing invaluable and unprecedented data-streams of real significance and application to the wider coastal zone – IMOS principally seaward of the 50 m depth contour, and TERN at estuaries and coastal catchments.

The missing gap between these two observation programs is the littoral zone encompassing the land-ocean boundary.

Nominally spanning water depths of 20 – 0 m and extending landward to include frontal dunes, this critical coastal region where the land meets the ocean currently falls outside any nationally-focussed monitoring effort.

In recognition of this growing need for sustained observations focussed at the coastline land-ocean boundary, in mid 2009, twenty representatives from across Australia with expertise in the coastal geosciences and coastal engineering research (Universities and CSIRO) plus key personnel from several state governments, met to workshop the key attributes for an Australian National Coastline Observatory (ANCO). The following core components were identified:

- routine and sustained shoreline and beach profile surveys (cameras/RTK-GPS/Lidar/...)
- co-located to existing regional and local wind, waves and water-level measurements
- shelf-to-shore bathymetry
- beach and nearshore sediment characteristics
- evaluation of paleo-coastline evolution
- water quality
- baseline ecology
- beach usage and hazards
A key conclusion of this group was the need for establishment of sufficient coastline monitoring sites nationally so as to adequately capture regional variability and trends. A far from comprehensive list of applications and outcomes of the ANCO were also identified:

- ability to quantify contemporary and future coastline variability and change
- make available ‘standard’ community data-streams for coastal sites encompassing regional difference around the Australian coastline
- baseline geo-coastal data-streams for testing and improving the next generation of coastal change forecasting tools
- underpin ‘now-time’ model <--- data assimilation
- coordinated network of coastline laboratories nationally, to support the next advances in fundamental and applied process-based geo-coastal field research.

At subsequent workshops hosted by the (then) NSW DECCW, IMOS and OPSAG at the Sydney Institute for Marine Science in August 2010, and again at the Coast2Coast Conference in Adelaide in September 2010, coastal practitioners from across Australia met to discuss and scope the needs for a National Coastal Observatory, reaching similar conclusions.

5. Summary and Recommendation
The ability to model coastline variability and change at a range of time-scales – spanning now-casting, extreme storm erosion and decadal-scale shoreline forecasting - offers the very real potential to inform and guide coastal planning decisions at all levels of government. Throughout this brief overview of present-day littoral zone modelling capabilities in Australia, it has been highlight that the key obstacle to further advancement is the critical paucity around Australia of the sustained observation data-streams that are required to underpin and continue this work. It is recommendation that, complimentary to other national observation programs recently initiated around the Australian continent, there is an immediate and pressing need for the establishment of an Australian National Coastline Observatory.

References:


Coastal sediment-transport modelling and observational needs

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Introduction
Sediments are integral to ecosystem health and services in coastal environments (Onishi, 1981; Kamphuis, 2000). High levels of suspended sediment impair light penetration through the water column and reduce availability of light to bottom habitats. Many pollutants found in coastal waters are sediment reactive and tend to accumulate in areas of sediment accretion. Particulate and adsorbed nutrients are associated with sediments, which play a vital role in their distribution and availability. Knowledge of sediment processes is critical to coastal development, engineering and energy and mineral resource extraction. Understanding sources, pathways and predicting the fate of coastal sediments, is a challenge because of the high complexity of sediment dynamics and limited understanding of key sediment processes (Dyer, 1989; Amoudry and Souza, 2011). Numerical models of sediment transport, increasingly used in coastal research and management, are based on semi-empirical relationships and, unless constrained with observations, are characterized by significant predictive uncertainty (Amoudry and Souza, 2011). The accuracy of such models could be improved through integration of models with observations, but progress in this direction is hampered by a number of factors, including the typically poor quality of sediment data in coastal waters and insufficient research into coastal data assimilation.

This paper outlines the key sediment processes and provides a brief overview of observational data sets required for the development of coastal sediment transport models. Application of state-of-the-art operational-research sediment transport models to coastal environments, and integration of these models with observations, is illustrated through a number of case studies. Major gaps in existing modelling strategies and observational capabilities are highlighted and directions for further research and development are discussed.

Key sediment processes and model errors
Coastal sediment transport is a complex, multidimensional and dynamic process that results from the interaction of coastal hydrodynamics, turbulence, and sediment particles. Key sediment processes commonly implemented into sediment transport models include gravitational settling of sediments suspended in a turbulent flow, resuspension and deposition of sediment particles from/onto the movable seabed, and sediment transport within benthic layers. Because of the large variability of sediment characteristics and critical gaps in understanding of fundamental processes driving and influencing coastal sediment transport (e.g. flocculation and settling of fine particles, self-weight consolidation and erosion of natural sediments, and characteristics of the turbulent boundary layer over the movable seabed), numerical models of sediment transport are typically based on semi-empirical relationships. The parameters of such models, established for one region, may not be applicable to another region. Apart from structural errors and unknown parameters, other sources of uncertainty in such models are associated with the stochastic nature of model forcing and boundary conditions (including the composition of the seabed), influences of
difficult-to predict biological factors such as bacterial films and disturbance by fauna, errors due to numerical approximations and the simplifying assumptions adopted in the model.

**Observations and integration with models**

The semi-empirical nature of sediment transport models and high uncertainty of their predictions highlight the role of, and need for, observational data sets. Observations underpinning such model development and applications can be broadly classified into two classes, one representing data sets required for the development of a pilot model (eg forcing data, boundary and initial conditions, data from process studies) and another set of data to test and improve this pilot model.

**Forcing data.** Sediment transport models require forcing data to drive sediment transport. These forcing data include currents and shear stress at the seabed, and are typically produced through hydrodynamic and wave model simulations. For a short-term simulation (when changes in coastal geomorphology are not an issue) these data can be simulated upfront with a stand-alone hydrodynamic and wave model which can then be used to drive sediment transport models in a mode decoupled from the hydrodynamic model run. This mode of simulation provides significant benefits in terms of computational costs compared to simulations with fully coupled models, albeit at the expense of excluding the feedback effects of sediments on hydrodynamics (the impacts of sediments on water density and light absorption).

**Boundary conditions.** One of the most critical, and often the least-known, input into coastal sediment transport models is the sediment load from catchments. Data from monthly monitoring programs tend to miss sediment inputs during extreme events while estimates from catchment models tend to have large errors and may not be provided on time-scales matching the requirements of the marine sediment model. SedNet, for example, is designed to provide average annual sediment loads (Wilkinson et al., 2009). Recent developments in catchment modelling are beginning to address this gap by using more advanced statistical modelling methods (LRE; Wang et al., 2011) or by explicitly representing processes relevant to daily timescales (dyn-SedNet; Wilkinson pers. comm.). These models, though promising, still have a large relative error (100 to 1300% of observed concentrations) and high degree of uncertainty.

Upscaling the model from the regional to national scales exacerbates this problem because of the lack of observational data for remote areas. One way forward might be more extensive use of high-frequency turbidity loggers, combined with sufficient total suspended solids (TSS) measurements to characterise the (usually strong) relationship between TSS and turbidity for each catchment in different flow conditions.

A secondary issue is characterisation of particle size distribution of sediments from catchments. If high flows are associated with larger sediment particles, this can affect the deposition and resuspension of this material once it reaches the sea.

**Initialisation data.** Benthic habitat maps specifying the distribution of various sediment classes (e.g. mud, sand, and gravel) and the seabed geomorphology are required to initialise sediment transport models. In some cases, the corresponding data could be acquired from regional and national data-bases. The Geoscience Australia MARine Sediment (MARS) database, for instance, contains detailed information on seabed sediment characteristics for
samples collected from Australia’s marine jurisdiction, including the Australian Antarctic Territory. Data are provided from quantitative analyses of the sediments, incorporating standardised measures such as mean grain size, mud, sand, gravel and carbonate content, plus information on mineralogy, geochemical properties and age determinations. New data are being added as they become available [http://www.ga.gov.au/oracle/mars/]. In addition, interpolated products depicting seabed sediment types are now available for the entire continental EEZ (Li et al. 2010, 2011; Li, 2011a,b,c).

The dbseabed data base is another example of seabed sediment data including critical shear stress values from mapping programs around the world [http://instaar.colorado.edu/~jenkinsc/dbseabed/]. For the Australian continental shelf, the GEOMACS (Hemer, 2006) model of bed shear stress has been used to model seabed exposure to physical disturbance by waves and currents, that in turn can serve as a proxy of potential shelf sediment transport (Hughes et al., 2010).

Assimilation data. Once a pilot sediment transport model is established, it needs to be further refined and constrained through the assimilation of relevant observations. The assimilation data could be represented by the suspended sediment concentration from monthly monitoring programs, turbidity records from moorings, sediment concentrations inferred from remote sensing, etc. Because of the spatial/temporal variation of the suspended and saltated sediment fields, particularly in macrotidal environments, spatial and temporal sampling needs to be related to the required model resolution.

Data-model fusion. Advances in observational programs, and in particular remote sensing, have stimulated the development and application of data assimilation schemes to suspended sediment transport models. The corresponding literature is sparse but the number of publications is growing (Yang and Hamrick, 2003; Pleskachevsky et al., 2005; Stroud et al., 2009; El Serafy et al., 2011; Margvelashvili and Campbell, 2012). The range of assimilation techniques varies from an ad hoc and heuristic tuning of model state variables to observations (e.g. Stroud et al., 2009), to the application of more comprehensive and sophisticated data assimilation schemes such as EnKF (El Serafy et al., 2011) and variational inverse schemes (Yang and Hamrick, 2003).

