THE DEPENDENCE OF SHORT-RANGE OCEAN FORECASTS ON SATELLITE ALTIMETRY

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ABSTRACT

Short-range ocean forecast and reanalysis systems routinely combine observations from satellite altimetry, satellite sea surface temperature (SST), and in situ temperature and salinity, to initialise global and regional ocean models. The most critical observation type for eddy-resolving applications is arguably satellite altimetry. To quantify the impact of satellite altimetry observations on a data assimilating ocean general circulation model we perform a series of Observing System Experiments (OSEs). We perform four OSEs that all assimilate in situ temperature and salinity observations and satellite SST observations. Different OSEs assimilate data from a different number of altimeters, including an OSE using no altimetry data, and data from one, two, and three altimeters. We show that the neglect of altimetry from a data assimilating model increases the model-observation mis-fits in high-variability regions by almost 40%.

1. INTRODUCTION

GODAE OceanView is the successor to GODAE - the Global Ocean Data Assimilation Experiment. One of the goals of GODAE was to demonstrate the feasibility of operational ocean forecasting. This goal has been achieved, with many operational centres now producing daily or weekly short-range ocean forecasts. All of the forecast systems assimilate satellite altimetry observations. The operational ocean forecasting community regards altimeter observations as the most critical observation type for mesoscale ocean initialisation. The purpose of this study is to quantify the importance of satellite altimetry for forecast and reanalysis systems like those developed under GODAE and GODAE OceanView.

To quantify the impact of satellite altimetry observations on a data-assimilation eddy-resolving ocean general circulation model, we perform a series of Observing System Experiments (OSEs). In the OSEs reported here, we systematically with-hold data from one, two, and three altimeters.

The ocean model and data assimilation system we use is the latest version of the Bluelink system, the predecessor of which was described previously [8, 10]. Bluelink represents Australia's contribution to GODAE and GODAE OceanView; and is a partnership between CSIRO, the Bureau of Meteorology, and the Royal Australian Navy. The Bluelink system has been previously used to perform operational ocean forecasts (www.bom.gov.au/oceanography/forecasts/; [1]), and multi-year ocean reanalyses [10, 15]. Output from Bluelink applications has been used to explore ocean dynamics [16, 17, 11], and for other observing system design and assessment [13, 12].

2. MODEL AND DATA ASSIMILATION

2.1. Model

The ocean model used here is a configuration of the GFDL Modular Ocean Model [6] and is called the Ocean Forecasting Australia Model (OFAM). To date, the developments of OFAM, under Bluelink, have focussed on modelling the circulation of the upper ocean in the Australian region. This is reflected in the OFAM grid, with 5 m grid spacings at the ocean surface and 10 m vertical grid spacings over the top 200 m. The horizontal grid spacings are 1/10° in the 90°-sector centred on Australia and south of 16°N, and coarser outside of this region. To accommodate the inhomogeneous resolution, the horizontal viscosity is resolution and state-dependent, based on the Smagorinsky-scheme [5]. The bottom topography for the configuration of OFAM that is used here was constructed from a range of different sources, as documented elsewhere [15]. The turbulence closure model used by OFAM is a version of the hybrid mixed-layer scheme [2], plus implicit tidal mixing [7]. To date, model runs performed using OFAM were forced by six-hourly atmospheric fluxes from ERA-Interim [3].

2.2. Data Assimilation

The data assimilation system used in this study is called the Bluelink Ocean Data Assimilation System (BODAS) [10], and is based on Ensemble Optimal Interpolation (EnOI; [9]). For this study, BODAS is implemented using a 180-member stationary ensemble of intraseasonal model anomalies, obtained from a non-assimilating model run, to quantify the system's background error covariance. For the experiments presented here we assimilate observations every 4 days. For every assimilation step we assimilate observations of in situ temperature and salinity for a 7-day time-window centred on the analysis time (i.e., plus/minus 3 days); satellite sea-surface temperature (SST) from AVHRR (using the 4-km resolution NAVO product) and AMSR-E for a 3-day time-window centred on the analysis time (i.e., plus/minus 1-day); and low-pass filtered, inverse-barometer-corrected sea-level anomaly (SLA) from tide-gauges for the analysis time. In this study, we perform different OSEs using along-track SLA (atSLA) observations from three, two, one, and zero altimeters. Satellite altimetry data used in this study is from the Radar Altimetry Database System (RADS; rads.tudelft.nl/rads/), with tides removed and an inverse-barometer correction applied.

