Combining Ensemble and Variational Data Assimilation

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LONG-TERM GOALS

The long-term goal of this project is to develop and apply practical methods for data assimilation to improve the short-range prediction of mesoscale ocean variability.

OBJECTIVES

The primary objective of this work is to develop an ocean data assimilation system that exploits the strengths of both the ensemble-based (e.g., Evensen 2003; Houtekamer and Mitchell 1998; Tippett et al. 2003) and variational (e.g., Bennett 2002) approaches to data assimilation. The first step in this project is to perform a comprehensive inter-comparison of an ensemble-based data assimilation system with a 4d-var system for a suite of coastal model configurations. The second step is to identify the strengths and weaknesses of each system and to improve both systems by *borrowing* components from the other system. Ultimately, a single ensemble-var system will be developed. We will investigate the extent to which the ensemble-var system can outperform both the ensemble-based and variational approaches, both in terms of forecast skill (accuracy) and computational efficiency (throughput).

APPROACH

An ensemble-based data assimilation system, based on an Ensemble Optimal Interpolation (EnOI) scheme (Oke et al. 2002; Evensen 2003), has been developed and tested for a range of applications by Dr. Oke (Oke et al. 2005; 2008; 2009; 2010), and a four-dimensional variational (4d-var) system, based on the representer method (Chua and Bennett 2001; Bennett 2002), has been developed and tested for coastal ocean applications by Dr. Kurapov (Kurapov et al. 2007; 2009 2010).

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Conceptually, both the ensemble and variational approaches perform analogous tasks. Both methods implicitly generate estimates of the system's background error covariance, both interpolate and extrapolate background innovations (model-observation differences) onto the full model state (including all variables at all model grid points), and both seek to minimize some norm of the model-observation misfits. The ensemble-approach has an advantage that it uses the non-linear model operator to generate and evolve the system's error covariance, but has the disadvantage that it is rank deficient (i.e., usually uses too few ensemble members to completely span the error sub-space of the system). The variational representer-based approach, by contrast, is full rank, but it uses linear operators to derive the system's error covariance, or representers. The ensemble-approach is typically implemented as a three-dimensional interpolation (e.g., Oke et al. 2005; 2008) and the representer-approach is fundamentally four-dimensional (Kurapov et al. 2007, 2009). There are pros and cons of both approaches. Under this project, we will exploit the strengths of both approaches, with the goal of developing a superior ensemble-var data assimilation system.

A first step in this project is to apply the EnOI and 4d-var assimilation systems to the same application. The performance of both systems will be assessed when they assimilate the same observations to constrain the same model. Work has begun to achieve this inter-comparison.

It is typical to use the 4d-var system to optimize the surface forcing for a model using the ocean observations. This approach is not commonly used for ensemble-based systems. Work has begun to establish a capability to update surface fluxes by assimilating ocean observations using the ensemble-based system. This is achieved by augmenting the ensemble with perturbations of the surface fluxes. This step will permit a more consistent comparison of the ensemble- and variational-based data assimilation systems, and should improve the performance of the ensemble-based approach.

Dr. Peter Oke is the P.I. on this project and leads the ocean data assimilation activities at CSIRO Marine and Atmospheric Research. Dr. Oke is working closely with Dr. Kurapov, from OSU, under this project, and also in collaboration with Dr. Terrence O'Kane and Dr. Chaojiao Sun from CSIRO.

WORK COMPLETED

Work has begun to port the 4d-var system, called the Advanced Variational Regional Ocean Representer Analyzer (AVRORA), to a common computing platform with the ensemble-based system. Work has also begun to prepare the 4d-var system for an inter-comparison with the ensemble-based system. The initial test-bed is a region off South Australia where wind-driven upwelling events regularly occur. The ensemble-based system has already been applied to this domain, with promising results. The initial tests with the ensemble system involved the initialization of an ocean model for a sequence of 7-day forecasts. The period chosen for this test was during a strong wind-driven upwelling event. The forecasts that were initialised using the ensemble system demonstrate positive forecast skill.