Case studies

Mecosed model
Mecosed is a 3D coastal sediment transport model coupled to CSIRO Environmental Modelling Suite (EMS) which integrates hydrodynamics, sediment transport and biogeochemical modules (Brinkman et al., this issue). The sediment transport model adds a multilayer sediment bed to the EMS hydrodynamic model grid and simulates sinking, deposition and resuspension of multiply size-classes of suspended sediment (Margvelashvili et al., 2009). Mecosed solves advection-diffusion equations for benthic and suspended sediments and is particularly suitable for representing fine sediment dynamics, including transport of biogeochemical materials. The numerical grid for sediment variables in the water column coincides with the numerical grid for the hydrodynamic model. Within the bottom sediments, the model utilises a stretched sediment-thickness-adapted grid. Horizontal resolution within sediments follows the resolution of the water column grid.

Mecosed has been developed and refined through a number of case studies around Australian coast (Robson et al., 2006; Margvelashvili et al., 2008, Condie et al., 2009). Recent applications of the code involved processing and assimilation of large volumes of
observations into the model. In the Fitzroy Estuary and Keppel Bay the model assimilated surface suspended sediment concentrations inferred from MODIS AQUA satellite observations (Margvelashvili et al., 2012). These satellite products were based on remote sensing algorithms developed specifically for the Fitzroy region (Brando et al., 2012). The main objective of simulations was to test the data assimilation scheme, based on error-subspace emulators (Margvelashvili and Campbell, 2012), using synthetic observations and identify potential issues and challenges when assimilating real data sets into the model. The assimilation algorithm proved capable of substantially reducing prior uncertainty of the model for both the scenario with synthetic observations and the scenario with satellite data. Significant remaining error in western Keppel Bay after assimilating satellite data (fig 1) is diagnostic of an underlying error in the system conceptualisation – in other words, it indicates that the primary source of error is not in the parameter values specified, but in the model structure, in the interpretation of satellite data or in the other input data.

In Moreton Bay (South East Queensland), the model was tested against Total Suspended Sediment (TSS) data as inferred from monthly turbidity measurements (Herzfeld et al., 2012). A challenge was to assimilate large volumes of sparse and noisy observations into the computationally expensive model (fig. 2). A number of strategies, including manual and automatic calibration of the model, have been tested to achieve this goal. The calibrated model was capable of reproducing broad-scale patterns of the suspended sediment distribution in the region. Best agreement between model and observations has been achieved for scenarios with spatially varying parameters.

Figure 1 A snapshot of the remote sensing surface TSS in Keppel Bay (left plot) and RMS error of the modelled suspended sediment concentration (right plot). The model error is normalised by the observation error and integrated over the 4 months simulation period.

Figure 2 Monthly monitoring sites in Moreton Bay (left plot, http://www.health-e-waterways.org/reportcard), and time series of simulated (blue) and observed (red) suspended sediment concentrations in the Brisbane estuary and Central Moreton Bay (right plots). Observations and the model are integrated over sub-regions and over the monthly filed campaign period. Error bars (lines) show the range of the observed (simulated) concentrations.
**Sedsim model**

Sedsim is a process-based stratigraphic forward model. It has been tested for the simulation of sediment transport over long time periods controlled by many of the major depositional processes, including fluvial systems, sea-level change, coastal waves and storms, carbonate growth, slope failure, density flows, and deep ocean geostrophic currents. The Navier–Stokes equations and the continuity equation are simplified and solved by using a marker-in-cell approach in two horizontal dimensions (Tetzlaff and Harbaugh, 1989). This technique combines the advantages of Eulerian and Lagrangian representations of fluid flow. Sedsim also simulates carbonate sediment production and re-distribution from reef, benthic and pelagic organisms. The simulations include biogenic carbonate that is believed to play a significant role in sediment generation and mobility, especially in the lower latitudes. Living corals influence both the availability of seabed sediment and also frictional resistance to currents, which in turn impacts on the current's capacity for transport and erosion. A fuzzy logic system is used to integrate these complex interactions into the process model (Nordlund, 1996) and a series of fuzzy rules are designed to predict the overall effects of the complex processes on the accumulation, erosion and re-distribution of carbonate sediment of biogenic origin on the seabed.

Sedsim has been applied to several real case studies including the entire Australian Margin at 2000 m resolution (Li et al. 2006a, 2006b, 2007, 2009), Salles et al (2011)). Beach replenishment at 5 m resolution has been modelled in South Australia (Young et al 2002) and Netherlands (Li et al 2004) and the past and future development of the Southern Baltic Sea Coast has been modelled using Sedsim (Meyer et al, 2011).

![Figure 3 Simulated seabed sediment grain size change in 50 years on the NW part of Australian Shelf for a high-energy climate change scenario. The trend of seabed sediment composition change in the next 50 years is a) sediment coarsening in the near-shore coastal area which reflects the strong wave and tide activity; b) fining process in the offshore waters where a very thin layer of fine grains deposits on the erosional surface; c) coarsening areas at the shoulder of the continental shelf and canyons by turbidity currents and slope failure. (It must be pointed out that the grain size comparison is made for the clastic grains only. Reef and non-reef carbonate production is excluded from this plot). (figure from Salles et al, 2011).](image)
Figure 4 Modelling results after 840 years. Distance from shore classification: (I) unchanged inland, (II) modified inland, (III) shoreline, (IV) marine but near shore, (V) open marine, (VI) unchanged open marine. a) Experiment A, active modules: WAVE (HEIGHT) and STORMS. b) Experiment B, active modules: WAVE (HEIGHT), STORMS, and SEA LEVEL. c) Experiment C, active modules: WAVE (HEIGHT), STORMS, SEA LEVEL, and TECTONICS. d) Experiment D, active modules: WAVE (HEIGHT), STORMS, SEA LEVEL, TECTONICS. In addition, the sea level height was set to the height of the storm flood in 1872 (Figure from Meyer et al, 2011)

Discussion
Why do we need sediment models?
Climate change, industrial developments, population growth and globalization increase the complexities and challenges for coastal management in the 21st century. Under such circumstances, demands for coastal decision support systems, and the value of numerical models and data streams underpinning, such systems are only likely to increase with time. Major uses of coastal sediment transport models and the underlying observations over next decade will, we believe, be concentrated (at least) on the following tasks

a) Tsunami mitigation: soft engineering design using scenario models of mangrove/seagrass/dune buffers (10 km resolution - 50 year simulations);
b) Sea level rise/storm wave spectral change/cyclone intensity change scenario modelling (100 m to 2000 m resolution - 50 years);
c) Coral platform/island survivability modelling for socio-economic migration predictions (1000 m resolution - 50 years);
d) Coastal infrastructure planning and maintenance (e.g. dredging) (5 m to 100 m resolution, 1 to 10 years);
e) Insurance/re-insurance risk modelling for coastal planning and engineering infrastructure design (1 to 1000 m resolution, 5 to 50 years);
f) Downstream catchment-to-coast impacts of altered land use practices, industrial developments and population growth. Coastal water quality. (100 to 1000m resolution, 1 to 50 years);
g) Accidental spills and contaminant cycling and transport (10 to 1000 m resolution, 1 hour to 50 years);
h) Near Real Time (NRT) monitoring and modelling of coastal environments and forecasting of extreme events (10 to 1000 m resolution, 1 hour to 10 days);

Each of these areas of application will have different data requirements and assimilation frequencies (some having both 'baseline' and post 'event' monitoring requirements). Observational systems need to be robust enough to capture extreme (about three orders of magnitude above baseline) characteristics (wave, wind, current, flux, grain-size etc.) at short time intervals as many existing systems are either missing most of the peak data that actually control sediment/seabed morphology or saturate prematurely. On the other hand, such systems must be sustained in time to provide an adequate, statistically representative description of long-term changes of coastal environments. Relevant time scales vary from hours and days to decades and beyond. Spatial scales could vary from meters to thousands of kilometers. Capturing all these scales of variability within a single observing system is a challenge yet to be overcome.

Towards a coastal observation infrastructure for Australia
Observations are important by themselves but also as an input into numerical models. Reducing the scope of the observing system to that of supporting coastal modelling studies does not significantly alleviate the challenge of the undertaking due to the large variety of coastal applications and corresponding models. There is no such thing as an all-purpose sediment transport model. Depending on problem to be addressed or hypothesis to be tested, the model structure (which processes are modeled) and physics simplifications (e.g. of turbulence) will vary from one application to another. Spatial and temporal scales of the problem will determine what input data sampling is appropriate, what assimilation frequency is appropriate, what processes are numerically modelled etc. Devising an all-purpose observing system to support all such models could be an unachievable task.

Despite these considerations concerning a general-purpose observing system, it is possible to design an infrastructure that would provide observational support to a sub-set of models representing very specific and yet sufficiently general and important class of sediment transport models. Such infrastructure would allow for rapid deployment of these models and quick evaluation of various “what if?” scenarios. Having such infrastructure in place may drastically improve the quality of the decision support and coastal management around the Australian coast.

The main function of such infrastructure would be to host and deliver (presumably through the web) a complete set of data required for set-up, simulation and evaluation of coastal models. In what follows we outline the key observational needs for two general classes of such models one representing receiving water quality suspended sediment transport models (Mecosed as an example), and another class comprising process-based stratigraphic forward models (Sedsim as an example). The former class of models is most suitable for relatively short-term (days and years) simulations including operational now-casting and forecasting tasks. The second class of models is most appropriate for simulating long-term (decades and centuries) changes in coastal geomorphology and sedimentary structure. We also outline key directions of further research that would facilitate the development and application of these models.