Each OSE is run for thirteen months, spanning February 2008 to March 2009. This corresponding to the period when Jason-1 and Jason-2 were in an interleaved orbit. The first month of each OSE is regarded as a spin-up period, and is not used in the analyses presented in this study. The initial conditions (1 February 2008) for each OSE are identical, and are taken from the end of a 20-year spin-up run with no data assimilation. The OSE with one altimeter uses data from Jason-2 (hereafter J2); the OSE with two altimeters uses data from Jason-1 and Jason-2 (hereafter J1+J2); the OSE with three altimeters uses data from Jason-1, Jason-2 and Envisat (J1+J2+N1).

Data assimilation involves two steps: the calculation of an analysis field, where observations are combined with a model background field; and initialisation, where the model is adjusted to match the analysis. To demonstrate the quality of the analyses produced by BODAS, we present the correlation between atSLA from all available altimeters (J1+J2+N1) and SLA fields (Figure 1) from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) [4]; OceanCurrent - an Australian system that produces daily, multi-mission SLA analyses (ocean current.imos.org.au); and BODAS, using analysed SLA from the OSE using J1+J2+J3. To generate the correlation fields shown in Figure 1 we first interpolate the analysis fields to the atSLA locations for each day between 1 March 2008 and 28 February 2009. We then bin all atSLA model-data differences into 2x2° bins, and compute the correlation for 1 year, yielding a map of correlations. This comparison (Figure 1) shows that the correlation between each analysis product and atSLA is comparable. Each analysis product shows high correlation > 0.8) in regions of strong variability and lower correlation ($\sim$ 0.4-0.6) in regions of low variability (e.g., around New Zealand, Great Australian Bight). In those regions, the magnitude of the SLA signal is comparable to the altimeter error (i.e., a few centimetres).

Both AVISO and OceanCurrent use optimal interpolation to produce analyses of atSLA. By contrast, BODAS uses EnOI to combine a model background field with at-

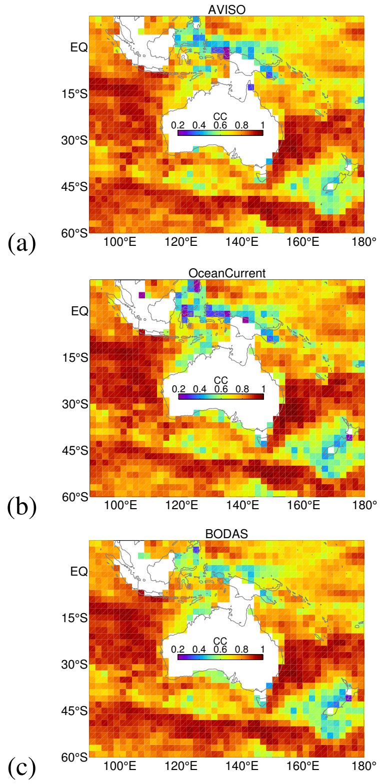

Figure 1. Correlation, computed over 1-year, between atSLA from all available altimeters (J1+J2+N1) and SLA fields from (a) AVISO, (b) OceanCurrent, and (c) BODAS.

SLA, in situ temperature and salinity, and satellite SST to produce analyses of SLA, and three-dimensional fields of temperature, salinity, and velocity. We note that even though BODAS combines multiple data types, the quality of the BODAS analyses for SLA are comparable to the SLA-only analyses.

