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Assessing the footprint of a regional ocean observing system

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ABSTRACT

We define the footprint of an ocean observation as the region that is well correlated to the observed variable at zero time-lag. The footprint of observations from an observation array provides an indication of the region that is effectively monitored by that array. This study examines the footprint of moorings that underpin the Australian Integrated Marine Observing System (IMOS). Based on sea-surface height, temperature, and velocity from a 17-year model run, we quantify the footprint of existing moorings to identify the extent to which the shelf circulation is likely to be represented by those moorings. We find that in combination, the nine long-term National Reference Stations (NRSs) effectively monitor, with a correlation of >0.8, the interannual (intraseasonal) variability of the shelf circulation in about 80% (30%) of the region around Australia. The 28 additional IMOS moorings expand the combined footprint for intraseasonal variability to cover up to 70%. We identify several gaps in the observing system that could be filled by additional observations, including the regions off the east coast, the central Great Barrier Reef, the Great Australian Bight, parts of the north–west shelf, and the Gulf of Carpentaria.

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1. Introduction

In this study, we quantify the variability of the shelf circulation around Australia, using a model and observations, and attempt to characterise different regions to provide guidance for the design of some components of the Australian Integrated Marine Observing System (IMOS; www.imos.org.au; Hill et al. (2010)). The Australian IMOS is a "distributed set of equipment and data-information services that collectively contribute to meet the needs of marine climate research in Australia". It is the goal of IMOS to facilitate the collection and provision of ocean observations to monitor ocean variability on time-scales of hours to years, on spatial scales of kilometres to thousands of kilometres, in the open ocean, over the continental shelf, and near the coast.

The Blue Water and Climate Node of IMOS includes Argo Australia, deep-water gliders, ocean remote sensing, ship of opportunity, and deep-water moorings. Apart from the deep-water gliders and moorings, the open ocean programmes are well aligned with other international efforts, such as Argo (www.argo.ucsd.edu), GHRSST (www.ghrsst.org), and SOOP (www.jcommops.org/soopip/). As a consequence, the influence of IMOS to modify the design of these observational programmes is limited.

The shelf and coastal components of IMOS include a number of regional mooring arrays, shallow-water gliders, a network of HF radars, and a network of National Reference Stations (NRSs). The IMOS

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network is also enhanced by a network of tide gauges around Australia that is managed by the National Tidal Centre (www.bom.gov.au/ oceanography/). In contrast to the open-ocean components of IMOS, the shelf and coastal observation platforms are flexible, and the specifications of their deployment are largely to be determined by those researchers directly involved in IMOS. In recognition of this opportunity, it is the planning of the shelf and coastal components of IMOS that we seek to contribute to in this study. Specifically, we quantify several aspects of the ocean circulation around Australia that provide insights that may enhance the design of IMOS. We focus our study on the continental shelf and slope regions around Australia (Fig. 1). This study domain is defined as all areas within 220 km of the Australian coast; but it extends to within 440 km of the coast in areas where the depth does not exceed 1000 m (e.g., Gulf of Carpentaria, Great Barrier Reef (GBR)).

An important activity under IMOS is the maintenance of the NRSs. The aim of the NRSs is to "provide the data to examine interactions between major coastal boundary currents and continental shelf ecosystems" (Lynch et al., 2008). This includes nine moorings in shallow water (20–100 m depth) around Australia that are labelled in Fig. 1; and includes three long-term NRSs at Port Hacking, Maria Island, and Rottnest Island, established in 1942, 1944, and 1951 respectively; and six relatively new NRSs, established between 2007 and 2010 (Lynch et al., 2011). The NRSs are intended to provide multi-decadal time series of the physical and biogeochemical properties of Australia's coastal oceans (Lynch et al., 2011). We seek to provide an objective assessment of the existing NRSs for their ability to monitor ocean variability on short time-scales and on climate time-scales. So doing, we wish to identify any specific "gaps" in the NRS network; and where gaps are present

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Fig. 1. The analysis domain used in this study showing the bottom depth, the locations of the national reference stations (NRSs; red dots and labelled), IMOS moorings (white diamonds), coastal tide gauges (black crosses), and key landmarks and regions (labelled in bold).

we suggest how those gaps might best be filled, and with what platforms. We also provide an assessment of the existing regional mooring arrays. At the time of writing, 28 IMOS moorings have been deployed (Fig. 1). We evaluate the extent to which these additional moorings are complimentary, and the extent to which they are complimentary to the long-term NRSs. Where possible, we make constructive recommendations about the design of the regional mooring arrays. Similarly, we seek to identify regions that are most suited to the deployment of different platforms. For example, we wish to provide some guidance about where HF radar arrays may be most suited, and where glider deployments may be most beneficial.

Many methods have been used to undertake observing system design and assessment studies - most of which borrow tools or ideas from data assimilation (Langland, 2005; Oke et al., 2009a; Rabier et al., 2008). Some methods simply analyse results from models to understand various aspects of ocean variability, including signal-to-noise ratios (e.g., Banks and Wood, 2002; Schiller et al., 2004). Other approaches include ensemble-based methods (e.g., Oke et al., 2009b; Sakov and Oke, 2008), including the Ensemble Transform Kalman Filter (ETKF: Bishop et al., 2001; Majumdar et al., 2006), adjoint approaches (e.g., Ancell and Hakim, 2007; Fujii et al., 2008), Kalman filter approaches (e.g., Hirschi et al., 2003), observing system experiments (e.g., Atlas et al., 2001; Oke and Schiller, 2007) and observing system simulation experiments (e.g., Alvarez and Mourre, 2012; Hackert et al., 1998; Morss and Battisti, 2004; Tranchant et al., 2008). One characteristic that all of these methods have in common is that they generally yield a quantitative evaluation of the impact of observations on a specific data assimilating system (e.g., Oke et al., 2009b). The obvious limitation of this is that the designed observing system is unlikely to be "optimal" for other uses. As a result, the likelihood of the designed observing system being implemented is low. Additionally, those methods referred to above typically yield an objective design of an "optimal" observing system with specific guidance. For example, they might conclude that an additional mooring should be deployed at a certain location to measure a specified variable. While this approach is valuable, we expect that a more qualitative approach may be just as valuable. Rather than using a specific data assimilation system to design an observing system that might be "perfect" for that system, we take a more general approach here, with the hope and expectation that the results will be more relevant to a broader community.

This paper is organised as follows. The data sets used in this study are described in Section 2, followed by a series of analyses and discussion in Section 3, and the conclusions in Section 4.

2. Data sets

We use three different data sets in our analysis that include 13 years of composite satellite sea surface temperature (SST) maps on a $1/5^{\circ}$ grid; 13 years of gridded sea-surface height (SSH) from altimetry on a $1/5^{\circ}$ grid; and daily averaged temperature, velocity and SSH from a 17-year model run on a $1/10^{\circ}$ grid. The details of these data sets are described below.