Future model developments and observational needs:
 a. Initialisation data. Further development and extension/consolidation of benthic habitat maps around the Australian coast (e.g. mars, dbseabed/auseabed). Mecosed

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model, for instance, requires data on mud, sand, gravel distributions in benthic sediments and seagrass and hard substrate coverage of the seabed (e.g. rocks, bedrock outcrops, reef platforms). To identify cyclic and event-driven changes to habitat pattern, repeat (could be random time interval) high resolution baseline studies with accurate positioning (± 0.5 m) are required. At present we have no idea what part of a cycle has been sampled and expect at least Nino \ Nina benthic oscillation around most of the Australian coast.

b. Forcing data. Readily available coastal hydrodynamic/wave forcing data on the national scale to drive sediment/ biogeochemistry/ecosystem models (e.g. the e-Reefs project and its upscaling to national level).

c. Input from catchments. Daily catchment loads for major rivers around Australian coast based on NRT models and observations [LRE and other GAMs, dyn-SedNet, turbidity monitoring]. Anthropogenic effects dominate around much of the Australian coast due to damming of river systems and entrapment of sediment. This means that catchment models are often not sufficient and estuarine sediment flux also needs to be monitored. In NE Australia the Torres Strait receives significant periodic silt flux from the Fly River in PNG where the sediment load is predominantly from mining activity and sediment flux is not directly a function of PNG catchment flux.

d. Assimilation data. Suspended and benthic sediment data to assimilate into models at adequate assimilation frequency and resolution (e.g. remote sensing, gliders, moorings, monthly monitoring, sensor networks, etc).

e. Near-real-time monitoring and modelling capabilities. Strategic goal here could be a “Digital Earth” running in parallel with the real one, and with an online exchange of data streams between the digital and the real worlds.

f. Research into DAS and uncertainty of coastal models. The capacity to uptake and to use efficiently high quality data sets is often hampered by the deficiency of the corresponding data assimilation schemes and the lack of science behind the coastal data assimilation. Manual “trial-and-error” calibration of models against large volumes of data is inefficient and unproductive.

g. Research into emulators (statistical surrogates) of complex models to speed up simulations and fill-up the gap between complex models and managers.

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The CAWCR\textsuperscript{1}-WfO\textsuperscript{2} ocean modelling review – from climate to coasts

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Introduction
The Australian Bureau of Meteorology is pursuing development of operational ocean modelling as part of its service delivery. On a global and regional scale, operational forecasts are currently delivered by the OceanMAPS system, but there is increasing demand from the maritime and coastal communities for coastal forecasts. This demand, together with international ocean-model developments, has led CAWCR and CSIRO to conduct a review of its modelling options.

Background
Operational models are those that are run regularly and automatically, have backup systems, are supported continuously (24/7), and would be expected to have downtimes of at most minutes. The archetypal operational systems are weather-forecasting models run by meteorological agencies around the world.

In Australia, operational oceanography and earth-system forecasting (with coupled atmosphere and ocean models) are in their infancy. Most of this modelling falls within Centre for Australian Weather and Climate Research’s (CAWCR) mandate, with the Bureau of Meteorology the ultimate implementing agency. The operational ocean systems at the Bureau are OceanMAPS, for forecast out to days, and POAMA, for seasonal forecasts. Climate and earth-system models are set up to run routinely, but not operationally.

A primary motivation for ocean modelling is to account for the ocean’s role in the global heat (and carbon) balance at seasonal to climate time scales and to develop predictive capability for these areas. The Australian community also has a practical and aesthetic interest in ocean dynamics for their coastal impacts, for example, on beach structure, ecological health and maritime safety. “Coastal” here is used in the global-ocean sense, signifying waters from the upper continental slope to the coast (say, less than 200 m deep). In reality, the most intense human activity and ocean productivity occur in inshore waters less than about 30 m depth. At seasonal time-scales and longer, the global ocean models are coupled with the atmosphere to provide climate simulations. These models are too coarse (~ 1 degree), and too inaccurate, to indicate the coastal consequences of climate variability or change. Because most of Australia’s coastline is exposed to the open ocean, prediction of coastal events requires knowledge of the large-scale circulation in the surrounding Pacific, Indian and Southern Oceans – often as communicated across the shelf through the Leeuwin and East Australian boundary currents. Shorter time-scale global predictions, out to days, are done at higher resolution (~ 0.1 degree), but even these model implementations are too coarse and approximate to simulate all important aspects of coastal dynamics.

At present, all the ocean climate and operational modelling in CAWCR and CSIRO uses the NOAA/Princeton University MOM model. However, MOM is written as a global model, and contains approximations that make it unsuitable for coastal applications. In Australia, while they may use MOM for boundary conditions, coastal modellers run different, specialist codes.
For the Bureau, particularly, with model implementations running operationally and repeatedly, there is a reluctance to maintain infrastructure for more than one model code. The Bureau has recently converted their weather-forecasting software to the UK Met Office model (called the "Unified Model", or UM) which covers all spatial scales, from cities to the globe. It is the basis for the Bureau's coupled seasonal and climate simulations. They would prefer to have a similar code for ocean modelling. In the relatively small CAWCR (and Australian) ocean-modelling community, a single code would also enhance collaboration and mobility across coastal and global groups.

**Global vs coastal models**

All state-of-the-art primitive-equation models of the ocean are the same, in the sense that they solve, numerically, some form of the Navier-Stokes momentum equations, transport equations for heat and salt, an equation of state, and an equation for the ocean surface. The models all contain significant approximations, most notably of sub-grid-scale processes that are not resolved by the model. The sub-grid scales include turbulence and molecular diffusion (the latter at the scale of centimetres), critical processes by which energy is removed from the ocean.

Global and coastal models tend to differ primarily in their representation of turbulence. In global models, the deep, relatively quiescent waters require great care to ensure that there is no artificial mixing across density (or, more strictly, neutral) surfaces. Such artificial mixing would, over long model runs, remove the temperature and salinity structure of the ocean. By contrast, coastal waters are more energetic over the full water depth, and coastal models tend to incorporate more sophisticated, and thus more computationally expensive, algorithms to describe vertical turbulence. These turbulence models are particularly relevant to high-shear environments that occur near the sea surface and, in shallow (< 200 m) water, near the sea bed.

There will be other differences between global and coastal models. For example, a coastal model will not necessarily include the effect of pressure on density, but may incorporate wetting and drying, that is, the ability of the water to run up and down a shoreline slope. Further, coastal models, by definition, have open boundaries that define the limit of the modelled area. The models must therefore include open-boundary conditions, that either make assumptions about ocean conditions beyond the modelled area, or allow the model to be nested inside, a large-scale (often global) model. Global models mostly ignore tides, which are difficult to represent accurately at low resolution. However, tides are essential in coastal models.

At present, global and coastal ocean models tend to be run separately, either with one-way, or coupled nesting. With more powerful computers, and smart grids (including, in the future, unstructured grids), it is likely that single model runs will produce not only global conditions, but also high (< 1 km) resolution of dynamics into the shore, for immediate uptake by the coastal community, including managers and maritime industry.

**Ongoing model development**

Many ocean applications require biogeochemistry and other dynamics in addition to the hydrodynamics. These may be investigations of natural productivity, or assessments of the impacts of human activity such as agriculture or aquaculture on nearshore water quality. The models may increasingly move from a nitrogen to a carbon focus in the context of climate change. Further, while it is most often ignored, there may be feedback from the biological to the physical system. For example, suspended material such as phytoplankton affects light
penetration into the ocean, which in turn affects the heat distribution. In a coastal model, full treatment of the physics and biogeochemistry also requires a sediment dynamics model.

We may also expect that physical models will increasingly incorporate surface waves, to better represent surface fluxes and surface dynamics. It has been known for decades that waves drive circulation in the littoral zone and over reefs. Now, there is increasing recognition that waves are likely to be important even at climate scales, affecting the way energy is transferred and transmitted from the atmosphere into the ocean. However, the techniques for coupling waves and currents in three-dimensions have been investigated only in the last decade, and are still under active discussion. Few models have incorporated three-dimensional coupling to date, and there are differing approaches and lingering doubts about accuracy.

Another development is variously described as unstructured-grid, or finite-volume modelling. At present, most models are run on orthogonal (but not necessarily rectangular) horizontal grids, with four nodes for each grid point. Unstructured grids allow for relatively arbitrarily-shaped grid cells, and permit much more flexibility in establishing the grid, so that the resolution can be varied across the domain. Most present-day models vary resolution either by using smart mapping techniques or with multiple nesting. The finite-volume approach is appealing, but the techniques are still under development, and computationally expensive. Some ocean models are now also incorporating non-hydrostatic dynamics which are important for particular processes, such as surface and internal waves, and convective overturning. Their inclusion increases the versatility of the models, and reduces the parameterisations required.

Data assimilation
A critical feature of most operational models is data assimilation, whereby observational data are used to correct the model before it moves into its predictive cycle. Data assimilation is also the foundation of reanalyses (i.e. ingesting quality-controlled past observations into the ocean model to achieve a model state which is consistent with observations). For ocean modelling, the important data sets are satellite sea-surface height and temperature, and Argo float profiles. However, these data are usually of limited use in coastal modelling. At present, the only reliable coastal data come from tide gauges operated by a variety of agencies, including the Bureau. However, as data streams from IMOS become established, and effectively available in real-time, they should significantly improve coastal ocean forecasting. We are paying particular attention to HF radar data.