We have augmented the ensemble with surface flux fields and performed some preliminary calculations to allow us to project the ocean observations of sea-level, temperature and salinity onto the surface flux fields that include the wind stress, all components of the surface heat flux, and all components of the surface freshwater flux. This development makes the ensemble approach more consistent with the 4d-var approach, and will permit a more consistent series of inter-comparisons. It should also render the ensemble-based system more optimal. Experiments to evaluate this are underway.

RESULTS

The initial test-bed for the inter-comparison between the EnOI and 4d-var data assimilation systems is a domain off Southern Australia. An example of the EnOI system applied to this domain is summarised in Figure 1. This figure shows the sea-surface temperature from observations (labelled 6-d AVHRR), from a 1/10th degree ocean reanalysis (labelled, BRAN), a coastal ocean model (labelled SHOC), and an assimilating coastal ocean model (labelled SHOC+DA). This example corresponds to a strong wind-driven upwelling event, when strong, upwelling favourable winds persisted for over 2 weeks. The result of this strong wind forcing was a cold upwelling plume, represented in Figure 1 by cold waters adjacent to the coast. This upwelling was reproduced, in a qualitative sense only, by both the large-scale ocean reanalysis and by the nested coastal ocean model. In both cases, the simulated upwelling was too weak. By contrast, the assimilating, nested ocean model reproduced a stronger upwelling plume that was in better agreement with observations. This demonstrates the success of the EnOI system in initialising the coastal ocean model. This is the initial test case for the 4d-var system.