For each data set, we remove a linear trend and filter each time series to isolate intraseasonal and interannual time-scales. We define the intraseasonal signal to correspond to variability on time-scales of less than 60 days, and isolate this signal by applying a high-pass filter to each time series, using a 60-day cut-off. Before performing the analyses presented in this paper, we compared a selection of results using a 30-day, 60-day, and 90-day cut-off, and found the results to be insensitive to this choice. Similarly, we define the interannual signal to correspond to variability on time-scales that are longer than 14-months. We generate each interannual time-series by applying a simple low-pass filter with a 14-month cut-off. We recognise that the 13-17 year time-series does not represent all of the variability of interest - namely the decadal and longer variability. To better understand the decadal and longer time-scales, a longer data set is required. However, we do not have access to any data sets that have sufficient spatial resolution - though the Earth Simulator, described by Masumoto et al. (2004) and Sasaki et al. (2008), may be a viable option.

We expect intraseasonal variability to have short correlation lengthscales — representing mesoscale circulation, and circulation features that are driven by weather. By contrast, we expect interannual variability to have longer correlation length-scales that include climate-scale variability associated with phenomena like El Nino, the Indian Ocean Dipole, and the Southern Annular mode. As a result, we anticipate that the observational requirements for resolving intraseasonal and interannual variability are likely to be different.

The observations that can be made from the platforms of interest here (e.g., gliders, moorings, HF radar) include surface velocity, bottom pressure, temperature, salinity, and velocity over the water column. All of the moorings at the locations considered here monitor temperature and velocity over the water column (Lynch et al., 2011), and all could be equipped with accurate bottom pressure sensors. In this study, we focus our analysis on SSH, SST, and velocity at 2.5-m depth (here-after near-surface velocity) that is the mid-depth of the model surface grid cell. This allows us to compare many of our model-based results to observational estimates. So doing, we provide an evaluation of the variability and co-variability in the model. We anticipate that much of the guidance and insight that we can extract from analyses of SSH, SST, and near-surface velocity will be relevant to other variables (e.g., near-surface temperature and velocity; and bottom pressure). We therefore consider our analyses to be relevant to the NRS network and the IMOS mooring network.

2.1. SST maps

The SST maps used in this study are processed at CSIRO Marine and Atmospheric Research (CMAR), are on a $1/5^{\circ}$ grid (~14-22 km × 22 km), with a single map for every day between January 1993 and June 2005. Each map is a mix of 7-day and 3-day average SST from AMSR-E, and 10-day composite from AVHRR satellites. The SST maps are themselves a composite of the above-mentioned SST products not an analysis. That is, the observations are not gridded using any form of objective analysis. Rather, observations within each grid cell are simply selected from the most accurate source available. For example, for a given grid point, if an error-free estimate of SST is available from a 10-day composite map, then it is used. The 10-day composite map itself is a composite of raw SST data from individual AVHRR swaths — taking the 65th percentile of all available SST observations within each grid cell over a 10-day window. In the absence of an observation from the 10-day composite map, a 3-day average is used from AMSR-E. In the absence of a 3-day average from AMSR-E, a 7-day average is used. This approach yields a near-complete map for every day. Maps of the SST fields used here are archived on www.cmar.csiro.au/remotesensing/oceancurrents/.

2.2. SSH maps

The gridded SSH maps used in this study are processed at CMAR, and are on a $1/5^{\circ}$ grid (~14–22 km×22 km), with a single map for every four days between January 1993 and December 2005. Gridded SSH maps are produced by applying an optimal interpolation algorithm to along-track SSH observations from all available satellite altimeters, and coastal tide gauges from around Australia. Both the long-term mean and isostatic response of the ocean to atmospheric pressure forcing are subtracted from each map. Details of the gridding process are described by Deng et al. (2010). Maps of the SSH fields used here are archived on www.cmar.csiro.au/remotesensing/oceancurrents/.

Note that no altimeter observations are used in water that is shallower than 200-m depth (marked by the transition from pink to blue in Fig. 1). This is because altimetric observations over the shelf have large errors associated with errors with the correction for tides. However, the gridded SSH fields used here include variability that is observed at the coastal tide gauge stations around Australia (denoted in Fig. 1; www.cmar.csiro.au/remotesensing/oceancurrents/datasources. htm). In practice, tidal-averaged, isostatically corrected SSH observations from the coastal tide gauges are interpolated onto a one-dimensional grid that follows the Australian coastline. The interpolated coastal SSH is then combined with altimeter observations of SSH to provide gridded SSH across the continental shelf (Deng et al., 2010). As a result, the SSH maps used here are expected to have larger errors over wide continental shelves and in data sparse regions — specifically in the Gulf of Carpentaria, the north–west (NW) shelf off Australia, and the GBR.

2.3. Model

We use results from the Ocean Forecasting Australia Model (OFAM; Schiller et al., 2008); and specifically data from version 6p8 of the spinup run (without data assimilation) that spans January 1992 to December 2008 (www.cmar.csiro.au/staff/oke/BRAN.htm). OFAM has 1/10° grid spacing around Australia (~8–11 km×11 km), 51 vertical levels, with 5-m resolution down to 40-m depth, and 10-m vertical resolution to 200-m depth. The topography for OFAM is a composite from Smith and Sandwell (1997), and other local sources. OFAM is forced with 1.5° resolution, 6-hourly surface heat, freshwater, and momentum fluxes from ERA-interim (Dee and Uppala, 2009). The model forcing includes seasonal river forcing from climatology, and relaxation to observed SST (though not exactly the same SST data set described in Section 2). The SST relaxation is applied as a surface heat flux that depends on the difference between the modelled and observed SST, and on the climatological mixed layer depth, with stronger restoring over shallower mixed layers. OFAM is based on version 4p1 of the Modular Ocean Model (Griffies et al., 2004), using the hybrid mixed layer model described by Chen et al. (1994). The explicit horizontal diffusion is zero. Horizontal viscosity is resolution and state-dependent according to the Smagorinsky viscosity scheme (Griffies and Hallberg, 2000).

2.4. Data limitations

OFAM has been used for several ocean reanalyses (e.g., Oke et al., 2005, 2008; Schiller et al., 2008), for a series of studies to understand

ocean dynamics and ocean variability around Australia (e.g., Oke and Griffin, 2011; Schiller et al., 2009), and has underpinned Australia's short-range ocean forecast system that has run operationally at the BoM since September 2007 (www.bom.gov.au/oceanography/ forecasts/). When OFAM is run in free model, without data assimilation, coastal sea-level at tide-gauge stations is within about 7 cm of observations off South Australia, where the standard deviation of sea-level is large (~16 cm), and within 4-6 cm elsewhere around Australia, where the standard deviation of sea-level is between 8 and 13 cm (e.g., Oke and Griffin, 2011; Oke et al., 2008). In reanalysis mode, OFAM has been shown to realistically reproduce the mesoscale ocean circulation. Specifically, in the region around Australia reanalysed model fields are typically within 6-12 cm of withheld altimetric observations, within 0.5-0.9 °C of observed SST, and within 4-7 cm of observed coastal sea-level. Comparisons with Argo profiles and surface drifting buoys show that reanalysed OFAM fields are within 1 °C of observed subsurface temperature, within 0.15 psu of observed sub-surface salinity, and within 0.2 m/s of near-surface currents tepOke-2008-OM. Phenomena that OFAM has successfully reproduced include eddy formation and evolution (e.g., Oke and Griffin, 2011), drifter trajectories in the Tasman Sea (e.g., Brassington et al., 2011), and locally-forced and remotelyforced temperature fluctuations on the GBR (e.g., Schiller et al., 2009). Chiswell and Rickard (2008) showed that although the Eularian spectra of velocities in OFAM compare well to observations, the model underrepresents short-wavelength eddies - probably due to excessive horizontal mixing in the model. Another weakness of OFAM is the implementation of the surface heat flux. To date, all versions of OFAM have been forced with prescribed surface fluxes (rather than a bulk flux). This has caused some problems in shallow water, where excess heating and excess evaporation have occurred. This aspect of OFAM has also resulted in a moderate warm bias, with model temperatures of up to one degree warmer than observations.