Modelling options
Are there models that are able to fulfil the Bureau and CSIRO requirement of accurate simulation from global to coastal scales, and across time scales from hours to centuries? We have done an initial investigation of most open-source ocean models, to assess their versatility across spatial scales. The investigation indicates two primary options: to retain MOM, and modify it for coastal applicability, or to adopt the European community model NEMO, for which this modification is already well advanced. The choice between models will depend on many factors, including the cost of adapting or replacing model infrastructure, the levels of support, the receptiveness of the development community, the availability of ancillary models and plans for future development. If MOM were retained, then CAWCR would have to take responsibility adding and maintaining its coastal functionality, since this is not a NOAA/Princeton priority. However, there is a high level of familiarity with MOM in the Australian oceanographic community. NEMO is the model used by the UK Met Office, the
original developers of the UM atmospheric model, in which CAWCR is now a co-development agency.

There is some urgency to establish a cross-scale operational forecasting capability, with immediate demand from Defence, the oil and gas industry and coastal (particularly Great Barrier Reef) managers. CAWCR and CSIRO have established an internal working group to examine the ocean-modelling options and recommend a development path to senior management. The working group will start by testing the assumption that a single model should be preferred over the maintenance of different coastal and global codes. With selection of either MOM or NEMO, or possibly another alternative, there will be a significant development path ahead, as the team learns, adapts and develops new code and infrastructure.
Modelling Activities in New Zealand: Development of an Adaptive Model Framework

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N.I.W.A., New Zealand, October 2012

The New Zealand coastal marine environment presents a series of challenges – outwith the scientific issues of quantifying and understanding the hydrodynamic response to multi-scale forcings – not the least of which is the scale and variety of coastal environments that need to be monitored and observed, especially given the relatively small population. This limits the observing capability, and places some onus on the modelling community to interpolate into the observational gaps in space, and then of course in time for predictive capability.

One of the bug-bears of course with ocean to coastal to embayment modelling is the change in the ratio of the number of (horizontal) sea points to the number of land points within the domain of interest; in the (open) ocean setting this ratio is large, but as land topography impinges this ratio rapidly reduces, and so to maintain the overall numerical efficiency the coastal to embayment modeller is forced to look at ways to circumvent the topographic land effect. For example, in a classical structured ocean model, grid points will typically have to be allocated for both the land and sea points, and so an overhead is required. The ways to address this in terms of the model grid and structure are manifold (with four examples shown in Figures 1 to 4); and then the ways that the discrete system can be represented and solved on each of these grids can vary dependent on (physical) circumstances; hence the (relative) proliferation of coastal models.

Each Figure represents an example of a configuration from each of the ocean to coastal models in use at NIWA, with each Figure coming from:

**Figure 1:** ROMS (Regional Oceanic Modelling System, Shchepetkin and McWilliams (2005), and NZ application Hadfield et al (2007));

**Figure 2:** RiCOM (River and Coastal Ocean Model, Walters (2005) and Walters et al (2010));

**Figure 3:** Delft3D (see [http://www.deltaresystems.com/hydro/product/621497/delft3d-suite](http://www.deltaresystems.com/hydro/product/621497/delft3d-suite));

**Figure 4:** Gerris (see [http://gfs.sourceforge.net/wiki/index.php/Main_Page](http://gfs.sourceforge.net/wiki/index.php/Main_Page) and references therein).

In Figure 1 for ROMS, the grid is structured, and the contraction of grid spatial scales is obtained by nesting; this works well at kilometre or so type scales, but becomes less efficient as the topography impinges. RiCOM in Figure 2 uses an unstructured, finite element grid; this now resolves the issue of land, and such models are certainly gaining popularity in the coastal modelling community. Delft3D in Figure 3 uses a curvilinear grid system, but allows for grid generation “grown along” splines and then reconstructed to produce the final curvilinear orthogonal system; in this way complex topography can be mapped. Finally, in Figure 4 is an example grid from the adaptive model Gerris; here the grid is “semi-structured” in the sense that points can be distributed to meet adaptive criteria, e.g. topography, eddy generation, wave steepening, bathymetry etc, but that the underlying structure is well-ordered in the form of an oc-tree (in three dimensions) or quad-tree (in two dimensions), with every cell connected and located to the root cell of the model via the relevant tree.
The models in Figures 1 to 3 have their grids set at the outset; wetting and drying is possible in each of the models, but only over those originally extant cells. In contrast the adaptive system of Gerris in Figure 4 maps the total domain (of course) for the initial condition, but is able to re-configure the grid internally using consistent, conservative methods in response to metrics representing physical criteria of relevance. Thus the adaptivity is both a useful spatial property, in that complex initial conditions can be factored through the adaptive metrics, but further is an even more powerful temporal property, in that the metrics allow response to scales of forcing and instability and mode representation that might not have been apparent or anticipated at the outset. Gerris was originally conceived and written as a CFD (computational fluid dynamics) flow solver; however, over the last 6 years or so, the applicability of Gerris to the GFD (geophysical fluid dynamic) regime has grown.

The fact that the NIWA coastal modelling examples are still four in number represents the level of complexity inherent in such modelling; the maturation of the single “best” variant remains just over the horizon. That complexity is manifest of course not only in the need for a sophisticated horizontal grid structure, but further in being able to deal with all the competing forcings (stratification, tide, topography, turbulence, wetting and drying, wind), the potential implications of hydrostatic versus non-hydrostatic processes in this environment, and the impact of a non-linear free surface. The models must also be able to accurately transport in-situ material (biota, freshwater, sediment etc) in the turbulent flows. Thus the fully three dimensional coastal model is a significant computational challenge. While progress has been made with the adaptive model Gerris -- in particular the recent advent of a layered variant that looks like a classical ocean model in the vertical but retains horizontal adaptivity, as well as its extension to global scale -- more effort and a wider user base is required to exploit and test it in the GFD regime. The latter continues at NIWA, exploiting data sets and experiments on-going and planned in the coastal environment, so that every opportunity is made to inter-compare and validate not only Gerris, but the other coastal models as well.

The requirements for accurate and efficient coastal models are evident from the demands from the commercial and research sectors in New Zealand. And of course increasing pressures for exploitation of the coastal zones for energy and food mean that advice and prediction of impacts from our coastal models are likely to grow substantially. The challenge then for the New Zealand research base is to satisfy that demand, as well as remain at the forefront of development of future potential tools – such as Gerris and its adaptive grid -- to improve and sustain our capability.

References


Figure 1: ROMS (Regional Oceanic Modelling System, Shchepetkin and McWilliams (2005), and NZ application Hadfield et al (2007));

Figure 2: RiCOM (unstructured, finite element grid)

Figure 3: Delft3D (structured, flexible curvilinear grid)

Figure 4: Gerris (semi-structured, adaptive grid)
The Marine Virtual Laboratory (MARVL) and Information System (MARVLIS)

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Introduction

Community modelling systems really started with the advent of the internet and so have been around for 20 years or so, and arguably the first of these was the Princeton Ocean Model (Blumberg & Mellor, 1987). Over the years since then numerous modelling codes have developed user communities (e.g. the Modular Ocean Model (MOM, Pacanowski et al., 1991), Coherens (Luyten et al., 1999), Regional Ocean Modelling System (ROMS, Haidvogel et al, 2000), Wave model WAM (Hasselmann et al., 1988)) to the benefit of the international science community. As time has progressed these modelling systems have developed into frameworks into which can be slotted modules to represent an array of processes from physics to biogeochemistry and data assimilation — ROMS is a good example of this, as is NEMO (Nucleus for European Modelling of the Ocean, http://www.nemo-ocean.eu/). These modelling frameworks/systems provide a library of coded modules enabling the researcher to set up the problem of their interest. This set up task is made easier by the availability of documentation and on-line forums that the researcher can consult.

In all modelling studies of realistic scenarios a researcher has to go through a number of steps to set up a model in order to produce a model simulation of value. The steps are generally the same, independent of the modelling system chosen. These steps include determining the time and space scales and processes of the required simulation; obtaining data for the initial set up and for input during the simulation time; obtaining observation data for validation or use in data assimilation; implementing scripts to run the simulation(s); and running utilities or custom-built software to extract results. These steps are time consuming and resource hungry and have to be done every time irrespective of the simulation — the more complex the processes, the more effort is required to set up the simulation.

The Relocatable Ocean Atmosphere Model (ROAM) developed as a component of BLUElink> (http://www.csiro.au/Outcomes/Oceans/Understanding/BLUElink.aspx), a partnership between CSIRO the Bureau of Meteorology (BoM) and the Royal Australian Navy (RAN), is a step in the direction of automating some of these procedures. ROAM is a tactical tool developed for the RAN to improve prediction of sonar range in the ocean and radar in the atmosphere. ROAM is designed to deliver forecasts out to 3 days for relocatable regional domains within the Australasian region, down to scales of ~2 km, using products from the BoM’s operational forecast models of ocean and atmosphere as boundary and initial conditions.
The Marine Virtual Laboratory (MARVL), being developed through the Virtual Laboratory program of NeCTAR\(^3\) is a new development in modelling frameworks for researchers in Australia. Using components of the ROAM framework MARVL incorporates many of the modelling preparation steps automatically in order to bring the researcher faster to the stage of simulation and analysis. The MARVL Information System (MARVLIS) is a set of tools designed to sit on top of MARVL, enabling a researcher to derive data products from the underlying model and observation data. In the current application these tools are directed towards enhancing environmental assessments.

Nationally, Australia lacks a research environment within which to explore the science questions around seamless integration of ocean-based sensing, marine information infrastructure, numerical modelling of marine and climate systems, and visualization of outputs. Integration of these components remains a key challenge, a need explicitly noted in the ‘2011 Strategic Roadmap for Australian Research Infrastructure’ (http://www.innovation.gov.au). The creation of a MARVL, through the NeCTAR Virtual Laboratory program (www.nectar.org) begins the process to address this.