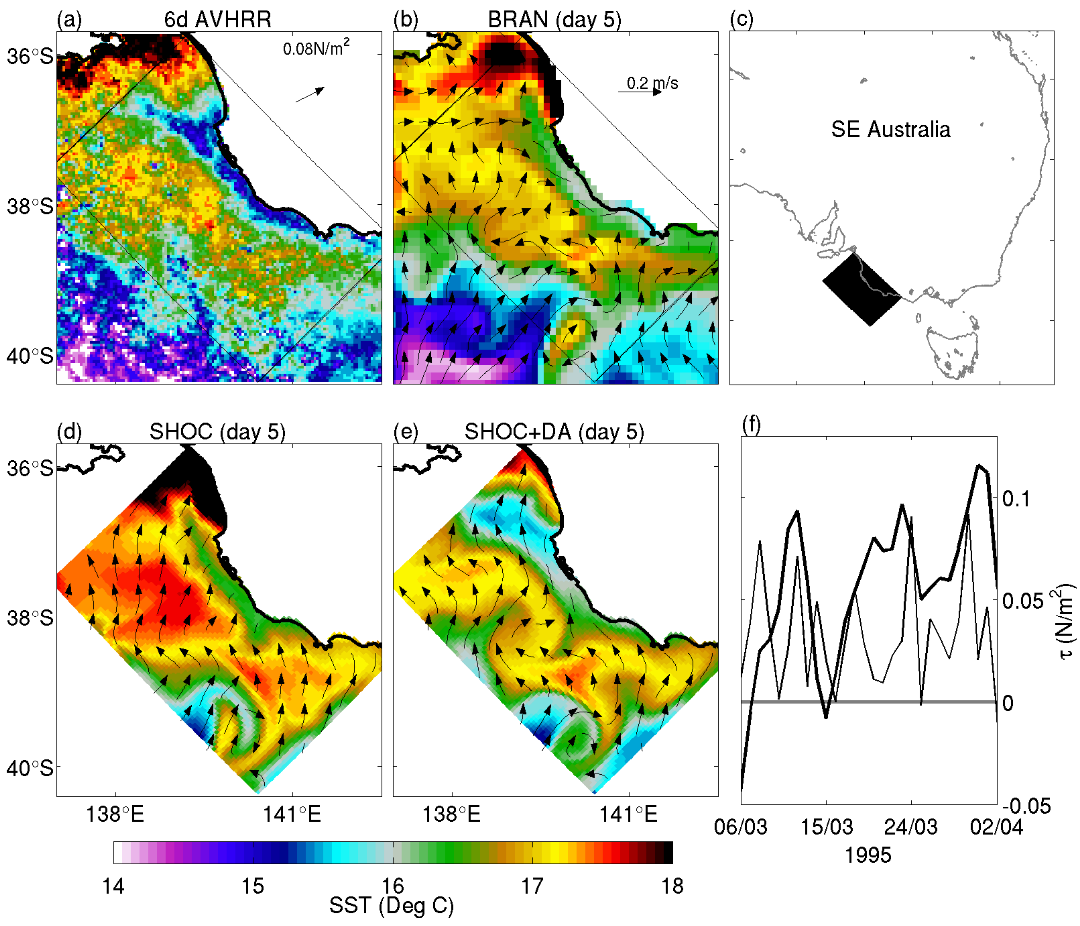

Figure 1: Sea-surface temperature for an upwelling event 27 March 1995 from (a) 6-day composite AVHRR observations, (b) the Bluelink ReANalysis (BRAN; Oke et al. 2008), (d) a nested coastal ocean model (SHOC; Herzfeld 2006; 2009), and (e) the nested coastal model with data assimilation. Panel (c) shows the model domain, and panel (f) shows the along-shore (bold; positive is upwelling favorable) and across-shore (thin) components of wind stress.
[Figure showing the positive impact of ensemble-based data assimilation on a coastal ocean model.]

For traditional sequential data assimilation, a model background field is combined with observations to construct an analysis. After each assimilation step, the model is initialised with the analysis and the model integration continues. Here, the analysis is simply the sum of the background field and the analysis increment. The analysis increment is an adjustment, or correction, to the model state. When ensemble-based methods are used, the model state is usually restricted to the model's prognostic variables - usually temperature, salinity, velocity, and sea-level. By augmenting the ensemble with the various components of the surface flux fields, our ensemble-based data assimilation system can be used to project ocean observations onto atmospheric fields and atmospheric fluxes. An example of the ensemble-based analysis increments to the surface heat flux and wind stress, based on the assimilation of ocean observations using an ensemble-based data assimilation system, is presented in Figure 2. For this example, the adjustment to the ocean state includes a decrease in surface temperature over much of the region. For the western-most part of the domain, this is consistent with a negative increment to the surface heat flux. Along the coast, the negative surface temperature increment is consistent with the upwelling favourable adjustments to the surface wind stress. This example demonstrates that, like 4d-var systems, ensemble-based data assimilation systems can be used to optimise surface fluxes.