As stated in Section 2, gridded SSH fields from altimetry have relatively large errors in shallow water. By combining altimeter data with coastal tide gauges as described by Deng et al. (2010), the impact of this over the shelf is reduced — but these data must be treated with caution in shallow water. In this study, we restrict our use of the observations to evaluate the relevant fields in the model — including the model standard deviations and correlation footprints. Most of our analysis is based on model fields.

Many coastal processes vary on scales of a few kilometres (e.g., upwelling, filaments, fronts). These processes are not resolved by the data sets we use here. Moreover, for a given variable each data set is characterised by a minimum correlation length-scale that is set by the resolution of the grid used and either the details of the mapping algorithm (e.g., assumed length-scales) or the model configuration (e.g., horizontal mixing). This minimum length-scale limits the ability of each data set to represent the small-scale processes of the ocean that are close to the grid-resolution. We approximate the minimum correlation length-scale for each variable in each data set in Fig. 2, where we show spatial correlation functions for each variable used in our analysis. Specifically, we show the correlation of each variable at a reference location, with the same variable elsewhere, for a random sample of 1000 reference locations in the domain of interest (Fig. 1). We include results from the observed and modelled intraseasonal SST and SSH, and the modelled intraseasonal near-surface velocity. Using a cut-off correlation of 0.6, we conclude that the minimum correlation length-scale for the observed SSH is about 40 km (~3 grid points); for the observed SST it is about 20 km (~1 grid point); for the modelled SSH it is 25-30 km (~2-3 grid points); for the modelled SST it is about 15–20 km (~2 grid points); and for the modelled near-surface velocity it is about 20-25 km (~2-3 grid points). This indicates that our analysis is unable to discriminate between observation locations that are within these distances of each other. The variability of interest - that is resolved by the data sets used here – includes the broad-scale (>40 km) wind-driven



Fig. 2. Spatial correlation functions for intraseasonal (a, c) SSH, (b,d) SST from observations (a, b) and the model (c, d); and (e) intraseasonal near-surface velocity. Each panel shows the correlation of each variable at a reference location with the same variable elsewhere, for a random sample of 1000 reference points. Correlation functions are plotted as a function of separation distance. The magnitude of the complex correlation is shown for velocity.

ocean circulation, the mesoscale circulation, and the alongshore transport of volume and heat over the continental shelf and slope, on both intraseasonal and interannual time-scales.

2.5. Example fields

An example of the types of features present in the model-based and observation-based data sets is presented in Fig. 3, showing the SST anomalies from a seasonal climatology and the SSH anomalies from a long-term mean. We show results from the model without data assimilation (Fig. 3a,d) and with data assimilation (Fig. 3b,e; using the latest version of the Bluelink ReANAlysis, BRAN; Oke et al., 2008). This figure is intended to demonstrate the types of phenomena represented in the model and observations we use in this study. It is also intended to demonstrate that the model produces realistic variability in the region of interest. We note that there is generally good



Fig. 3. Example of SST anomaly from the (a) model without data assimilation, (b) the model with data assimilation (BRAN; see Oke et al., 2008), and (c) observations; and SSH anomaly from the (d) model without data assimilation, (e) the model with data assimilation (BRAN), and (f) observations, for 11 February 2008. SST anomalies are from a seasonal climatology, and SSH anomalies are from a long-term mean. The 200 m isobath is denoted by the thin black contour. The areas shallower than 150-m depth in panel (f), where the SSH observations are unreliable, are denoted by black crosses.

agreement between the modelled and observed fields. A comprehensive evaluation of the model is published elsewhere (e.g., Oke et al., 2005, 2008).

In the examples shown in Fig. 3, there is evidence of wind-driven upwelling off the Bonney coast and a cold-core eddy encroachment near Port Hacking (34° S; denoted in Fig. 1). There is also local warm (e.g., GBR) and cold (e.g., 33° S) anomalies over the shelf. Although upwelling is not well resolved by either the 14–22 km resolution observational fields or the 8–11 km resolution model, the shelf-scale impact of the upwelling is evident in both the model and the observations (particularly Fig. 3b,c). Additionally, SST variability over the shelf and slope that is associated with the broader shelf circulation, including eddies, meanders, wind-driven flow is also adequately represented by the SST database. By contrast, processes that are out of scope for this

study, like upwelling filaments, fronts, and sub-mesoscale eddies are not well represented here — although, consistent with the analysis in Section 4, the model shows variability on finer scales than the observations (particularly for SST), owing to the higher spatial resolution.

We note that it is possible that the method of combining data from multiple satellites may result in the observed SST fields that are noisier than reality. There is some evidence of this in Fig. 3c over the GBR (see the warm pixels), offshore of the 200 m isobath around 14° S (see the cold bullet), and in other locations (e.g., Bass Strait, Sydney) where isolated cold or warm pixels are evident.

The SSH anomalies shown in Fig. 3d–f, show large amplitude coldand warm-core eddies adjacent to the shelf. The variability over the shelf that is reproduced by combining the altimetry with the coastal tide gauge observations (denoted in Fig. 1) is also evident — including the low SSH associated with the Bonney coast wind-driven upwelling and the encroachment of a cold-core eddy near Sydney. However, the limitations of the altimeter-based SSH fields are also evident in Fig. 3. We note the contrast between the model and the observations in the Gulf of Carpentaria. In this case the high SSH anomaly in the model is the "set-up" of sea-level due to the strong, persistent westerly winds. This feature is not evident in the observed SSH anomalies. Clearly, the altimeter-based SSH fields are unrealistic in this region of shallow water.

3. Analysis and discussion

3.1. Variability

An important consideration in the design or assessment of any observing system is the signal-to-noise ratio. Observations should be made in locations where the signal that we seek to observe is large compared to the expected "noise" of the observations (where "noise" refers to the signals that may obscure that which we are interested in). This concept is most relevant for observation platforms that are sparse in time (e.g., gliders, XBT or CTD transects), or for observation platforms that might yield observations with large or poorly understood errors (Laws et al., 2010, e.g., HF radar). Suppose a glider is deployed, or a ship-board survey conducted, in some region once every 2 or 3 months, with the intention of monitoring the interannual variability. This approach is commonly used in combination with time series measurements from a mooring array. In this case, the intraseasonal variability that is not properly resolved by the glider or ship-board observations can be considered noise. It is beneficial, in this case, to make observations in locations where the interannual signal is large, but where the intraseasonal signal is small. To obtain an overview of the relevant fields here, we analyse estimates of the standard deviation of SSH, SST, and near-surface velocity on intraseasonal and interannual time-scales below.

