Articles

BLUElink> Progress on operational ocean prediction for Australia

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Introduction
"…a woman has been reported overboard off Australia's east coast. The last known sighting was (152,2E,36.3S) at 7pm. A pleasant sailing trip in the Tasman Sea went horribly wrong when a storm whipped up from the South-west. The search and rescue coordination centre have commenced planning the search area and a crew are now on standby. At their disposal are analyses and forecasts from the Bureau's new operational ocean forecasting system. The surface currents combined with wind and sea state are being used to help estimate the search area. The emergency staff have gained confidence in the guidance they are now receiving from the new products and are hopeful it will lead to a shorter search time and the safe return of the woman to shore…"

An Australian government initiative called the BLUElink project will help this vision for the future in search and rescue to become a reality. The Bureau of Meteorology, CSIRO and the Royal Australian Navy have formed a partnership to develop and implement Australia's first operational ocean prediction system. Operational oceanography, in this context, refers to the hindcast, nowcast and forecast of the three-dimensional ocean state (temperature, salinity and pressure) and currents for the short-range timescales out to one month. The system will represent a revolution in oceanographic information for the Australian public with many of Australia's marine activities including naval defence, marine environmental management and eco-tourism all set to benefit from the new capability.

The ocean exhibits "weather" patterns that have many similar characteristics to their atmospheric counterpart. Indeed ocean dynamics are represented by the same conservation laws, which lead to similar governing equations. As a result the development of ocean prediction systems have many structural similarities to numerical weather prediction (NWP). However, there are also many unique features that make ocean forecasting both simpler and more complex relative to NWP. For example modelling the troposphere must represent complex physical processes related to changes of state of water vapour and ice crystals that are known as cloud physics. Sea-ice formation is the counterpart for the ocean, however this is constrained to the most northern and southern latitudes. The coastal ocean weather off Australia's mainland is not impacted directly by sea-ice processes. Radiation physics are also simpler in the ocean than in the atmosphere. Ocean attenuation of penetrative solar radiation is $0.03m^{-1}$ in clear water and is therefore only important over the top 50m. The deeper ocean is essentially opaque. Radiation physics in the top 50m is important for many applications and is made more complex by the impact of photo-synthesising biota. However, compared with the atmosphere radiation physics it is a relatively simple parameterisation.

The complexity and technical challenges in ocean modelling come from characteristics such as: (a) the equation of state, (b) irregular ocean bathymetry, (c) air-sea fluxes and (d) turbulent dynamics. Ocean density is a nonlinear function of the three state variables, temperature, salinity and pressure, which does not have a simple analytical approximation. The ocean is confined by gravity to a complex array of basins inter-connected by the Southern Ocean, archipelagos, straits and passages. The irregular shape of the ocean bathymetry dominates the response to atmospheric forcing and leads to a variety of circulation features, from basin scale ocean gyres, to continental shelf scale boundary currents. Surface fluxes of mass, momentum and heat dominate the ocean circulation over the top 1000m. Surface fluxes are determined at the air-sea interface, which separates two turbulent boundary layers and also includes wave dynamics. Fluxes are difficult to measure directly or represent dynamically and accuracy is limited. Both the ocean and atmospheric exhibit "mesoscale" weather however the greater density $O(1000kgm^{-3})$ lead to smaller spatial scales (internal Rossby radius of deformation) in the ocean. A model that resolves ocean weather is referred to as an "eddy-resolving" model and requires approximately >1/8^o horizontal resolution. Ocean prediction, as discussed in the next section, requires greater resolution and computational resources than NWP to resolve similar dynamics.