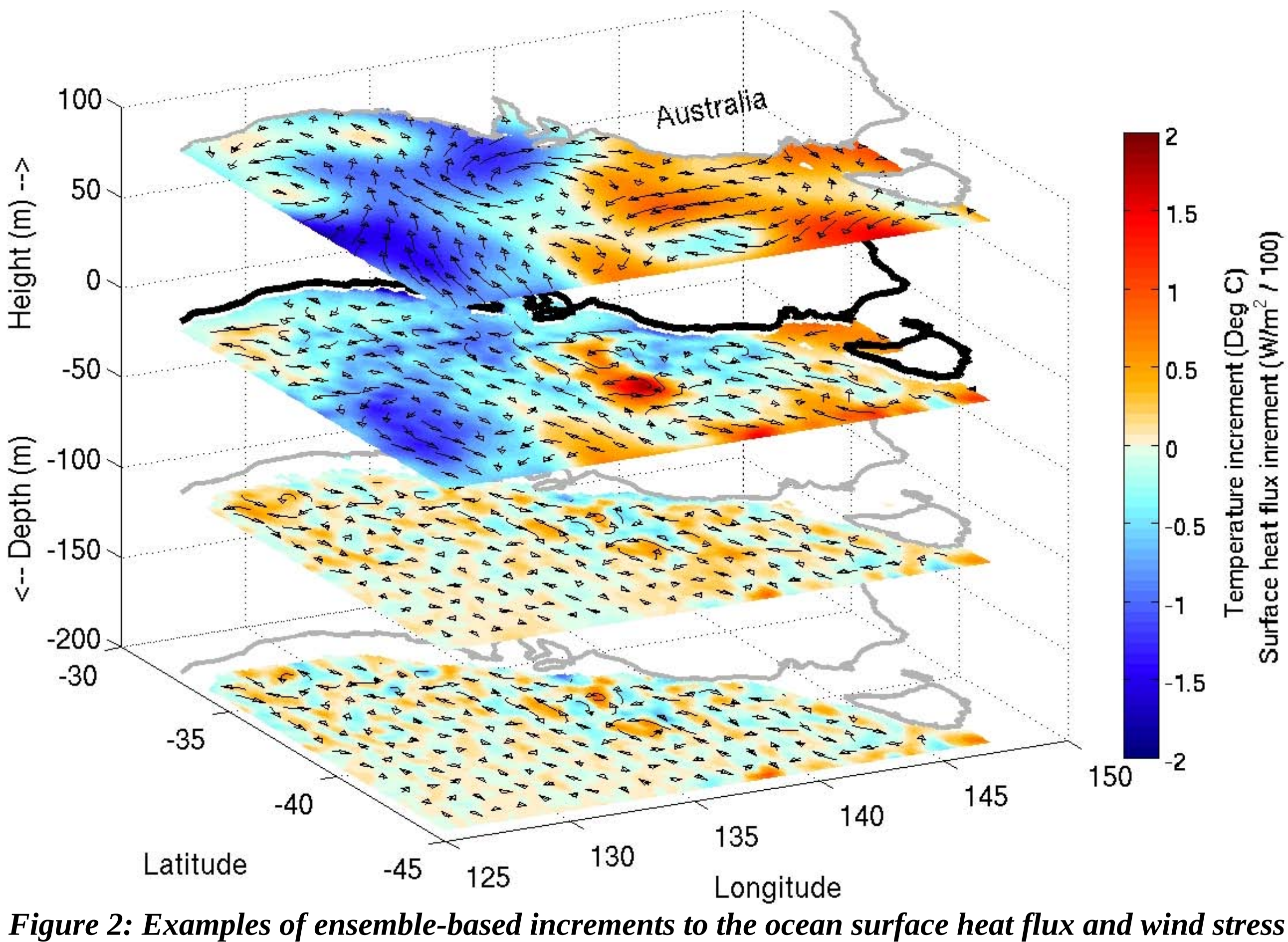

Figure 2: Examples of ensemble-based increments to the ocean surface heat flux and wind stress (1st layer), and the ocean temperature and velocities at different depths (2nd-4th layer) for a region of southern Australia.

[Figure showing impact the projection of ocean observations onto the ocean and atmosphere.]

IMPACT/APPLICATIONS

A typical implementation of AVRORA, the 4d-var system we are working with under this project, involves the optimization of the ocean initial conditions and the surface forcing fields. The extension of the ensemble data assimilation system to update atmospheric fluxes as well as ocean fields, using ocean observations, facilitates a clean inter-comparison of methods. This is an important first step of this project. More generally, the augmentation of an ensemble-based ocean data assimilation system with atmospheric variables is a step towards coupled ocean-atmosphere initialisation. It opens up several possibilities, including the assimilation of satellite-derived observations of wind stress (or other atmospheric observations) into an ocean model; coupled initialisation, which could improve the predictive skill of the coupled system for applications where the coupling is important (e.g., tropical cyclone prediction); and the extension of data assimilation to include other variables that can be directly related to the ocean circulation (e.g., ocean colour observations from MODIS).