Maps of the standard deviation of SST on intraseasonal and interannual time-scales are shown in Fig. 4. These include estimates from the model (labelled OFAM) and from observations (labelled Obs). Consider first the intraseasonal SST (Fig. 4a–b). In this case, it is clear that in most of the analysis domain, the observed variability is greater than the modelled variability. This could be because of the sampling issues in the observations that are referred to in Section 2, and/or because the resolution of the surface forcing applied to the model is coarse (1.5° resolution). Despite the quantitative differences, the regions of relatively high variability in the observed and modelled fields correspond well. For example, both the observed and modelled fields show maxima off south–west Australia, off south–east Australia, and off southern Tasmania; and both products show low variability in the Great Australian Bight (GAB), Bass Strait, and off much of northern Australia.

Consider now the interannual SST (Fig. 4c–d). There is generally good agreement between the modelled and observed estimates of the standard deviation of interannual SST. The main difference is the higher modelled variability adjacent to the coast over the north–west shelf, in the Gulf of Carpentaria, and over the GBR. We attribute the differences



Fig. 4. Standard deviation of SST from OFAM (a, c) and observations (b, d) on intraseasonal time-scales (a, b) and interannual time-scales (c, d).

adjacent to the coast to differences in resolution — the model better resolves the coastal processes. However, we also note that errors in the heat fluxes applied to the model have the greatest effect in shallow water — so this may also explain the different estimates.

The implications of the results in Fig. 4 suggest that appropriate regions to monitor interannual SST over the continental shelf with an observation platform that is not continuous in time is off the GBR and off south–east Australia, between about 33° S and the southern tip of Tasmania. In those regions, the magnitude of the interannual signal is about twice as large as the intraseasonal variability.

Maps of the standard deviation of SSH on intraseasonal and interannual time-scales are shown in Fig. 5. The magnitudes of the intraseasonal SSH variability in the model and in the observations (Fig. 5a-b) compare well. The most notable exception is off south-eastern Australia, between 37° S and 29° S off the shelf, where the observed standard deviation is 6–7 cm greater than the modelled standard deviation suggesting that perhaps the model's depiction of the mesoscale variability is too weak. The model also shows high variability in the Gulf of Carpentaria that we attribute to wind-driven flow in response to variability in the trade winds. The observed SSH fields in the Gulf of Carpentaria are unreliable because of the lack of reliable altimeter data there, as described in Section 2.

The standard deviation of the interannual SSH (Fig. 5c–d) in the model and observations are quite similar. The only exceptions to this, where there are significant differences between the observed and modelled estimates, include a region of southern Australia adjacent to the coast, between about 125° E and 140° E and in the Gulf of Carpentaria. In both of these cases, the model estimate is higher than the observed estimate. We attribute the differences in the Gulf of

Carpentaria to limitations in the observation-based product (as discussed above), and we attribute the high variability in interannual SSH in the model to the impact of the trade winds. We attribute the differences off southern Australia to differences in the horizontal resolution. Recall that the model resolution is twice as fine as the resolution of the gridded observations. There are also differences in the details of the variability of interannual SSH off south-eastern Australia, where the model has a maxima in variability over a smaller region than the observations. In both the model-based and observation-based fields, the locations of the relatively high SSH variability correspond well, with maxima immediately offshore of the continental shelf off south-eastern Australia that correspond to the mesoscale variability of the East Australian Current (EAC). High interannual variability is also evident in patches off south-west Western Australia (SW WA) that may be related to changes in the level of activity associated with mesoscale eddies that spawn from the Leeuwin Current system (Waite et al., 2007).

The implications of the results in Fig. 5 suggest that the best region around Australia to monitor interannual SSH (or similarly, bottom pressure) over the continental shelf with an observation platform that is not continuous in time is off WA, between about Darwin and Perth (near the Rottnest Island NRS; see Fig. 1). In that region, the magnitude of the interannual signal is two or three times greater than the intraseasonal variability. This indicates that observation platforms that are spatially-resolving, but are sparse in time (e.g., gliders or ship-board surveys) are suitable for monitoring interannual variability off North–West (NW) Australia. This also indicates that the XBT line (IX1) that runs approximately between Fremantle (near the Rottnest Island NRS) and Sundra Strait (~105° E, 7° S) is well suited to monitor interannual variability.



Fig. 5. As for Fig. 4, except for SSH. The areas shallower than 150-m depth in panels b and d, where the SSH fields are unreliable, are denoted by white crosses.

Conversely, off southern Australia the interannual SSH variability over the shelf is much smaller than the intraseasonal variability (Fig. 5). In that region, the use of an observation platform that is sparse in time (e.g., quarterly glider surveys in the absence of other platforms) may be inappropriate for monitoring interannual variability.

The standard deviation of the intraseasonal and interannual nearsurface velocity from the model is presented in Fig. 6. These maps indicate that the near-surface velocity is dominated by intraseasonal variability. In all regions around Australia, the variability of the intraseasonal near-surface velocity exceeds the interannual near-surface velocity. This is not surprising because the ocean surface is driven directly by the surface winds and this directly impacts the surface velocities. This implies that monitoring near-surface velocity with sampling that is sparse in time (e.g., isolated quarterly ship-board ADCP surveys) is not a suitable approach for monitoring interannual variability. Such sampling strategies are not typical, apart from glider-based velocity surveys. The observation platforms that are most relevant to this analysis are HF radars or moorings that measure velocity. Because both HF radars and moorings typically sample for extended periods of time, the timeseries can readily be filtered to exclude the intraseasonal signals and isolate the interannual variability. However, the results in Fig. 6 do provide some guidance for HF radar deployments. We note that the errors in HF radar data are relatively poorly understood (Laws et al., 2010). Consideration of the standard deviation of intraseasonal nearsurface velocities (Fig. 6a-b) provides a target for the accuracy of HF radar observations. If the errors in HF radar data exceed the intraseasonal signal, then the usefulness of the observations is reduced. Therefore, the deployment of HF radar arrays in regions where the intraseasonal variability is large is warranted. Such regions include the east coast of Australia, south of about 25° S, and the Leeuwin current region off WA, south of about 22° S.

3.2. Correlation fields

The *footprint* of a hypothetical observation is an informative metric for the design or assessment of an observing system. In any given region, the ocean tends to be spatially correlated. That is, the temperature fluctuations at a given location vary with temperature fluctuations in the surrounding region. In some regions, the distance over which such fluctuations are correlated can be quite large. For example, in the tropics, where SST variability in the open ocean might be dominated by the surface heat flux, SST fluctuations are likely to be correlated over long distances. In this case, we might describe such an observation as having a *large footprint*. By contrast, in regions of strong mesoscale variability, or in regions where a coastline or topography interrupts the circulation, a variable might be relatively uncorrelated with the circulation around it. In this case, the correlation lengthscales are short – and we might describe such an observation as having a *small footprint*. Regions where the footprints of observations are large generally require only a sparse observation array to monitor the variability over a broad region. By contrast, regions where the footprints are small generally require a dense observation array to monitor the variability over a broad region that might include spatially-resolving observation platform (e.g., gliders or HF radar). We can readily quantify the footprint of a hypothetical observation by computing the correlation



Fig. 6. Standard deviation of zonal near-surface velocity (SSU; a, c) and meridional near-surface velocity (SSV; b, d) from the model on intraseasonal time-scales (a, b) and interannual time-scales (c, d).

between the variable at a given location, with the variable elsewhere. We present a series of examples below.