2.3. Initialisation

As stated above, each OSE assimilates observations every 4 days. For each assimilation cycle, OFAM is integrated for 5 days, with daily mean fields stored for every model day. All fields needed to "seamlessly" initialise the model at the start of day 5 are stored. BODAS then computes an analysis of the entire model state by combining observations with the daily mean field from the last day of the previous model run (i.e., day 5). OFAM is then restarted for the start of day 5, and temperature, salinity, and velocities are then nudged to the analysis for one day using an adaptive nudging scheme [14]. Note that unlike previous versions of the Bluelink ReANalysis [8, 10, 15], we do not explicitly initialise sea-level in the model. We have found that initialising temperature, salinity, and velocities is sufficient to cause the model sea-level to adjust to the sea-level analysis computed by BODAS (but not used).

3. RESULTS

To evaluate the relative performance of each OSE, we compute the mis-fit between the modelled SLA and atSLA from all altimeters. We interpolate the modelled daily-mean SLA to the location of each atSLA and compute the area-averaged correlation and the standard deviation of the model-observation differences (Table 1) for the entire Australian domain (using the domain shown in Figure 1); and for the high-variability regions in the Australian domain, where the standard deviation of SLA exceeds 0.1 m; and for the low-variability regions in the Australian domain, where the standard deviation of SLA is less than or equal to 0.1 m.

The results in Table 1 show that the area-averaged model-observation mis-fit (correlation) for SLA when data from all three altimeters are assimilated is 6.1 cm (0.67). When no altimeter data is used in the assimilation, the model-observation mis-fit (correlation) increases (decreases) to 7.9 cm (0.45). That is, the model-observation mis-fit (correlation) for SLA increases (decreases) by 29.5% (0.22) when no altimeter data are used. Similarly, in the high-variability regions the average model-observation mis-fit (correlation) for SLA increases (decreases) from 8.6 cm (0.75) to 12 cm (0.52) when all altimeter data are withheld, representing an increase (decrease) in the mis-fit (correlation) of 39.5% (0.23).

Maps of the correlation between the modelled and observed SLA for each OSE are shown in Figure 2, using the same approach used to generate Figure 1 that is described in section 2.2. Consistent with the area-averaged statistics presented in Table 1, this analysis demonstrates that the model-observation correlations for SLA increases with the addition of each satellite altimeter. The most significant improvement is made when data from the first altimeter is assimilated. Significant differences between the OSE with no altimeter and the J2 OSE are evident in the eddy-rich regions (e.g., western Tasman Sea; Antarctic Circumpolar Current, ACC) and in the regions of strong seasonal Rossby waves at around 12-15°S. Improvements in the correlation when data from a second and third altimeter are used is also evident in Figure 2, particularly in regions of strong mesoscale vari-

Table 1. Area-averaged Correlation (Corr) and the standard deviation of the difference (StdD; in cm) between SLA in each OSE and atSLA from all altimeters for the whole Australian region (90-180°E, 60°S-10°N); in the high-variability Australian region (> 0.1 m); and the low-variability Australian region (< 0.1 m).

	J1+J2+N1	J1+J2	J2	Zero
Corr	0.67	0.65	0.61	0.45
StdD	6.1	6.3	6.7	7.9
Corr(>0.1m)	0.75	0.73	0.69	0.52
StdD (>0.1m)	8.6	8.9	9.5	12
Corr(>0.1m)	0.64	0.62	0.58	0.43
StdD(<0.1m)	4.5	5.3	5.7	6.7