RELATED PROJECTS

Bluelink is a partnership between CSIRO, the Bureau of Meteorology and the Royal Australian Navy. Many of the research activities undertaken in Bluelink have strong synergies with the project that is the subject of this annual report. The main objective of Bluelink is the development and application of an ocean forecast system for the mesoscale circulation around Australia. Applications of the Bluelink system are well documented (e.g., Oke et al. 2005; 2008; 2009; 2010; Schiller et al. 2008). An example of results from the latest Bluelink ReANanalysis (BRAN) experiment is presented in Figure 3. This figure shows monthly-mean sea-level fields from BRAN (version 2p2; Oke and Griffin 2010) with drifter-derived velocities and trajectories overlaid. The drifter data are from the entire month. The drifter data represent the time-varying ocean circulation and are therefore a measure of the time-integrated circulation. This is not necessarily well represented by the monthly mean sea-level fields of BRAN. However, provided the variability of the circulation over each month is not too large, this comparison provides an independent assessment of the reanalysed circulation. Note that data from the surface drifting buoys are not assimilated into BRAN. In general there is good agreement between the drifter trajectories and the sea-level contours, indicating that there is independent agreement between the reanalysed and observed circulation. This comparison demonstrates that an ensemble-based system, developed under Bluelink, does a good job of constraining an eddy-resolving ocean general circulation model and reproduces realistic ocean variability.

Other recent developments under the Bluelink project include the performance and evaluation of a new BRAN experiment. Improvements to the latest reanalysis include a modified initialisation scheme, the adoption of a new ensemble, and the assimilation of additional sources of observations, including multiple sources of sea-surface temperature. Another important development under Bluelink, is the development of a new global model that has $1/10^{th}$ degree resolution between the latitudes of 75^{o}S and 75^{o}N. This new model will form the basis of Australia's next operational short-range ocean forecast system (Brassington et al. 2007) and will be used in future BRAN experiments.

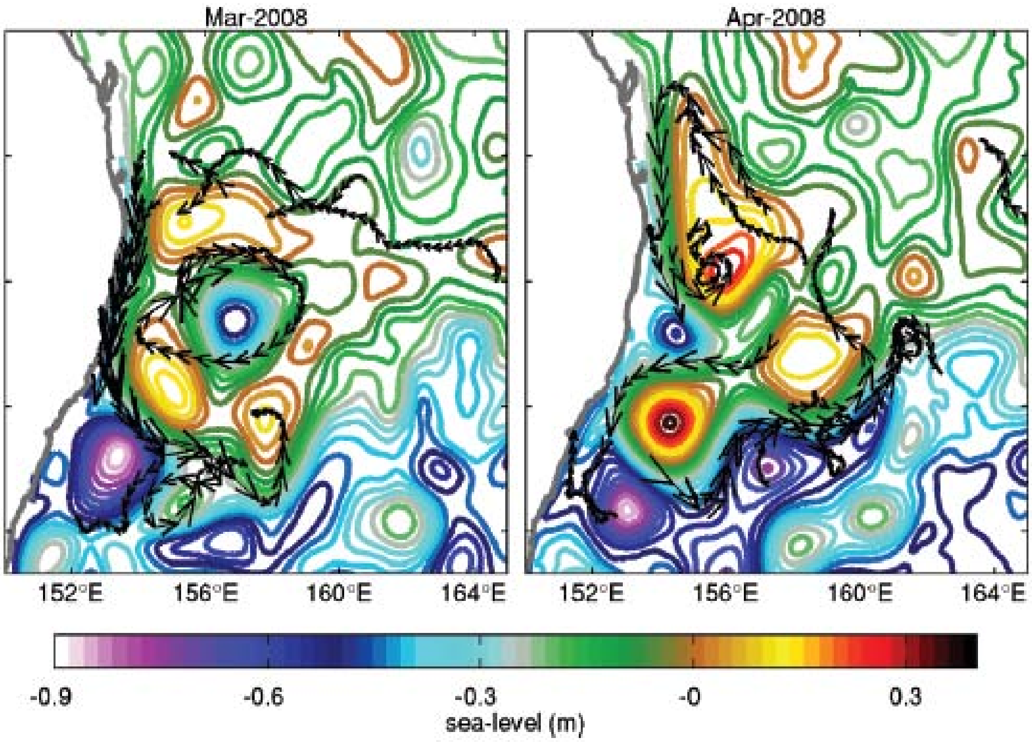

Figure 3: Monthly mean sea-level from the Bluelink ReANalysis (BRAN, version 2p2; Oke and Griffin 2010) with surface drifter velocities overlaid (Adapted from Oke et al. 2010). [Figure showing good agreement between the Bluelink system and independent observations.]

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