In undertaking this analysis, we have computed an extensive set of correlation maps for reference locations (existing or potential observations) about every 50 km around Australia for multiple variables. This is too much information to display in a single publication, so we have chosen to present some selected examples that we find instructive and relevant to the Australian IMOS. It is our intention to make the complete database of correlation maps publicly available so that they can be "mined" by the broader community and decision makers.

An example of a location with a large footprint is the site of the Darwin NRS. A series of correlation maps for SSH (a proxy for bottom pressure), SST, and near-surface velocity, using model fields, are shown for interannual and intraseasonal time-scales in Fig. 7. For interannual SSH, for example, the correlation map (Fig. 7a) is simply the correlation between interannual SSH at the reference location (denoted by the green bullet) and interannual SSH at each point in the analysis domain.



Fig. 7. Examples of model-based correlation maps for the NRS off Darwin showing correlations for interannual (a, c, e) and intraseasonal (b, d, f) SSH (a, b), SST (c, d), and near-surface velocity (e, f).

In computing these fields, care has been taken to ensure that there is no linear trend in the time series being used — such a trend artificially inflates the correlation, giving misleading results. Generally, the examples in Fig. 7 show that the interannual correlations tend to have longer length-scales than the intraseasonal length-scales.

Correlation maps for velocity show the magnitude of the complex correlation (or vector correlation) of the velocity vector as described by Kundu (1976). The amplitude of the complex correlation is invariant to the coordinate system, and has a range between 0 and 1. In almost all examples presented in this manuscript, the length-scales for intraseasonal velocity are shorter than the length-scales for interannual SSH. On interannual time-scales, we expect the velocity to be mostly geostrophic. The velocities are therefore expected to be closely related to SSH. In this case, the shorter length-scales for velocity are simply because they scale like the spatial derivative of SSH. On intraseasonal time-scales, this relationship is less clear because the velocities are more ageostrophic.

The correlation map for the reference location off Darwin for interannual SSH (Fig. 7a) shows that variations off Darwin are approximately in phase with variations of SSH over the NW shelf, with correlations over 0.9 and along the shelf break off Western and Southern Australia, with correlations in excess of 0.7. This follows the path of the Leeuwin Current (Ridgway and Condie, 2004) and indicates that the NRS off Darwin is a good location to monitor some aspects of Leeuwin Current variability on interannual time-scales (probably including only coarse metrics like in along-shore transport). By contrast, the footprint of intraseasonal SSH off Darwin (Fig. 7b) shows that on time-scales of less than 60 days the correlation length-scale is a few hundred kilometres. Although this is much shorter than for interannual SSH, it is still a large footprint for these time-scales as we will see in the results that follow. The length-scales for interannual SST (Fig. 7c) and intraseasonal SST (Fig. 7d) are about 500 km and 200 km in the alongshore direction, respectively. Thus, interannual SST off Darwin is well correlated with interannual SST variability in the Gulf of Carpentaria, particularly near the coast, and in Joseph Bonaparte Gulf, south-west of Darwin. The footprint for intraseasonal SST is smaller than interannual SST, but still covers a fairly large region around Darwin and in Joseph Bonaparte Gulf. The footprint for near-surface velocity off Darwin is very similar for interannual and intraseasonal variability (Fig. 7e-f). In both cases, an observation of near-surface velocity at the NRS off Darwin is likely to represent variability over a few hundred kilometres around Darwin. The large footprint for all variables at the NRS off Darwin indicates that the location of the existing mooring is appropriate for monitoring both interannual and intraseasonal variability – and that a single mooring at that location is informative. However, we note that given the broad length-scales in the north, perhaps any location in the general vicinity of Darwin would be equally suitable. By contrast to a single mooring, other platforms, like HF radar and possibly gliders, are likely to be less suitable, as they may over-sample this region and could be better employed to yield more information elsewhere

To assess the suitability of the network of NRSs for monitoring interannual variability around Australia, we show a combined correlation map in Fig. 8, using the nine different correlation fields with reference locations from all NRSs. To construct the combined correlation map in Fig. 8a, we compute the correlation between the interannual



Fig. 8. Combined correlation maps for interannual SSH (a, b) and interannual SST (c, d) from the model (a, c) and observations (b, d). The location of each NRS is marked with a green bullet. The areas shallower than 150-m depth in panel b, where the SSH fields are unreliable, are denoted by white crosses.

SSH at the location of each NRS with interannual SSH elsewhere in the analysis domain. This yields nine separate correlation maps, each like those presented in Fig. 7a. We then identify the maximum absolute correlation for each grid point in the analysis domain from these nine maps. This is intended to identify "gaps", where the variability is uncorrelated with the variability at the observation locations. For a "perfect" network of NRSs, this combined map would yield a map that is entirely black; comprised of ones, indicating that every point in the analysis domain is perfectly correlated with at least one NRS.

The results are shown for interannual SSH and SST from both the model and the observations in Fig. 8. At some locations, the maximum absolute correlation is negative, indicating that the variability at those locations is out of phase with the variability at one or several of the NRSs. The clearest example of this is the negative correlations in both the model and observations for interannual SSH offshore of the GBR. Offshore of the GBR, the dominant processes are different to, and out of phase with, those processes over the reef.

The results shown in Fig. 8 indicate that with the existing network of nine NRSs, the interannual SSH and SST variability around Australia is remarkably well monitored. It was our assumption, at the beginning of this study, that an array of nine moorings around Australia's long coastline would have left many regions effectively unmonitored. The model-based estimates (Fig. 8a,c) and the observation-based estimates (Fig. 8b,d) are in agreement, with the combined correlation fields matching closely in many respects. For example, the spatial extent of the high correlation regions around each NRS is similar in both estimates for both SSH and SST; the regions of relatively low correlation (e.g., for SSH off the shelf in the EAC region and Tasman Sea); and even the region of negative correlation offshore of the GBR match closely.

Although the combined correlation maps presented in Fig. 8 do not explicitly represent the contributions from each individual mooring, some information can be inferred. For example, close inspection of the fields for SST (Fig. 8c-d) show that the lengthscales for SST off eastern Australia (North Stradbroke Island and Port Hacking) are short, and the footprint of observations there is small compared to many of the other NRSs. By contrast, the orientation of each high correlation around each NRS indicates that the lengthscales for SST at all other NRSs are all long in the along-shore direction. The contribution of each individual NRS is difficult to see clearly for SSH, where the correlation is above about 0.9 over most of the shelf region. In some cases, this simple interpretation is complicated by long-distant correlations. For example, the large negative correlations off SW WA in Fig. 8d are due to high negative correlations with the NRS off Darwin; and the large negative correlations offshore of the GBR are also partially related to correlations with the NRS off Darwin (compare Figs. 8a and 7a). These long teleconnections have been noted previously in models and observations on seasonal time-scales (Hendon and Wang, 2010).

Like the NRS off Darwin (Fig. 7), we find that the NRS in the GBR at Yongala, is particularly well positioned for monitoring interannual variability. The high correlations over the GBR in each case presented in Fig. 8 are all attributable to high correlations with Yongala.