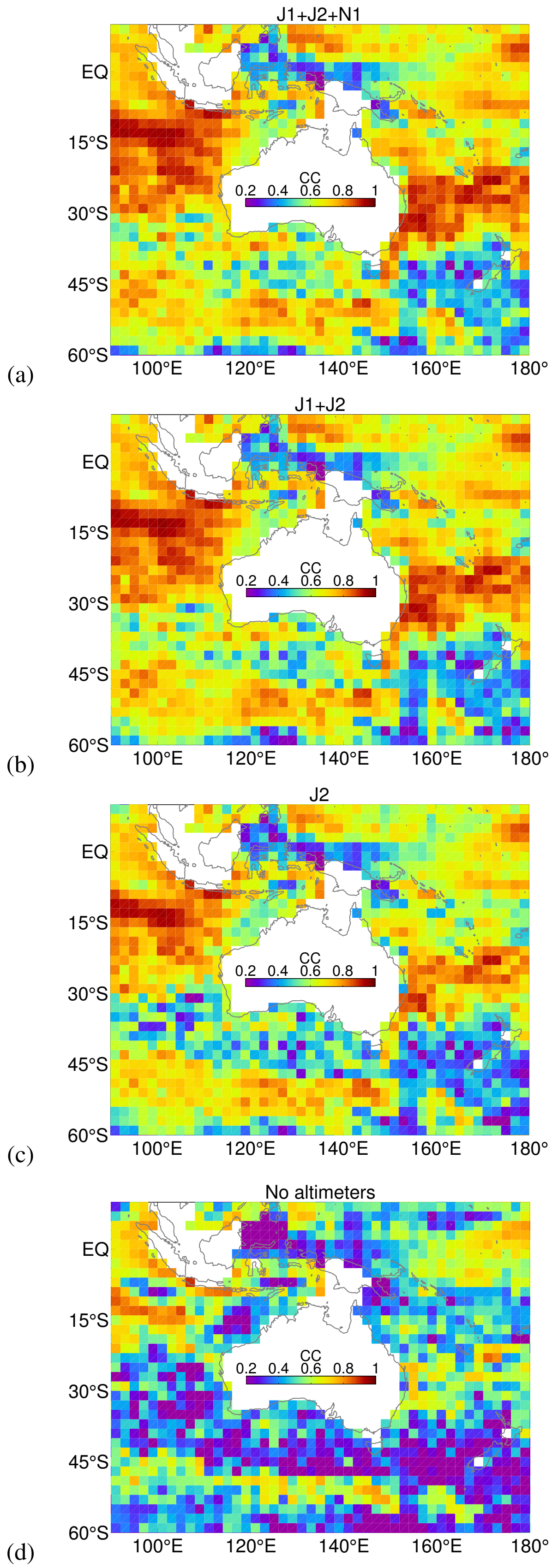

Figure 2. Correlation between modelled and observed SLA for the OSE using data from (a) J1+J2+N1, (b) J1+J2, (c) J2, and (d) no altimeters.

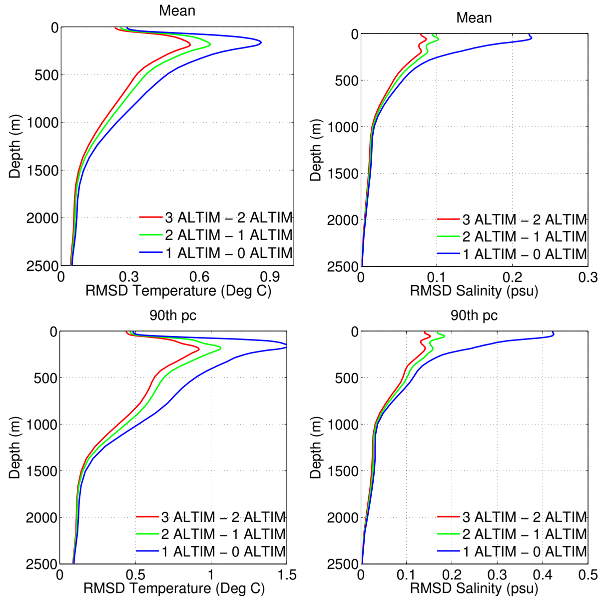

Figure 3. Profiles of the area-averaged (top) and 90th percentile profile of the RMS difference for temperature (left) and salinity (right) between OSEs using zero and 1 altimeter (blue), 1 and 2 altimeters (green), and 2 and 3 altimeters (red).