**The Marine Virtual Laboratory**

The foundation of MARVL is the ROAM modelling system, which permits ocean circulation and wave simulations. Integration of these components takes place in a controlled environment (schematic, figure 1) driven through a graphical user interface (figure 2).

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\(^3\) National eResearch Collaboration Tools and Resources, www.nectar.org.au
ROAM is a ‘hard-wired’ system in so much as it offers the user a single hydrodynamic model (SHOC, Herzfeld, 2006), a single wave model (SWAN, Booij et al, 1999) and pre-defined datasets for initialisation and forcing. The system runs on the user’s desktop and is extremely robust and easy to use.

![Figure 2 – example ROAM user interface](image)

In MARVL we are adapting components of ROAM, and developing an open source application, providing more model choices (SHOC, ROMS, MOM, WW3\(^4\), SWAN\(^5\), providing the addition of integrating observations, and developing a web-based environment (schematic in Figure 3) that will allow researchers to:

1. efficiently configure a range of different community ocean and wave models for any region, for any historical time period, with model specifications of their choice, through a user-friendly web application,
2. access data sets to force a model and nest a model,
3. discover and assemble ocean observations from the Integrated Marine Observing System (IMOS, www.imos.org.au) and the Australian Ocean Data Network (AODN, http://portal.aodn.org.au/webportal/) in a format that is suitable for model evaluation or data assimilation, and
4. Run the assembled configuration in the NeCTAR cloud or on an HPC system, or download the configuration to run on any other system of the user’s choice.

\(^5\) Simulating Waves Nearshore, http://www.swan.tudelft.nl/
In its initial application MARVL will be applied to the estuarine / coastal region of the Derwent Estuary of Tasmania, which has an established observing system, modelling system, and management regime.

The MARVL Information System

We will use the MARVL infrastructure to explore scenarios, and demonstrate how a virtual laboratory can enable underpinning science to support marine management in a specific regional context. MARVLIS, supported by the Applications program of the Australian National Data Service (ANDS, http://andsapps.blogspot.com.au/), is a library of application tools to derive value-added products from underlying observations and model data. In the case of the Derwent Estuary this is to support the local marine management. The library will interface directly with MARVL thus allowing the framework to be extended to better support marine management wherever MARVL is deployed. The Derwent has specific issues associated with a strong aquaculture industry and environmental water quality. In these first applications, value-added products will be developed from the MARVL application in the Derwent Estuary to support

- a) Real-time prediction of beach water quality, and
- b) The assessment of Ecosystem health for improved environmental reporting and, potentially, aquaculture management.

So, aside from MARVLIS assisting MARVL by delivering a transportable library of ‘functions’, MARVLIS will be directly benefiting local business, organisations and communities, who use and have a vested interest in the Derwent Estuary. Local shellfish and fish farmers will have access to current water quality and project future trends, allowing them to be more productive and prepared for changes in the local eco-system. Local government and councils will also have access to additional information, allowing them to be more pro-active and informed, allowing them to better manage the Derwent estuary. The new data products provided by MARVLIS will also help in the management of risks in regard to public health, utilising CONNIE-2 (http://www.csiro.au/connie2/) for this purpose.
Once the Derwent Estuary demonstration of MARVL is complete, its scope will be extended to the rest of the Australian ocean-shelf domain. Six applications around Australia will show the versatility of MARVL to address a range of issues over different time and space scales. Each of these applications will be run alongside existing projects, using existing, manually-developed model systems to evaluate the efficacy of MARVL, and to facilitate a cost-benefit analysis of MARVL in each case.

References


Establishing the Climate and Weather Science Laboratory

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A collaborative partnership has been established between the Centre for Australian Climate and Weather Research (CAWCR), a partnership between the CSIRO and Bureau of Meteorology, Australian National University (ANU), and CoE for Climate System Science to develop and deploy a new NeCTAR Virtual Laboratory and web portal called “the Climate and Weather Science Laboratory” at the National Computational Infrastructure (NCI) facility located at ANU. The laboratory will leverage and integrate existing infrastructure to support an intrinsically complex Earth-System Simulator that allows scientists to simulate and analyse climate and weather phenomena.

Objective
The virtual laboratory’s objective is to provide an integrated facility for model development, the provision and assessment of climate and weather simulations, and establish a readily available archive of climate and weather data. The laboratory will utilize recent Australian Super Science initiative investments in computational and storage infrastructure to improve the Australian capability in climate change science and earth system science research.

The virtual laboratory’s goal is to enrich the scientist’s access to resources, reduce the technical barriers to using state of the art tools, facilitate the sharing of experiments and results, reduce the time to conduct scientific research studies, and to elevate the collaboration and contributions by the Australian research community to the development of the Australian Community Climate Earth-System Simulator (ACCESS) and climate system science.

Through the proposed integration and enhancements of existing community software such as ACCESS, the laboratory will produce an integrated facility for climate and weather process studies in areas such as weather prediction and extreme events, atmosphere-ocean-land-ice interactions, climate variability and change, greenhouse gases, water cycles, and carbon cycles. Additionally, the laboratory will provide a facility for the analysis of climate simulations, which will assist in the assessments of Australian climate change and contribute to the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC).

Architecture of the virtual laboratory
The virtual laboratory is composed of four work packages (WP) to build the web portal and integrated services for simulation modelling, model analysis, and data management. We envision the need for additional laboratory services to support future community science
capabilities such as data assimilation, particle transport analysis, air quality analysis, etc. See Figure 1, diagram of the virtual laboratory architecture for services and frameworks and future research capabilities (purple boxes).

**Work package 1 (green): Climate and weather modelling and simulation service** is to prepare and run of coupled and uncoupled model experiments within a framework designed for reproducibility, ease of use, support, and sharing of code, data, and experiments. The ACCESS atmospheric model and simulation service is derived from the UK Met Office Unified Model infrastructure and extends the infrastructure to support the ACCESS coupled modelling systems.

**Work package 2 (orange): Model analysis service** is to provide a facility for scientific workflows in climate and weather model analysis and scientific graphics within a framework designed for reproducibility, ease of use, support, and sharing of code and data.

**Work package 3 (blue): Facility interfaces and data library service** is to provide Facility interfaces and services for data management, discovery, storage, and access to climate and weather repositories through community protocols and services at national/international facilities.

**Work package 4 (cyan): Web services and laboratory integration** is to provide access to the range of laboratory services including software, data, and content produced through projects, experiments, workflows, and analyses by scientist.

![Figure 13: Diagram of the virtual laboratory’s services and infrastructure building blocks](image-url)
ACCESS modelling and simulation

The Australian Community Climate and Earth System Simulator (ACCESS) is an earth system modelling architecture of integrated software frameworks to support scientific research in weather and climate modelling, and is developed as a joint initiative of the Bureau of Meteorology and CSIRO in cooperation with the DCCEE and university community in Australia. ACCESS is intended to be the national climate and earth system modelling infrastructure supporting research and operational needs of the nation.

The ACCESS earth system modelling system consists of observation processing, data assimilation and closely coupled model components for atmosphere, ocean, land surface, sea ice, and chemical and ecosystem modelling, supporting weather and climate applications across all time scales. (See Figure 2)

![Figure 14: Schematic for the ACCESS system for climate and weather applications](image)

The ACCESS modelling infrastructure and service is based on the UK Met Office Unified Model infrastructure, which is to be enhanced to support the ACCESS earth system model for coupled climate and weather model applications. Substantial progress has been made towards providing and supporting a first version of a shared infrastructure with systematic version control and documentation that can be utilised effectively by the entire ACCESS community at ANU/NCI. At this time, the ACCESS modelling infrastructure for simulations of the atmosphere model, (the Met Office’s Unified Model (UM)), is complete but not fully integrated for the facility.

Today, the system provides an infrastructure where researchers from different institutions are able to share model source code, experimental configurations, and data in a stable and
fully supported environment. The system provides the key ingredients necessary to run atmospheric model simulations in a consistent and reproducible environment, and this will be extended to the earth system modelling system. These achievements have provided considerable value to those scientists who develop, run, and analyse data produced by the model.

The ACCESS modelling infrastructure makes use of the ANU/NCI high performance computing system and job scheduler. The service produces a significant amount of data from experiments ranging from short single model runs simulating only a few days to complex ensemble modelling spanning hundreds of simulated years. The infrastructure plan is to better manage this data and register it within the NCI data library for improved data management and collaboration.

**Climate model analysis**

A scientific workflow enables scientists to easily run analyses involving multiple steps, reproduce those analyses, help enforce a controlled vocabulary, and create better metadata for traceability and reproducibility while reducing the need for specialist skills in high performance and cloud computing.

A scientific workflow tool has been developed within CAWCR over the last 18 months. The current tool is different from other scientific workflow packages as it is capable of handling the repetition of workflow steps for many distinct inputs to produce distinct outputs.

The system is currently a command-line tool driven by an XML workflow document which describes the data and analysis tasks to run. This is usable and functional for a user with the skills to edit and manipulate XML documents and has all the data sitting in a file-system where they work. There is much scope for enhancing its utility and merging these features with an existing supported workflow package and extending them to meet the needs of the climate and weather community.

To meet the needs of the community, a Model Analysis Service is proposed within the virtual laboratory for climate and weather research. This will be achieved by enhancing an existing workflow tool such as YABI, Kepler or Workspace, so to improve interfaces to climate and weather model analyses and integration to a data library service within a virtual laboratory. This will require further developments in three key areas: ease of use, collaboration, and integration.