Based on the combined correlation maps in Fig. 8 are there any obvious "gaps" in the NRS network for monitoring interannual variability? Clearly, the observations at the NRSs represent variability adjacent to the coast, probably associated with the ocean's response to wind forcing and variability associated with fast-propagating coastal trapped waves. However, the observations from the NRSs don't represent the interannual variability in SSH well off the shelf of southeastern Australia. This is consistent with the results of Vinogradov and Ponte (2011) who noted significant differences between altimetry and coastal tide gauge measurements that they attribute to short spatial structures in coastal sea level at interannual time scales. Vinogradov and Ponte (2011) made specific reference to the measurements off eastern Australia, noting very large differences between coastal sea-level and offshore sea-level. However, we also note that Hill et al. (2008) found a high correlation between interannual temperature at the Maria Island NRS and time-lagged basin-scale winds over the Southern Pacific Ocean.

Another way to quantify the degree to which the NRSs (and IMOS moorings) monitor the circulation is by calculating the percentage of total area that is "effectively monitored". Table 1 shows the percentage of area over the continental shelf (defined as shallower than 200 m depth) and for the entire model domain (Fig. 1) that has a combined correlation of greater than 0.6 or 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. By contrast, Table 1 indicates that the NRSs effectively monitor 28% and 12% of the shelf region for intraseasonal SSH and SST, respectively.

One of the goals of the NRS network is to "monitor major coastal boundary currents" around Australia (Lynch et al., 2008). To gain insight into the extent to which the nine existing NRSs meet this goal, we present combined maximum correlation maps for near-surface velocity from the model on both intraseasonal and interannual timescales in Fig. 9a,c. In this case, we use near-surface velocity to represent transport near the ocean surface. We also present the combined correlation maps for near-surface velocity for the NRSs plus the additional IMOS moorings in Fig. 9b,d. The additional IMOS moorings include 5 extra moorings off South Australia (SA), 6 extra moorings off NSW, 9 extra moorings over the GBR, and 8 extra moorings off SW WA.

Let us first consider the results for the nine NRS locations only for near-surface velocity (Fig. 9a,c). The combined correlation fields for the nine NRSs provide a less optimistic picture than the analyses for interannual SSH and SST in Fig. 8, owing to the shorter lengthscales for velocity. We find that the nine NRSs provide reasonably good coverage for interannual velocity (Fig. 9c), however there are some regions where the interannual near-surface velocity is not monitored by the NRS locations. These regions are approximately mid-way between each of the NRSs, and include the Gulf of Carpentaria, the centre of the NW Shelf, immediately south of NW Cape, southern Australia east of 125° E, and some parts of central eastern Australia. The region off central Eastern Australia is poorly monitored, despite the presence of a NRS off North Stradbroke Island. Similarly, the region off SA is poorly monitored, despite the presence of the Kangaroo Island NRS. Table 1 indicates that the NRSs effectively monitor about 20% of the shelf region for intraseasonal and interannual near-surface velocity.

A detailed impression of the footprint of intraseasonal and interannual near-surface velocity at the North Stradbroke NRS is shown in Fig. 10 (a similar analysis for Kangaroo Island follows below). The stated purpose of the North Stradbroke NRS, established in 2008, is to monitor water quality at the entrance to Moreton Bay and "to observe currents to the west of the EAC" (Lynch et al., 2011). The footprints for both intraseasonal and interannual near-surface velocity are similar (Fig. 10), showing a localised correlation with short decorrelation length-scales. This indicates that a near-surface velocity observation from

Table 1

Percentage of area with a combined correlation of greater than 0.6 or 0.8, for the NRS and the NRS plus the IMOS moorings (in parentheses), based on estimates from the OFAM model.

	Percentage area			
	Shelf (<200 m)		Full domain	
	>0.6	>0.8	>0.6	>0.8
Intraseasonal SST	59 (67)	12 (15)	35 (41)	7 (8)
Interannual SST	98 (100)	68 (87)	93 (96)	55 (70)
Intraseasonal SSH	48 (52)	28 (37)	30 (37)	16 (24)
Interannual SSH	99 (100)	81 (83)	83 (87)	60 (64)
Intraseasonal surface velocity	60 (70)	21 (36)	51 (67)	17 (27)
Interannual surface velocity	65 (77)	19 (34)	44 (60)	11 (21)



Fig. 9. Combined correlation maps for intraseasonal near-surface velocity (a, b) and interannual near-surface velocity(c, d) from the model for all the NRSs (a, c) and for all the NRSs plus the existing IMOS moorings (b, d). The location of each NRS is marked with a green bullet.

a single mooring at this location (say, the upper-most velocity from the ADCP) is not suitable for monitoring the variability associated with the EAC (recall that the original "aim of the NRS network is to provide the data to examine interactions between major coastal boundary currents

and continental shelf ecosystems", Lynch et al. (2008)). A velocity observation at the North Stradbroke NRS only represents the variability at the observation site, and within a few tens of kilometres in the along-shore direction. In this location, a suitable observation strategy for monitoring



Fig. 10. Examples of correlation maps for intraseasonal (a) and interannual (b) near-surface velocity at the North Stradbroke NRS off Brisbane. The location of each reference location is marked with a black bullet.

the EAC, the major boundary current off Australia's east coast, might involve multiple closely spaced moorings, a HF radar array, a fleet of gliders, or a NRS at a different location. We understand that an additional array of moorings is planned for this region.

Let us consider now the results for the nine NRSs, plus the additional IMOS moorings (Fig. 9b,d). Table 1 indicates that the addition of the 28 IMOS moorings to the NRS network increases the percentage of area over the shelf that is effectively monitored (with a correlation of greater than 0.8) by over 70% for near-surface velocity (from 21 to 36%), and by 25–33% for SST and SSH. We explore the enhancements to each region in detail below.

3.2.1. SAIMOS moorings

The stated objective of South Australian IMOS (SAIMOS) activities is to determine the temporal and spatial variability of the shelf and slope currents, including the cross-shelf exchange, off SA; and to understand their connection with, and modulation by, variability in the Southern Ocean, the Leeuwin Current, and the EAC (http://imos. org.au/plans.html; accessed June 2011). The SAIMOS deployments include a mix of moorings, with temperature sensors and ADCPs, gliders, and a HF radar array.

Correlation maps for intraseasonal SSH and intraseasonal nearsurface velocity from the model off the SA coast provide good insights into the variability and observability in that region (Figs. 11 and 12). In this case, we show correlation maps for intraseasonal SSH off SA at the locations of the SAIMOS moorings. These examples include moorings near the coast, moorings near the shelf break, and moorings over the upper slope. Note that the name of each mooring is given in the title to each panel. It is clear that the variability represented by many of these locations are complimentary, and some are somewhat redundant for intraseasonal SSH (though we stress that redundancy in any observing system is essential — to establish robustness during instrument failure or maintenance). Specifically, the shallow moorings all represent the variability adjacent to the coast (Fig. 11b,c,e,g), probably associated with the ocean's response to the wind (Middleton and Bye, 2007); and the shelf and upper-slope moorings (Fig. 11d,f) represent



Fig. 11. Examples of correlation maps for intraseasonal SSH from the model for the SAIMOS moorings, showing the combined correlation map (a) and the correlation maps for each mooring (b–g). The location of each reference location is marked with a green bullet and the name of each mooring location is given in the title of each panel.