Ocean model development

Ocean circulation can be represented using a numerical model that solves the appropriate non-linear equations of motion for a fluid on a rotating sphere. The numerical software for these equations is referred to as an Ocean General Circulation Model (OGCM). There are several freeware models developed largely in the United States that are made available to the broader community for non-commercial use. The Modular Ocean Model (MOM) is one community model that has been developed continuously from the 1980's at GFDL and is currently available in its fourth major revision (MOM4). CSIRO has similarly been adapting MOM for the Australian science community throughout this time. The Ocean Forecast Australia Model (OFAM; Schiller et al., 2005) is based on MOM4 and has been specifically developed by CSIRO for the BLUElink ocean prediction system. Specific extensions include the implementation of a mixed layer parameterisation, a solar radiation attenuation model and optimisation for the infrastructure of the High Performance Computing and Communications Centre (HPCCC), a joint Bureau/CSIRO facility. The development also includes a specification of the horizontal and vertical grid points for the B-grid model. OFAM is a global model where the longitudes and latitudes are shown schematically in Fig.1. The grid has 1/10°×1/10° resolution in the Australian region (90E-180E, 75S-16N) and stretched resolution away from this region down to climate scale resolution in the North Atlantic. This grid design provides "eddy resolving" resolution in the Australian region, "eddy-permitting" resolution in the Indian and South Pacific Oceans and removes the need for nesting strategies for open boundaries such as occur with limited area designs. The vertical grid employs 47 levels with uniform 10m resolution over the top 200m and is then gradually coarsened to a total depth of 5000m. OFAM is at the high-end of computing with a ~40GByte executable that requires ~11.5 minutes of wallclock to integrate one model day using 42 processors on an NEC SX6. On-going efforts to improve model algorithms and further optimisation continue to reduce these costs.

Observational oceanography

Observational oceanography has seen a rapid expansion in instrumentation over the past two decades driven by the need to observe the climate system and respond to climate change science. Although the driving force for much of the observing system is for modelling and monitoring the climate system, the same instrumentation can also support short-range ocean forecasting. A pilot project called the Global Ocean Data Assimilation Experiment (GODAE; Smith and Lefebvre, 1997) has set out a vision for supporting the development of the assimilation of data from the Global Ocean Observing System into state of the art numerical models in near real-time (NRT). GODAE promotes the sharing of data, standardising metrics for model intercomparisons and supporting common infrastructure, formats and protocols for data servicing. Several earth-observing satellites are in orbit, which are providing NRT observations of sea surface height and sea surface temperature. In addition to satellite oceanography, several in-situ observational programs have been undertaken including SOOP (Ship Of Opportunity Program) that deploys XBT (expendable Bathy-Thermograph), TAO (Tropical Atmosphere Ocean) that maintains a network of moorings in the tropical Pacific and Argo: a program to deploy autonomous vertical profiling drifters. Some of the oceanographic variables being routinely observed together with the instruments to be used by the ocean prediction system either directly or indirectly are outlined in Table 1.

Data assimilation

An ocean prediction system requires a data assimilation system to provide a best estimate of the initial ocean state based on a model background and a sparse set of observations. Data assimilation uses the estimated statistical error covariances of ocean model variables to distribute the "innovations" (the differences between the ocean observations and the model background) and computes a weighted least squares fit over all observations. Estimating the covariances and computing the appropriate weights together with the constraints of computational cost lead to a wide variety of implementations. OFAM will be initialised by the BLUElink Ocean Data Assimilation System (BODAS; Oke et al., 2005). BODAS is an ensemble-based, multi-variate, optimal interpolation scheme where the model error covariances are based on a 72-member ensemble of intra-seasonal anomalies. These stationary anomalies are obtained from a 9 year integration of OFAM using ERA-40 surface fluxes (Kallberg et al., 2004). Two examples of the spatial structure of the ensemble are shown in Fig.2. These correlations have clear physical interpretations to the known dynamics of the region, namely the Zeehan coastal current off Tasmania (Fig 2a) and the equatorial waveguide off Indonesia (Fig 2b).

Figure 1: Ocean Forecast Australia Model horizontal grid. Water cells are coloured according to the depth of bathymetry, every 30th grid point is shown as a grey dot.