This type of functionality can be built upon the workflow generation, execution and scheduling functionality of the tool. It will also draw upon many other pre-existing tools and services.

The workflow scheduling system is managed by a module, which determines how the job can be run. This eliminates the need for the user to know how to use a job scheduling system such as PBS. It is possible to create other modules/plugins for different grid or cloud based systems. Additional modules will be used to manage data access and interoperability.
Data library and facility interfaces

The data portal and access services are based on the existing Earth System Grid Federation (ESGF) software system. The Earth System Grid Federation is a collaboration of major climate research institutions and organisations that have come together to build an open source software infrastructure for the management and analysis of earth systems data.

The ESGF is designed to provide a data library that allows an end user to search for data across all systems via the browser interface (e.g. Google Chrome, Mozilla Firefox). For example, a user registered with the ESG gateway at ANU/NCI is trusted by all other ESG nodes and therefore is allowed to search and access data from other nodes such as PCMDI/LLNL, BADC and DKRZ/MPI.

The data library provides a universal platform for building an integrated set of data analysis and graphic tools for the international climate community. The node provide interfaces for a growing number of rich desktop applications, including UV-CDAT (Ultra-scale Visualization Climate Data Analysis Tools), efficient data movement, the CDX (Climate Data Exchange) toolkit, and a range of tools with extensions for OPeNDAP’s data access protocol.

The implementation work over the NeCTAR period is to deliver the ESGF Peer-to-peer (P2P) implementation. This is a major upgrade requiring multi-site deployment and testing across the core ESGF nodes. There have been many features requested by the research community that will be addressed. The major deliverables are:

- General system enhancements related to scaling the capability to millions of data sets and petabytes of data volume;
- An enhanced capability to perform server-side data reduction and calculations, which will reduce the volume of data transferred to the users via the Internet; and
- An online imaging capability that will allow users quick inspection and comparison of data sets from multiple locations.

The data portal may utilize components of the Marine and Climate Data Discovery and Access Project (MACDDAP) to improve the data and metadata capabilities of the laboratory. The data portal will support OPeNDAP data access services, OGC Web Map Services (WMS), and other data library services and tools that align with ESGF P2P stack development and Australian research infrastructure services.
Each ESGF node is composed of a configurable suite of applications and services to publish, search, download, and analyze the data (see Figure 3). A node is configured with the following functionality:

- **Data Node**: containing services to publish and serve data through a variety of protocols such as HTTP, GridFTP, OPeNDAP, THREDDS Data Server (TDS), etc.
- **Index Node**: containing services to harvest metadata and enable data discovery
- **Identity Provider**: providing the facilities to register, authenticate and authorize users. ESGF uses OpenID for authentication. Each gateway maintains its own IDP in a trusted federation with the other gateways/nodes and access facilitated by MyProxy.
- **Compute and Visualisation Node**: containing applications servers for data reduction, analyzing and visualizing the data.
- **Gateway**: a specialized web application that exposes higher-level services for user management, data search and discovery.

**Establishment of the Virtual Laboratory**

The virtual laboratory is a new community project to establish an integrated national facility for research in climate and weather sciences that complements and leverages the Australian Super Science initiative investments in computational and storage infrastructure at the ANU/NCI facility, and the strong collaboration in place by National Computational Infrastructure (www.nci.org.au) at the Australian National University, Australian Bureau of Meteorology (www.bom.gov.au), the CSIRO (www.csiro.au/cmar), the Centre for Australian Weather and Climate Research (www.cawcr.gov.au), and the Australian Research Council’s Centre of Excellence for Climate System Science (www.climatescience.org.au).
The laboratory will serve the interests of the earth system modelling community for climate and weather research, and we’d like to understand the requirements of the ocean and marine community. The data portal service will allow researchers to discover and access a variety of data sets generated within the laboratory, from the Australian National Meteorological and Oceanographic Centre, and from international climate and meteorological centres for the purposes of Australian scientific research. Using the web portal and workflow tools, we look forward to creating an improved research experience for our community and collaborators.
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Dense Shelf Water Cascade (DSWC) on the Rottnest Continental Shelf in South-western Australia

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Temperature and salinity (and associated density) data collected using autonomous shallow water Slocum ocean gliders along the Rottnest Continental Shelf, revealed the formation and propagation of dense water masses which is defined as dense shelf water cascade (DSWC). DSWC is a common occurrence in shallow depths of the shelf (<50m) and continues throughout the year with varying degrees of intensity. The region experiences a Mediterranean climate with hot summers and cold winters. During the summer months the inner continental shelf waters increases in salinity due to evaporation. In winter as this higher salinity waters cool and its density is higher than offshore waters and a gravitational circulation is set-up where the inner shelf water are transported as higher salinity plumes into deeper waters. The density currents are estimated to be ~1-2 cm/s, which are similar to those measured in other similar regions globally. Slocum ocean glider data obtained in 2009 and 2010 (41 transects) indicated that there is a cross-shelf density gradient with higher density water inshore throughout the year providing the mechanism for the DSWC. However, the DSWC is controlled by wind action: during the summer regular strong wind events due to persistent sea breezes results in no vertical stratification thus an absence of DSWC. In contrast, during autumn and winter DSC, is a regular occurrence interrupted by storm events. The DSWC plays an important role in cross-shore exchange of water and material in Rottnest Continental Shelf.
Development and application of ROMS based models for the South Australian region.

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Funded by the South Australian State Government ($ 620K) through Marine Innovation South Australia (MISA) the Hydrodynamic, Wave and Biogeochemical Modelling Facility was established in 2007 at SARDI Aquatic Sciences. Building on oceanographic data streams from the South Australian Integrated Marine Observatory System (SAIMOS), the facility has developed a suite of ROMS (Regional Ocean Modeling System) -based models to provide cost-effective scientific solutions for researchers, industry and government agencies. Here we present an overview of the primary shelf and coastal observing systems and hydrodynamic models developed for the South Australian region including; the South Australian Regional Ocean Model (SAROM) and a nested high resolution Spencer Gulf model (SGM). Examples from the hydrodynamic models coupled with wave (SWAN), biogeochemical (NPZD Fennel) and particle tracking (LTRANS) sub-models are shown to demonstrate how developments in multi-disciplinary ocean modelling are helping to deliver sustainable growth and management of aquaculture, fisheries and marine resources in South Australia. These include applications to determine the sustainable carrying capacity of aquaculture and the optimisation of harvest strategies for the western king prawn fishery in Spencer Gulf, South Australia.
Interaction between the Leeuwin Current and continental shelf along the Rottnest shelf and Perth Canyon

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The use of High-Frequency radar for measuring surface currents on continental shelves has been well established through development for over 30 years. The West Australian Integrated Marine Observing System (WAIMOS) has access to two HF Radar systems are operated by the Australian Coastal Ocean radar Network (ACORN): a WERA phased array system with shore stations located at Leighton Beach and Guilderton and a CODAR Seasonde beam-forming system with shore stations located at Seabird and Cervantes. These systems cover the coastal region from Cape Peron to Jurien Bay, extending up to 150 km offshore. The systems provide hourly values of surface currents on a regular grid with spacing of 4-6 km. The WERA data have been analysed in detail to provide time-series consisting over 10,000 to provide information on seasonal variability and the interaction between the two major current systems: the Leeuwin and Capes currents with the latter present mainly during the summer months. The surface currents measured by the HF Radar together with coincident sea surface temperature images indicated the presence of several eddies, particularly within the Perth canyon. Here, a topographically trapped eddy was observed many times and appears to be a quasi-permanent feature. However this eddy migrates to the north and south of the canyon which leads to either upwelling or downwelling at the head of the canyon which was confirmed by a current mooring at the 200m contour. The presence of the eddy confirmed previous numerical modelling of the region which also predicted the presence of the eddy within the canyon. The surface currents also revealed the rapid changes in the current system through the passage of a continental shelf wave generated by Tropical Cyclone Bianca in January 2011.
Modelling meso-scale dynamics along western and southern Australian shelf and slopes: A ROMS modelling approach

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As part of a study on “ocean-shelf exchange with an emphasis on the roles of waves, tides, eddies and cross-shelf flows on carbon exchange”, funded through ANNIMS, a three-dimensional (3D) model was configured to include the western and southern Australian shelves, slopes and the adjacent deep ocean using the Regional Ocean Modelling System (ROMS). The model domain, extending from the Kimberley to Bass Strait, uses curvilinear-orthogonal grids with 2-4 km horizontal resolution for the entire region with 1-2 km resolution in the sub-domains (north-west, central-west and south-west) with 30 sigma layers in the vertical water column. The model was forced with daily atmospheric (wind and air pressure) and air sea fluxes (heat and freshwater). The model open boundaries were specified with monthly salinity and temperature climatology. The model forcing included tides and monthly mean sea levels. The model initial and forcing data (2000-2010) were extracted from various global and Australian oceanographic/meteorological data sources and interpolated in to surface horizontal mesh and open boundary vertical sections.

In this presentation, we highlight the major physical processes in the region using ROMS model output. The model is able to reproduce the tidal characteristics, major surface and sub-surface currents systems (e.g. Leeuwin Current, Leeuwin Undercurrent, Capes current etc.), and associated eddy fields. The model also reproduced the seasonal processes such as: summer upwelling along Ningaloo and the Capes region, dense water formation and cascading in the central western Australian shelf. The model predicted surface currents were compared with HF radar data (Perth region) and cross-shelf flows with current meter moorings. Model predicted SST and SSH was compared to satellite measurements.