Fig. 12. As for Fig. 11, except for intraseasonal near-surface velocity. Recall that correlations for velocity are the magnitude of complex correlations.

variability over the shelf break and along the upper continental slope, probably associated with the Leeuwin Current (Ridgway and Condie, 2004). The length-scales of the intraseasonal SSH extend over several hundred kilometres in the along-shore direction, but over only tens of kilometres in the across-shore direction. We also note that the Deep Slope mooring (Figs. 11f and 12f) and the Canyon mooring (Figs. 11d and 12f) have different footprints to the other moorings. The Investigator Strait mooring (Fig. 12g), although it has only a small footprint for velocity, is the only mooring that represents the velocity variability within Investigator Strait. We conclude that the SAIMOS array appears to capture the dominant intraseasonal SSH variability in the vicinity of the array, as indicated by the extensive region of high correlation in the combined correlation map (Fig. 11a).

3.2.2. NSW IMOS moorings

The stated objectives of NSW IMOS that relate to the physics of the ocean are to investigate the EAC, its strength, separation from the coast, and the resultant eddy field (http://imos.org.au/plans.html; accessed June 2011). NSW IMOS also seeks to monitor Bass Strait outflow and the coastal trapped wave field, and to quantify the impact of the onshore encroachment of the EAC on slope water intrusions, upwelling, downwelling, and internal waves. The "backbone" of the

NSW IMOS deployments include moorings off Coffs Harbour (30° S), the EAC separation zone (32° S; that is yet to be deployed), Sydney (34° S), and southern NSW (37° S). HF radar deployments are also planned for Coffs Harbour and the EAC separation zone. NSW IMOS also maintains monthly biogeochemical sampling off Sydney (Thompson et al., 2009), and 2–3 glider deployments in the Tasman Sea each year (Baird et al., 2011).

Correlation maps for intraseasonal SSH and intraseasonal nearsurface velocity from the model off the NSW coast are shown in Figs. 13 and 14. The NSW IMOS mooring array includes three lines of moorings: two lines with two moorings (off Coffs Harbour and Narooma) and one with three moorings (off Sydney; that includes the Sydney Ocean Reference Station). The cross-shelf moorings include a mooring over the mid-shelf and a mooring near the shelf break. The continental shelf off NSW is narrow, so these moorings are fairly close to each other — within 20 km. Our analysis in Section 4 indicates that this is at the limit of the model resolution for velocity — but is not resolved for SLA. As a result, the footprint of the mid-shelf and shelf-break moorings are similar for intraseasonal SSH, and we cannot confidently distinguish between them. Consequently, we focus our conclusions on the along-shore spacing of the moorings. We find that the NSW IMOS moorings cover most of the shelf along the NSW coast.





Fig. 13. As for Fig. 11 for intraseasonal SSH, except for moorings off NSW.

There is a region of lower correlation around 32° S — particularly in the velocity-based correlations (Fig. 14a), where the EAC separates from the coast (Godfrey et al., 1980) and where an additional line of moorings and a HF radar deployment is planned. Overall, the locations of the NSW IMOS moorings appear to be suitable for monitoring the variability of intraseasonal SSH over the continental shelf between 37° S and 29° S.

One result that is clear from Fig. 13 is that the intraseasonal shelf circulation is not correlated with the circulation offshore. This means that the shelf observations are unlikely to represent the variability offshore. This result is consistent with the findings of Vinogradov and Ponte (2011). We note that other observation platforms, including satellite altimeters that measure SSH and satellite radiometers and microwave sensors that measure SST provide good coverage of the mesoscale variability offshore.

Another result that is clear is that the across-shore length-scales of the circulation are short — and will therefore require multiple moorings to resolve the structure of the circulation. This can be seen by the differences between the footprints of near-surface velocity off Coffs Harbour over the 70-m isobath (Fig. 14b) and the 100-m isobath (Fig. 14c). We note that the mooring over the 100-m isobath will not represent variability in velocity adjacent to the coast. We suspect that the short across-shore length-scale along the NSW coast is a characteristic that is attributable to the narrow jet-like structure of the EAC (e.g., Cresswell, 1994). This result is in contrast to the characteristics off, for example, Darwin, where the projection of an observation at a single point spans much of the continental shelf (Fig. 7).

3.2.3. Q-IMOS GBR moorings

The stated objectives of Q-IMOS that relate to the physics of the ocean include the monitoring of changes in temperature, mixed layer depth, and heat content in the Coral Sea; understanding the relationships between variability in the North Queensland Current and the EAC with climate indices (e.g., ENSO, SOI); and the influence of the EAC on the circulation over the GBR (http://imos.org.au/plans.html; accessed June 2011). The core deployments undertaken by Q-IMOS include moorings, gliders, and HF radars.

Correlation maps for intraseasonal SSH and intraseasonal nearsurface velocity from the model over the GBR are shown in Figs. 15 and 16. The combined correlation map in Figs. 15a and 16a, suggest that together the Q-IMOS moorings could provide good coverage of the intraseasonal SSH and velocity variability over the entire GBR. The most significant gap in the Q-IMOS array is around 16° S, where velocity is not well covered (Fig. 16a). This gap could potentially be filled by





Fig. 14. As for Fig. 11, except for intraseasonal near-surface velocity and for moorings off NSW. Recall that correlations for velocity are the magnitude of complex correlations.

additional observations — perhaps either an addition mooring or two, or a HF radar. Several of the moorings have similar footprints, indicating that there is some redundancy in the mooring array. However, several moorings provide unique, complimentary information. For example, the Lizard Island moorings (Figs. 15e,j and 16e,j) provide the best coverage over the northern GBR; Palm Passage (Figs. 15d and 16d) provides the best coverage over the central GBR; and the Heron Island moorings provide the broadest overall coverage (Fig. 15f,g and 16f,g; note that the model doesn't adequately distinguish between the Heron Island moorings because Heron Island is not properly represented in OFAM; see Section 4).

3.2.4. WA IMOS moorings

The WA IMOS array has been designed to monitor the Leeuwin Current and its influence on the continental shelf environment (http://imos.org.au/plans.html; accessed June 2011). The backbone of WA IMOS includes shelf moorings, gliders, and HF radars.

Correlation maps for intraseasonal SSH and intraseasonal nearsurface velocity from the model off SW WA are shown in Figs. 17 and 18. The WA IMOS mooring array includes a cluster of 8 moorings – 5 moorings at Two Rocks (\sim 31.5°S) across the shelf; and 3 moorings in and around the Perth Canyon. Despite the stated goal of the WA IMOS moorings to monitor the Leeuwin Current, the close spacing of the moorings, spanning a region of roughly 50×50 km, indicates that the array is also intended to monitor the small-scale circulation around the Perth Canyon. The model fields used in this study are only marginally appropriate to discriminate between the different footprints at each mooring, as indicated by the results presented in Section 4 In this case, a higher-resolution regional model is required to properly discriminate between the footprints of each mooring. However, we note that regional models are rarely integrated for a long enough duration (>10 years) to provide rigorous statistics of the variability.