Variables	Instrument	Source
Sea surface height	GFO Jason-1, Topex/Poseidon ENVISAT	US Navy/NAVO JPL/PO.DAAC ESA
Temperature/salinity	TAO ARGO XBT	NOAA/PMEL USGODAE/Coriolis GTS
Sea Surface Temperature	AVHRR/NOAA-17 AATSR/ENVISAT AMSR-E/AQUA	NOAA ESA NASA/EOS
Wind stress	QuikSCAT	JPL/PO.DAAC

Table 1: Global ocean observing instrumentation that is being used directly or indirectly by the BLUElink ocean prediction system

Operational ocean prediction system

The proposed operational system, Ocean Model Analysis and Prediction System (OceanMAPS), is being prepared for operational trials beginning in 2006 with the system scheduled to begin operations in 2007. OceanMAPS combines a number of component systems including: (a) a system to form the NRT database/archive, (b) a system to prepare the data for the analysis and forecast system, (c) BODAS (d) OFAM and (e) a product archive and server as shown schematically in Fig 3. Collectively the database and archiving system are referred to as the data management system.

There are three observation types assimilated in the present version of BODAS, sea surface height anomalies and temperature and salinity profiles. Sea surface height anomalies are not directly observed by altimetry but instead are processed at a number of international centres including JPL/NASA, NAVO/USNAVY, NOAA and ESA. The anomalies are calculated based on a number of corrections including satellite positioning, atmospheric state and ocean tides. In order to meet the NRT delivery targets (e.g., 5-7hrs for Jason-1) the corrections make use of less precise positioning systems and forecast NWP and tide models. The more precise orbit corrections and analysed model fields are not available until several days after real-time. At present, data from each satellite is made available in a semi-operational mode from each of these centres. The data are retrieved from ftp servers, from specified directories using a unique convention for the filename. Each centre uses its own unique file formats which are typically non self-describing and require decoders and documentation from each provider to determine their content. The Bureau manages this data by re-formatting each source into a common format BUFR, which is then stored in the database. The Argo profiles are provided in real-time from three sources: GTS, USGODAE and Coriolis. This data contains many duplicates, which are sorted at the Bureau into a best daily observation file prior to undergoing model-independent quality control.

The backbone of the Bureau's computational infrastructure to support the operations branch is the NEC SX6 managed through the HPCCC. The SX6 is accessed through an NQS based queue system that provides pre-emptive priority service to operational jobs while still providing services for research and development tasks performed by other sections of the Bureau and CSIRO. The SX6 is front-ended by dual NEC TX7 servers, each having 16 CPU and 16GB of memory. The TX7s provide global file system services for the SX6 nodes, and also scalar services for tasks associated with file transfers and data handling. The computational resources required by OceanMAPS are at the high-end of high performance computing and these facilities are critical to producing timely ocean forecasts. Access to a joint facility has also been critical to the successful collaboration between Bureau and CSIRO scientists in the BLUElink project.

The analysis cycle of OceeanMAPS is being trialled in two streams: (a) a delayed/symmetric analysis and (b) a NRT/asymmetric analysis. The first analysis is designed to be a number of days behind real-time which will allow both a higher quality and a larger quantity of observations to be included in the analysis. This best estimate of ocean state for the prediction system is used as the starting point for launching a NRT analysis sequence. The NRT analysis is closer to real-time and will have fewer high quality observations and an asymmetric analysis window. This ocean state is used temporarily to produce an ocean forecast. Including the delayed analysis increases the computational cost of the system, which must be evaluated and justified during the operational trials.

