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 inter annual 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 north-west 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.

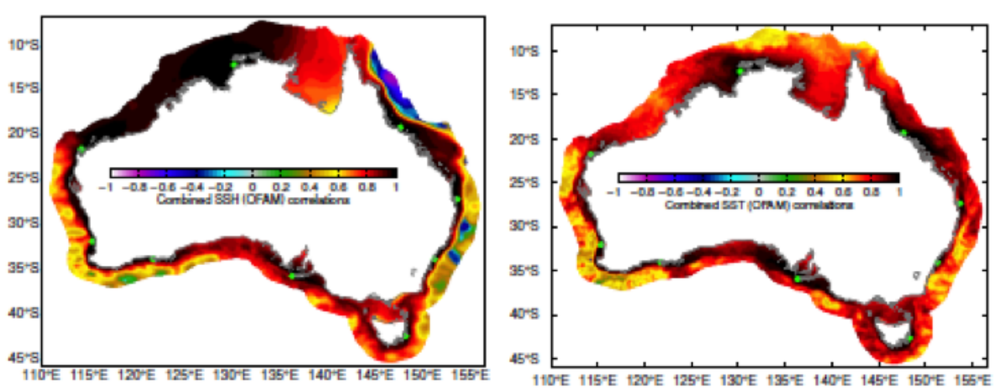

Figure 1: Combined correlation maps for interannual SSH (left) and interannual SST (right) from OFAM2. The location of each NRS is marked with a green bullet [8].

Table 1: 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].

	Percentage area	
	Shelf (< 200 m)	Full domain
	>0.8	>0.8
Intraseasonal SST	12 (15)	7 (8)
Interannual SST	68 (87)	55 (70)
Intraseasonal SSH	28 (37)	16 (24)
Interannual SSH	81 (83)	60 (64)
Intraseasonal surface velocity	21 (36)	17 (27)
Interannual surface velocity	19 (34)	11 (21)

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.

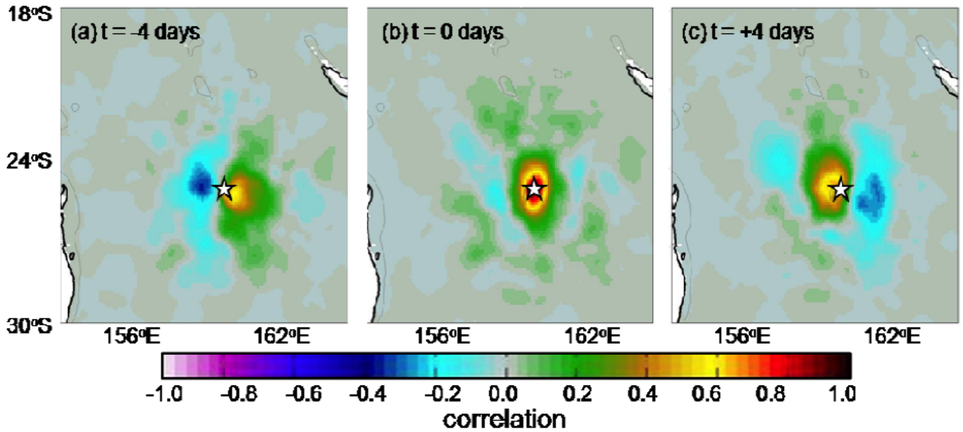

Figure 2: An example of four-dimensional ensemble-based correlation fields showing the spatio-temporal influence of a sea-level observation in the open ocean, south-west of New Caledonia. Each panel shows the ensemble-based correlations between sea-level at t = 0 days and sea-level in the surrounding 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 with-hold 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.

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