The combined correlation maps in Figs. 17a and 18a indicates that the WA IMOS moorings represent the variability over the continental shelf between about 28° S and Albany (~118° E, 35° S). The moorings over the 50-m, 100-m and 150-m isobath at Two Rocks (Figs. 17b,c,d and 18b,c,d) have similar footprints, representing the variability over the mid-shelf to the north, and in much of the Perth Canyon to the south. By contrast, the moorings over the 200-m and 500-m isobath at Two Rocks (Figs. 17e,f and 18e,f) have shorter decorrelation length-scales compared to the shallower moorings at Two Rocks. The moorings at Perth Canyon (Figs. 17h and 18h) and Perth Canyon South (Figs. 17i and 18i) have



Fig. 15. As for Fig. 11, except for intraseasonal SSH for moorings off Queensland.

similar footprints, representing the intraseasonal variability to the north and south of each mooring, including the variability around the southwestern tip of WA.

Our analysis implies that there is some redundancy in the existing WA IMOS mooring array for measuring the variability of the Leeuwin Current. However, based on the close-spacing of the moorings, it is clear that this array is intended to resolve variability on scales that are smaller than those resolved by the 8–11-km resolution model used here. In this case, a higher-resolution regional model should probably be used to better quantify the footprint of each mooring, as suggested above.



Fig. 16. As for Fig. 11, except for intraseasonal near-surface velocity and for moorings off Queensland. Recall that correlations for velocity are the magnitude of complex correlations.



Fig. 17. As for Fig. 11, except for intraseasonal SSH for moorings off WA.

4. Conclusions

One of the goals of this study is to demonstrate the usefulness of a simple, practical approach to observing system design and assessment. We have achieved this by presenting analyses of the standard deviation of different variables on different time-scales, and by describing a simple approach to estimate the correlation footprint of an observed

variable. We have used a combination of observation-based and model-based fields to demonstrate the versatility of this approach.

Based on comparisons between the standard deviation of the variability on intraseasonal (<60 days) and interannual (>14 months) time-scales, we conclude that regions that are well-suited to monitor interannual variability with non-continuous observation platforms (e.g., gliders, ship-board surveys) are over the GBR, south eastern Australia,





36°S 112°E 114°E 116°E 118°E

E O 0.4

0.3

114°E Fig. 18. As for Fig. 11, except for intraseasonal near-surface velocity for moorings off WA.

116°E

118°E

112°E

between Sydney and the southern tip of Tasmania, and off WA, between Perth and Darwin. We note that several long-term observation programmes have been established in those regions, including the Maria Island and Rottnest Island NRS and the IX1 and PX34 (Sydney-Wellington, New Zealand) XBT line.

114°E

Corr

116°E

118°E

а

28°S

29°S

30°S

31°S

32°S

33°S

34°S

35°S

36°S

d

28°S

29°S

30°S

31°S

32°S

33°S

34°S

35°S

36°S

g 28°S

29°S

30°S

31°S

32°S

33°S

34°S

35°S

36°S

112°E

An important component of Australia's IMOS is the NRS network. The overall aim of the NRS network is to "provide the data to examine interactions between major coastal boundary currents and continental shelf ecosystems, especially in the context of climate change" (Lynch et al., 2008). We find that the existing nine NRSs provide a good representation of the interannual variability in up to 80% of the shelf region around Australia. Of the NRSs, we find that two may not be suitably positioned to monitor velocity associated with coastal boundary currents. Firstly, the North Stradbroke Island NRS appears unlikely to

monitor the EAC, although we note that Lynch et al. (2011) state that this NRS is specifically intended to monitor water quality at the entrance to Moreton Bay. Secondly, Kangaroo Island NRS that is intended to monitor wind-driven circulation, the Leeuwin Current and indirectly, the Flinders Currents (Lynch et al., 2011) may not be well positioned to monitor variability associated with these flows. Based on the analyses presented in this paper, we expect that velocity observations at these moorings may only be representative of velocities in close proximity to each mooring. We therefore recommend that additional analysis of these NRSs be considered, either with higher resolution models (or databases) to more precisely quantify their footprints, or through analysis of the data to evaluate the extent to which they meet their stated goals. Many of the NRSs have a large footprint for velocity – and observations from those mooring locations represent the ocean variability over a broad region around each mooring. The two NRSs with the largest footprint are the moorings off Darwin and Yongala.

We examine the footprint of the individual IMOS moorings that exist off SA, NSW, Queensland, and WA. In general, we find that the locations of individual IMOS moorings are well positioned to monitor the intraseasonal variability that is inadequately monitored by the nine NRSs. We find that each regional array includes moorings that are likely to represent different aspects of the circulation. For example, shallow moorings tend to represent variability adjacent to the coast, and moorings located over the outer shelf or upper slope tend to represent variability in a strip that extends approximately along isobaths. We conclude that the addition of the IMOS moorings expanded the area that is effectively monitored by the mooring network by up to 15%.

We find that there are several gaps in the Australian IMOS for monitoring the variability of intraseasonal velocity around Australia. For example, there is a gap in the observing system off NSW where the EAC separates from the coast, plus a gap off central eastern Australia, between about 29° S and 25° S. We recommend that additional observations be considered for those regions, and note that some IMOS plans include deployment of additional platforms in those regions. Other regional gaps in the observing system that would benefit from additional observations include the central GBR, the Gulf of Carpentaria, the GAB, NW Cape, and the NW shelf. Of these gaps, we expect that the most critical ones, and those that are most readily filled, are those near major population centres that include those identified off Australia's east coast and GBR.

The data sets we use in this study do not resolve all scales that are of interest to the Australian IMOS community, and every product is characterised by a minimum correlation length-scale. As a result, the results of analyses using the approaches outlined in this paper are likely to be dependent on the details of each data set (e.g., resolution, mapping length-scales, model parameterisation etc.). Clearly, every data product has limitations — but we regard the products used here as the most appropriate that are available, given the scope of the study. The limitations of the model and observational products we use here should be taken into account when considering our results and our recommendations.

The next step in the process of designing and assessing the Australian IMOS is to repeat the calculations described in this study with results from a longer model integration (e.g., OFES; Masumoto et al., 2004; Sasaki et al., 2008) and with higher resolution (~1–2 km) regional models, and higher resolution observational products in order to independently evaluate our findings. The major challenge in that task is to identify, or generate, high resolution model runs that are realistic enough and long enough (>10 years) to permit a robust examination of their variability. Another logical step is to conduct a multivariate analysis — either through multivariate correlations, or through a variance reduction analysis, like that of Oke et al. (2009b). The calculations presented here only take into consideration the correlation between likevariables. In practice, information from one variable can provide information about another — this is a common feature of data assimilation systems (e.g., Oke et al., 2008). This can readily be achieved through a

quantitative, variance minimising analysis, like that presented by Sakov and Oke (2008). Such an analysis would also extend the correlation analyses, presented here, to include the variance, and relative errors of different observation platforms. Another possible way forward is to include time-lags in the calculations. In practice, the correlation between the variability at a given location and another location may peak after some time lag that reflects either advection of a signal, or wave propagation — from coastal trapped waves, for example. This could be achieved either by extending the current analysis to include time-lags (an expensive, but probably insightful undertaking), or by exploiting a data assimilation model, where the propagation of information in time and space is accounted for implicitly.

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