Conclusion

Ocean forecasting for the Australian community is set to become a reality over the course of 2006. A workshop was held in October 2005 at the Bureau to review the science and technical implementation plan for OceanMAPS. The first system is being prepared for 6 months of operational trials in the first half of 2006. At the conclusion of this period the final configuration will be determined and implemented in a semi-operational mode for monitoring and evaluation. Provided the system satisfies the performance levels required for operational systems, OceanMAPS will be certified and will begin to deliver operational forecasts in 2007. OceanMAPS represents a significant investment by the Australian government and will provide information that will benefit many known applications and will likely facilitate the development of many exciting new applications. Some of these applications include: heat content forecasts for coral bleaching events and tropical cyclones, current forecasts for search and rescue, pollution mitigation and shipping. Effectively identifying and engaging with the users of OceanMAPS products is a critical activity for the Bureau and CSIRO that will develop as OceanMAPS and its products emerge.

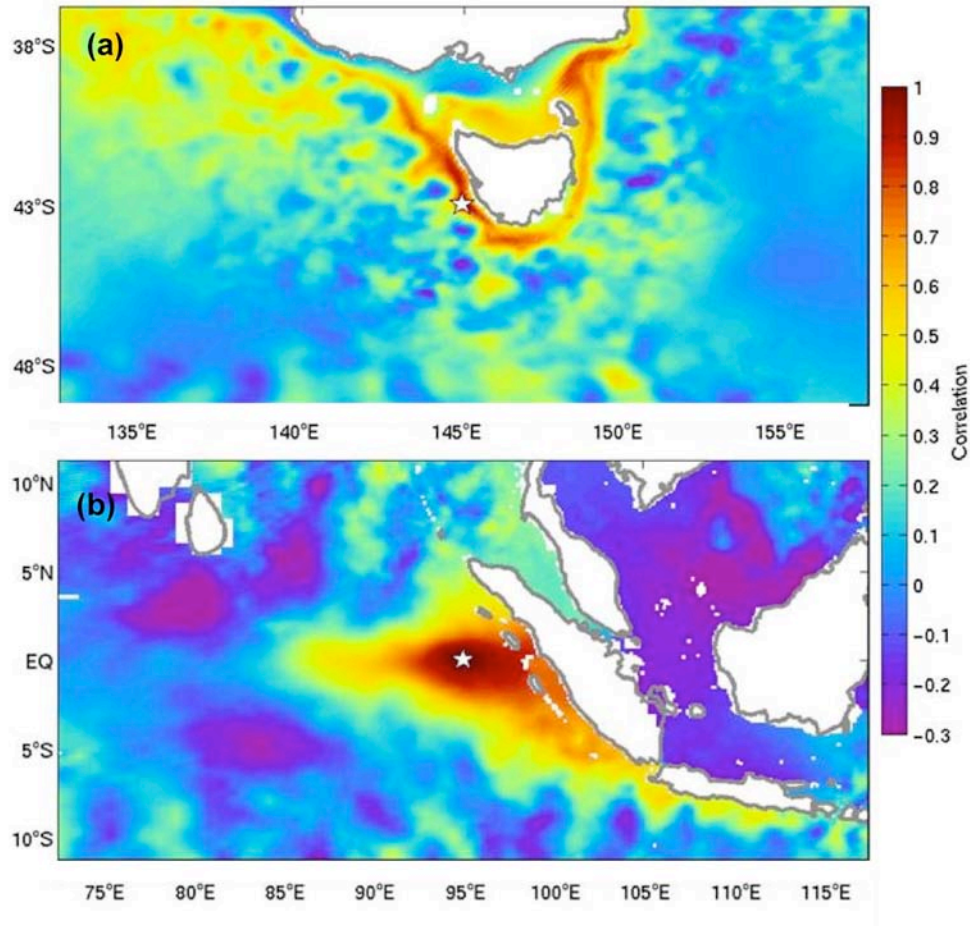

Figure 2: Horizontal spatial correlations of sea surface height anomalies based on an ensemble of modelled states for the locations marked with a star (a) off Tasmania and (b) off Indonesia (adapted from Oke et al., 2005)