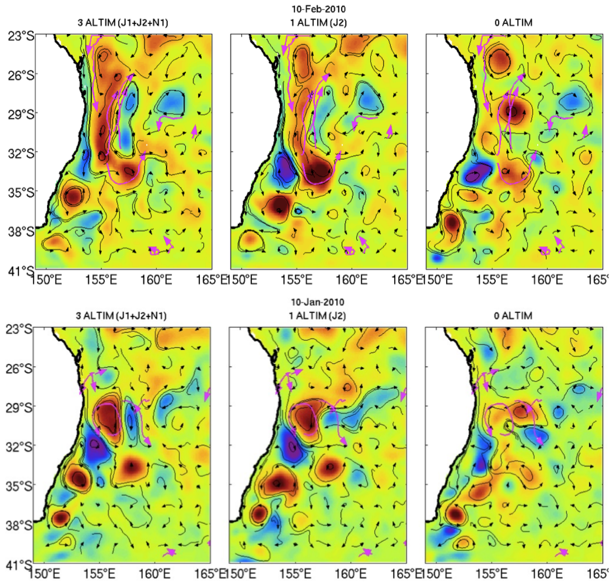

Figure 4. Examples of the modelled SLA with modelled near-surface velocities overlaid (black) from OSEs with 3 altimeters (left), one altimeter (middle) and no altimeters (right); and velocities from surface drifting buoys (pink). The colour axis ranges from -0.6 (purple; corresponding to cyclonic eddies) to 0.6 (red; corresponding to anti-cyclonic eddies), and zero is yellow-green.

ability, including the region off south-west Western Australia, where the Leeuwin Current generates a complex field of eddies.

To quantify the impact of each altimeter on the subsurface temperature (salinity), we compute the area-averaged root-mean-squared (RMS) difference and the $90th$ percentile of the RMS difference between the temperature (salinity) in the OSEs using 1 and zero altimeters; 2 and 1 altimeter; and 3 and 2 altimeters (Figure 3). This analysis shows that with the addition of the first altimeter, the average temperature changes by 0.9°C at 100-200 m depth (Figure 3, top), but by as much at 1.5°C in some locations (Figure 3, bottom). Similarly, with the addition of the first altimeter the salinity average changes by about 0.2 psu at the surface, and by as much as 0.4 psu in some locations (see the $90th$ percentile). The addition of the second and third altimeter also has a significant impact on temperature and salinity, with average RMS differences of 0.5-0.6°C and 0.08-0.1 psu; and extreme changes in excess of 0.9-1°C and 0.15 psu in some locations.

The qualitative impact of assimilating data from a different number of satellite altimeters is shown in Figures 4 and 5. The first thing to note from Figures 4 and 5 is that the modelled circulation in the J1+J2+N1 OSE is consistent with the circulation inferred from the trajectories of the drifting buoys. The degree of qualitative agreement shown in these figures is representative of the full year that the OSEs were performed.

The first example in Figure 4 (top) demonstrates that the OSE with no altimeter data can reproduce some of the mesoscale features evident in the OSE with three altimeters (e.g., anti-cyclonic eddy at 35-36°S). However, the OSE with no altimeter data also reproduces mesoscale features that are not present in the OSE with three altimeters, and that are inconsistent with the trajectories of the surface drifting buoys with drifter trajectories flowing through the middle of eddies (see the strong anti-cyclonic eddy at about 29°S). The first example in Figure 4 also demonstrates that often, the eddy field in the OSE using one altimeter has significant differences from the eddy field in the OSE with three altimeters (see the eddies between 32-35°S west of 160°E). The second example in Figure 4 demonstrate that sometimes, the OSE with only one altimeter produces eddy fields that are very similar to the OSE with three altimeters, indicating that sometimes one altimeter may be sufficient to constrain strong mesoscale variability. However, we note that this sort of inconsistent performance - sometimes working well, and sometimes working poorly - is unacceptable for most applications because a user does not know *a priori* whether the forecast circulation is realistic or not for the time and location of interest to them.