We have also examined the contribution from different forcing agents on physical processes in the region by including and excluding different model forcing terms or assigning forcing variable to constant value or zero. We found that the distribution of atmospheric pressure (in addition to other forcing agents) also significantly influences the strength of southward flowing currents (e.g. Leeuwin current). Currently we are in the process of coupling the physical and biogeochemical ROMS model to study the influence of these different processes on the shelf carbon exchange process.
Observations and Modeling of the North West Shelf of Australia during Austral Summer 2011/2012

Jeffrey W. Book, Derek M. Burrage, Philip Chu, James Richman, Clark Rowley
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Ana E. Rice, National Research Council
Richard M. Brinkman, John Luetchford, Craig Steinberg, Australian Institute of Marine Science
Gregory N. Ivey, Nicole L. Jones, Samuel Kelly, Ryan J. Lowe, Charitha Pattiaratchi, Matthew D. Rayson, University of Western Australia
Jennifer Ayers, Peter Strutton, University of Tasmania

During the austral summer of 2011/2012, a series of collaborations between U.S. and Australian funded projects led to the collection of a large observational and modeling dataset for the North West Shelf of Australia. Key collaborations included the Naval Research Laboratory’s (NRL) “AUV Data Analysis for Predictability in Time-Evolving Regimes” (ADAPTER) project focused on methods for preventing operational data aliasing due to internal tides during data assimilation, the Australian Research Council funded project on “Coupled physical and biogeochemical dynamics on the Australian North West Shelf”, and the Office of Naval Research Global funded project on “The connectivity of the Australian North West Shelf with the Leeuwin Current”. The observational plans for these three projects were integrated with the Integrated Marine Observing System (IMOS) Australian National Mooring Network arrays for Ningaloo and Pilbara, and were coordinated with observing plans for the Western Australian IMOS node.

These partnerships resulted in the deployment of 30 moorings at 23 different sites and 5 AUV gliders for various intervals of measurement between November 2011 and August 2012. The measurement program peaked during April 2012 when almost all of these resources were still deployed and a series of cruises by the R/V Solander collected 120 CTD and 318 microstructure profiles. In addition to the observational field work, NRL ran a high resolution version of the Naval Coastal Ocean Model (NCOM) for the North West Shelf and further model runs of both NCOM and the Regional Ocean Modeling System (ROMS) are planned. Analysis of this large dataset has just begun.

Early results show the expected occurrence of strong non-linear internal tides throughout the area. To begin work on ADAPTER research goals, an extended empirical orthogonal function analysis was applied to mooring data allowing the description of fully non-linear internal tide packets with only a few modes of variability and describing the spring/neap cycle of packet evolution. By projecting glider observations on these modes, the spatial and temporal components of the variance can be separated allowing for estimation of the underlying mesoscale features desired for data assimilation. Future analysis is planned to test these and other data assimilation methodologies with this dataset and to focus on the other primary research questions of the collaborating projects.
Observations and modelling of the seasonal cycle of sea level around Australia

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The seasonal cycle of sea level (SCSL) is highly variable around the coast of Australia in terms of annual amplitude and timing of maximum level and has been investigated using monthly mean sea level (MMSL) datasets from satellite altimetry, tide gauges and a barotropic hydrodynamic model for the period 2000 to 2010. We used the Danish Hydraulic Institute’s MIKE21 FM (flexible mesh) suite of modelling tools with the e grid resolution was chosen based on the region’s coastal topography and local water depth variability and with a resolution of ~20–30 km at the open ocean boundaries, decreasing to < 2.5 km along the whole Australian coast. The model was forced using astronomical tidal levels, from a global tidal model (TPX07.2), and meteorological fields, from a global reanalysis (NOAA/NCEP).

The annual amplitude of SCSL exceeds 0.3 m in the Gulf of Carpentaria and peaks in January and is a minimum in July. In this region the barotropic signal accounts for more than 80% of variability. Our model results with different model extents clearly showed the open boundary extent is extremely sensitive for capturing the barotropic (wind setup) signal, particularly in the Northern part of Australia. The model domain extended up to Banda and Java Seas accurately captured the barotropic seasonal signal in Gulf of Carpentaria. The model results showed a significant barotropic SCSL with amplitude ~0.1 m occurs along the eastern Great Australian Bight and peaks in August-September.

The altimeter data and model output have been combined to map the distribution of the barotropic and baroclinic monthly mean sea level (MMSL) and seasonal cycle of sea level around Australia. The estimated baroclinic signal (altimeter minus barotropic model) was compared with steric heights derived from temperature and salinity climatology obtained from the World Ocean Atlas (WOA-09). Our analysis showed the annual steric amplitude and its phase speed along the western and southern Australia is strongly correlated to the strength of the barotropic signal in northern Australia.
Q-IMOS and eReefs: a Partnership to Monitor the Currents along the Great Barrier Reef

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A major goal of the Queensland Integrated Marine Observing System (Q-IMOS) seeks to understand the impact of the Coral Sea, in particular boundary currents and cool and warm water intrusion events on the Great Barrier Reef (GBR). These interactions can induce significant changes in the physical-chemical properties of the seawater of the lagoon impacting on its biodiversity and ecological health. In this context, four mooring pairs deployed along the continental slope, nominally in 200 – 300m of water together with a matching one on the outer continental shelf within the GBR matrix in depths of 30 to 70m. A near-real time 4 km resolution three-dimensional hydrodynamic model covering the entire GBR and western Coral Sea is being developed under the eReefs project. Clear advantages of the model are the spatial coverage compared with the sparse observational network and the availability of near-real time data improves our ability understand and interpret events as they occur.

Severe Tropical Cyclone Yasi made landfall in northern Queensland, Australia on 3rd February 2011. It was the most powerful tropical cyclone to cross the Australian Coast in a century. As the system moved south-westwards towards the Australian coast, it passed near the Q-IMOS infrastructure located near the continental shelf break northeast of Townsville. This provided the opportunity to compare the observations of this extreme event with the eReefs model. Concurrent time series from the observations and model reveal low frequency events down to 200m are reproduced reasonably well resulting in observed warming of water at 200m by over 10°C. Longer period thermocline variability of the model is also in general agreement with the observations.

The eReefs project is a collaboration between the Great Barrier Reef Foundation, Bureau of Meteorology, Commonwealth Scientific and Industrial Research Organisation, Australian Institute of Marine Science and the Queensland Government (AIMS), supported by funding from the Australian Government’s Caring for our Country, the BHP Billiton Mitsubishi Alliance, and the Science Industry Endowment Fund. (source: http://www.barrierreef.org/OurProjects/eReefs.aspx). Q-IMOS GBR Moorings are operated and maintained by the AIMS and funded by the Queensland Government and the Australian Government’s National Collaborative Research Infrastructure Strategy and the Super Science Initiative. All observed data is made freely and openly available through the IMOS ocean data portal that is accessible from www.imos.org.au.
Refined Source Terms in WAVEWATCH III with Wave Breaking and Sea Spray Forecasts

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Ocean Wave forecasting relies on using a non-phase resolved spectral model to forecast the complex wave field. While advection plays an important role, the models rely heavily on 3 source terms: the Snl - the non-linear source energy transfer term, Sin - the input of energy to the wave field from the winds, and Sds - the wave dissipation source term which transfer wave energy to the currents and turbulence.

In this talk we discus the development of new input and dissipation source terms, as part of an ONR funded NOPP program, to incorporate recently developed physics into the operational wave models. The input source term includes the effects of sheltering of the the input to smaller waves by larger waves, as well as known physical constraints such as drag coefficient. The dissipation term is based on a thresholded breaking wave energy dissipation term, with back ground turbulence, and is used to forecast the breaking crest length per unit area, and the total energy dissipation. These are compared against observations, and forecasts are made out to 100 m/s.
Sea breezes force near-inertial waves close to the critical latitude for resonance

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Inertial oscillations are anti-cyclonic motions at the local inertial frequency and are observed globally in regions with weak frictional damping. Near the latitudes 30° south and north the inertial frequency is approximately diurnal. Periodic forcing at these ‘critical latitudes’, by tides or diurnal variations in wind stress, can cause a resonant response in the currents. Observations from the WAIMOS Two Rocks shelf and slope transect mooring array, located near the critical latitude for resonance, reveal strong anti-cyclonic circular motions that often exceed the mean Leeuwin current speeds by > 0.3 m s⁻¹. The observations were made in a region of particularly low tidal energy, therefore the resonant response of the currents is purely driven by the diurnal sea breeze system. As a result, the influence of the wind was observed to depths > 250 m (much larger than then the Ekman depth of ~ 70 m). The sea breeze system in south-western Australia is one of the strongest worldwide, frequently exceeding 15 m s⁻¹, and contributes to 35% of all wind patterns annually. Consequently, in the absence of significant tidal mixing, the sea breeze forcing of near-inertial waves in this region is an important candidate for vertical mixing across the pycnocline.
Statistical modelling of ocean variability on the southeast Australian continental shelf

Eric C. J. Oliver, Neil J. Holbrook

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There is a scarcity of spatially and temporally homogenous measurements of ocean variability on the Australian continental shelf. The ocean reanalysis product Bluelink ReANalysis (BRAN) provides estimates of ocean variability around Australia at 1/10 degree resolution. BRAN reproduces the large-scale patterns of sea surface temperature (SST) in deep water, such as those associated with the East Australian Current and the Leeuwin Current, but performs poorly over the continental shelf. We have developed a linear statistical model to more accurately estimate in-shore SST using off-shore SST from BRAN. SST variability is separated into the mean, seasonal cycle, and the residual variability and separate models are developed for each component. The off-shore locations used to inform the model are determined by jointly taking into account (i) the quality of BRAN at each location, (ii) the strength between the in-shore and off-shore variability, and (iii) the proximity of the in-shore and off-shore locations. Model performance is demonstrated at a point location in Bass Strait and then it is extended onto the continental shelf around southeastern Australia. We will discuss the regional variation in model performance as well as the role of the large-scale circulation in providing accurate predictors on on-shore SST. We will also discuss the possibility of applying the model to dynamically downscaled future ocean projections of the 21st century.
The Australian Bureau Of Meteorology's Core Marine Observing Networks

Boris A. Kelly-Gerreyn 1, Graeme Ball, Helen Beggs, Eric Schulz, Joel Cabrie, Ping Robinson, Julian Rodriguez & Brendan Casey.