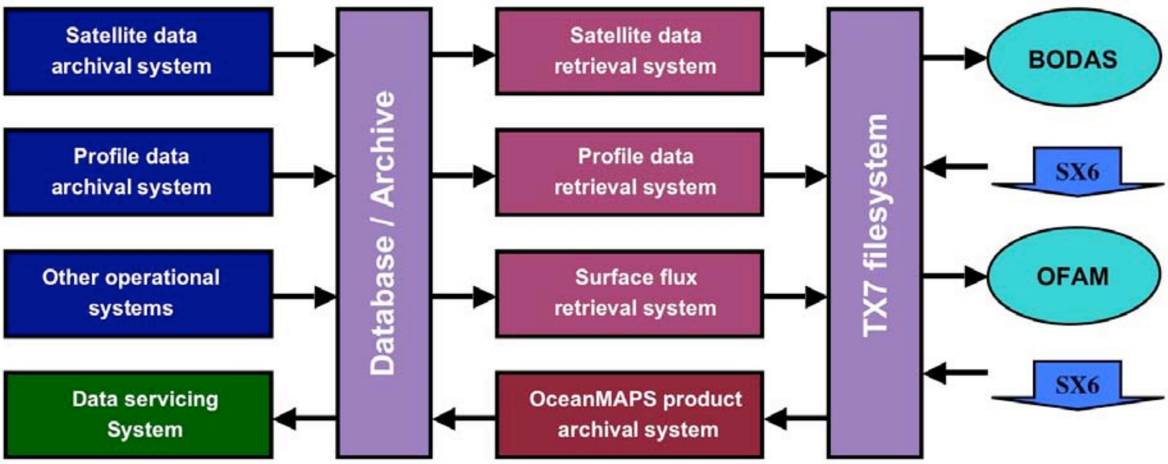

Figure 3. Schematic representation of the major system components and flow of information in the Ocean Model and Analysis Prediction System (OceanMAPS).

In addition to OceanMAPS, the BLUElink project also includes many other developments including: (a) a relocatable ocean-atmosphere model (ROAM), (b) an improved ocean climatology, (c) a high resolution operational sea surface temperature analysis, (d) the BLUElink ReANalysis (BRAN), a 12 year ocean reanalysis, (e) an evaluation of the Bureau's NWP surface flux products, (f) an evaluation of a coupled ocean-atmosphere system for tropical cyclone forecasting and many other experimental projects.

Oceanography in Australia is set to experience a revolution in information across a broad range of applications that will further invigorate the ocean research community. BRAN has already delivered unprecedented information on the circulation and current systems in Australia's territorial waters. Analyses of this database have only scratched the surface of the information contained in the dataset. It needs to be acknowledged that the proposed system will not provide the complete solution for all users in the marine environment. In particular, the proposed system could be significantly improved in the coastal and near shore region where many processes have smaller spatial and temporal scales than OceanMAPS will resolve. The nested ROAM system with a horizontal resolution of up to 2 kms will resolve many shelf and coastal features. ROAM will be run operationally by the RAN. The priority for the first OceanMAPS is not just performance but robust operational delivery, which must balance the system's complexity. Like its NWP counterpart, OceanMAPS merely initiates a process of vigorous and continuous improvements in performance and extensions in capability. A follow-on project, BLUElink II, is currently being developed amongst the existing partners to advance and improve the suite of products available to the Australian community beyond the present project.

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The Tropical Warm Pool International Cloud Experiment (TWP-ICE)

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A major experiment to study tropical convective cloud systems and their impacts will take place around Darwin, Northern Australia in January and February 2006. The Tropical Warm Pool International Cloud Experiment (TWP-ICE) is a collaboration including the DOE ARM (Atmospheric Radiation Measurement) and ARM-UAV programs, NASA centers, the Australian Bureau of Meteorology, CSIRO, Airborne Research Australia (ARA) and universities in the USA, Australia, Japan, the UK and Canada. Detailed atmospheric measurements will be made through the Austral summer, giving unprecedented coverage