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Observations of weather, ocean surface and sub-surface conditions are vital for ocean, weather and seasonal climate forecasting as well as for detecting global climate change.

The Australian Bureau of Meteorology operates a number of marine observing networks to provide data for day to day weather forecasting for the public and the marine user communities in Australia. The marine data collected by the Bureau are also distributed and used internationally as input to computer-based weather and ocean prediction systems, and support the seasonal scale climate prediction of events such as El Niño and La Niña in the Pacific. These data are also archived as a long-term record of how the world's climate is changing.

This poster will describe the marine observing networks, additional observing platforms brought about through IMOS funding and their usage within and beyond the Bureau.
The Australian Coastal Ocean Network, ACORN.

Lucy Wyatt, Sven Rehder, Arnstein Prytz, Alessandra Mantovanelli, Jasmine Jaffrés, Mal Heron and Dan Atwater

School of Earth and Environmental Sciences
James Cook University
Townsville, 4811, QLD

This poster will provide an overview of the IMOS ACORN facility and the data it provides. Methods that have been, or are being, developed to improve the quality of these data and increase availability will be discussed. Some examples of applications of the data will be presented. This will include a number of particle tracking and coral reef management applications in the Great Barrier reef. Some work on wave measurement, in particular directionality, will also be described. Potential applications, using examples from systems elsewhere in the world, will be outlined.
The evolution of a Cold-Core Eddy in a Western Boundary Current

Macdonald, Helen¹, Moninya Roughan¹,², Mark Baird³ and John Wilkin⁴

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Cold-Core Eddies (CCEs) are a common feature in Western Boundary Currents such as the East Australian Current (EAC). We use The Regional Ocean Modelling System to investigate the ocean state during the formation of one such CCE in the EAC during October of 2009. This eddy initially appears as a small billow which cuts into the edge of the EAC. We make use of particle release experiments to investigate the eddy’s source waters. Nearly all of the surface particles within the eddy (and hence source waters) originated on the continental shelf. Particles above 500 m within the eddy came from both north (as expected) and south of the eddy. Particles come from the south due to a northward flow on the continental shelf just prior to eddy’s formation. Close to 100% of particles in the top 50 m of water in the eddy came from water which was located in the top 100 m on the continental shelf prior to the eddy formation. We also investigate the impact of 3 wind forcing scenarios: upwelling, downwelling and realistic winds. The hydrography of the continental shelf changes in response to the wind forcing, producing cooler or warmer surface temperatures. Despite the difference in wind forcing, an eddy still forms in each of the scenarios but, the path on which the eddy travels differs. The different scenarios also have different isothermal displacement. Interestingly, the maximum uplift of the 17oC isotherm is produced in the downwelling winds scenario. This study is the first of its kind to investigate CCE’s in the EAC and entrainment of shelf waters which can serve as biologically significant source of nutrients or seed populations.
The Leeuwin Current: the roles of topographic trapping, mixing, and advection in a buoyancy driven eastern boundary current

Jessica Benthuysen$^{1,2,5}$
Ryo Furue$^3$, Julian McCreary$^3$
Nathaniel L. Bindoff$^{1,2,4,5}$, Helen Phillips$^5$

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$^5$Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia

The Leeuwin Current is a poleward eastern boundary current that is shelfbreak intensified. For a buoyancy driven basin, numerical experiments are used to investigate how shelf-slope topography, mixing, and advection contribute to an eastern boundary current’s speed, transport, and spatial structure. The buoyancy forcing is composed of a meridional density gradient distributed over an upper layer depth. This density structure supports a near-surface eastward flow that converges over topography. The position where the upper layer intersects the slope sets the offshore width of the current by topographic trapping of Rossby waves. Vertical diffusion thickens the upper layer, strengthening the poleward current. Horizontal viscosity modifies the current width over which the zonal flow converges and hence controls the jet speed. Poleward density advection forms a cross-shelf density front, intensifying the poleward flow near the surface. Offshore density advection by frictionally driven, near-bottom flows can contribute to the jet’s frontal position near the shelf break.
Tidal characteristics in Bass Strait, south-east Australia

Sarath Wijeratne, Charitha Pattiaratchi, Matt Eliot and Ivan Haigh

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We used a two-dimensional, barotropic, numerical model to examine the complex behaviour of the tides in Bass Strait. Bass Strait, located in south-east Australia between the Australian continent and Tasmania, has the appropriate dimensions to create a half-wave tidal resonance for the $M_2$ tides. The $M_2$ tidal wave (amplitude $<0.4$ m) enters the strait from both strait openings, increasing the $M_2$ tidal amplitude towards the central northern Tasmanian coast to a maximum of $~1.1$ m. The tidal phases and current ellipses in the strait showed the $M_2$ tides resembled a half-wavelength resonance in a curved, open basin. The semidiurnal, $S_2$, and diurnal, $K_1$ and $O_1$, tidal amplitudes were comparatively small ($<0.2$ m), progressive in nature and mostly constant through the strait. The model simulations revealed that when only open boundary tidal (OBT) forcing was included in the model, the model over predicted the $M_2$ amplitudes by $~10–15\%$ in the strait’s central region; however, when OBT and direct gravitational tidal (DGT) forcing were included, the model accurately reproduced the observed tidal amplitudes. DGT forcing was used to generate resonantly amplified $M_2$ tides (amplitudes of 0.1–0.3 m) locally, with destructive interference between the OBT-forced and DGT-forced tides occurring in the centre of the strait. The model simulations also revealed that storm systems propagating west to east attenuated the $M_2$ tidal amplitudes within the strait. The greatest decrease in the tidal amplitudes occurred along the central northern Tasmanian coast and was attributed to tide-surge interaction and resonance behaviour in the strait.
Understanding the Shark Bay Outflow through field experiments and numerical modelling

Yasha Hetzel¹, Charitha Pattiaratchi¹, Ryan Lowe², Richard Hofmeister³

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The success of many marine mollusc species is strongly dependent upon hydrodynamic conditions that retain or transport larvae to favourable settling grounds. To effectively manage these fisheries, it is therefore essential to understand the dominant physical processes that control the hydrodynamics in these regions. In Shark Bay, Western Australia, longitudinal density gradients drive gravitational circulation that is important for bay-ocean exchange and transport of biological matter such as larvae. In this inverse estuary higher salinity water is exported through the two main entrance channels at depth and is replaced by lower salinity ocean water at the surface. Recent winter field experiments in Shark Bay’s entrance channels recorded dense water outflows that varied in intensity and frequency between the two main entrance channels. The outflows occur during periods of low tidal mixing which allows for the vertical water column to be stratified and thus can be predicted in advance. The General Estuarine Transport Model (GETM), a three-dimensional baroclinic hydrodynamic model, was used to investigate the spatial variability of the dense bottom water outflows and the inhibiting effects of mixing by tidal currents and wind. The model results indicated well-defined transport pathways consistent with the field measurements. The outputs from the hydrodynamic model were used to drive a passive particle dispersal model, to simulate the dispersal of scallop larvae and establish source-sink relationships between stocks. We found that stocks near to the entrance channels were susceptible to flushing by the dense water outflows and that a hydrodynamic ‘barrier’ existed between the southern and northern regions of the Bay. These results support the practice of treating the two areas as separate spawning stocks and will aid in fisheries management decisions. More broadly, the results support the hypothesis that the main pathway for the export of hypersaline bay water and biological material such as larvae is out of the northern entrance to Shark Bay, and that density-driven bottom currents likely play a major role in exchange between the bay and ocean.
Using a suite of models to define multiple scales associated with coastal sand transport around complex reefs

Cyprien Bosserelle, Shari L. Gallop, Charitha Pattiaratchi and Ivan D. Haigh

School of Environmental Systems Engineering and UWA Oceans Institute, The University of Western Australia,

Field measurements suggest that coastal reefs cause strong spatial variability in sediment transport pathways. A suite of numerical models over multiple spatial scales was used to investigate the sediment transport processes around complex reefs at a perched beach in Western Australia. The multi-scale methodology focused on the simulation of tides, storm surges and waves from the: (1) ocean basin and continental shelf scale (using the Wave Watch 3 model for the whole of the Indian Ocean basin for waves and the MIKE 2DH barotropic model for tides and storm surges); (2) the regional scale (SWAN model for waves); (3) the coastal scale (Xbeach for morphology) and (4) the single wave scale (Smoothed Particle Hydrodynamics, SPH model). The model outputs of sea level and realistic directional wave spectra were used to force the XBeach morphological model at the coastal scale. The transition between spatial scales allowed the conservation of wave spectral information and therefore provided a realistic forcing to the coastal model. The simulations revealed dramatic wave dissipation over the offshore and coastal reefs allowing only a fraction of the wave energy to reach the coast. The XBeach model was used to estimate the maximum erosion likely to occur during a single extreme storm. The single wave scale shows the resuspension events due to the wave breaking near the reef forming a scour step in front of the reef. This multi-scale approach resolved the spatial variability in the sediment transport pathways around the reefs.
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