The examples of SLA and surface velocities off southwest Western Australia demonstrate that the OSE with one altimeter sometimes reproduces mesoscale features that are consistent with the OSE with three altimeters (Figure 5, top). However, we note that it is more common for the OSE with one and zero altimeters to reproduce fictitious mesoscale features (e.g., see the strong cyclonic eddy at about 27.5°S) that are not present in the OSE with three altimeters (Figure 5, bottom). Examination of

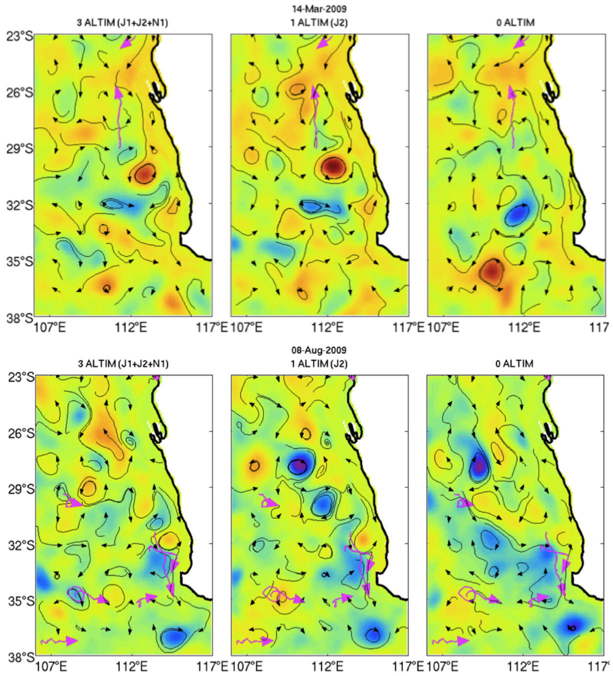

Figure 5. As for Figure 4, except for south-west Western Australia.

the fields shown in Figure 5 for the full year of the OSEs leads to the conclusion that agreement between the modelled circulation using one and three altimeters is uncommon. This indicates that in regions of modest mesoscale variability, one altimeter is not sufficient to constrain an eddy-resolving general circulation model. By contrast, we conclude that three altimeters (at least) are needed to represent the mesoscale variability.

3.1. Conclusions

We perform a series of OSEs for the period March 2008 to February 2009, when Jason-1, -2, and Envisat were returning data and Jason-1 and -2 are in an interleaved orbit. In the OSEs we systematically with-hold data from each satellite altimeter to demonstrated that satellite altimetry is critical for constraining an eddy resolving ocean general circulation model. Focussing our analysis on the 90°-sector around Australia and south of 10°N, where our model has 1/10°-resolution, we show that without satellite altimetry, an eddy-resolving ocean model generates many fictitious eddies. Similarly, we find that when data from only one altimeter is assimilated, the model still generates many fictitious eddies. We find that a single altimeter can sometimes constrain the circulation in regions of strong mesoscale variability, including seasonal Rossby waves at 12-15°S - but often one altimeter is inadequate. We therefore conclude that multiple altimeters are needed to consistently constrain the mesoscale variability in a data-assimilating ocean model. Furthermore, we note that while data from three altimeters appears sufficient for realistically constraining the mesoscale variability on scales resolved by a 1/10°-resolution model, it is not clear how many altimeters are needed to resolve the sub-mesoscale on scales of less than say 30 km. But it appears that three altimeters are likely to be insufficient for such an application.

Through the OSEs presented here, we demonstrate that when all three altimeters are with-held, the model-observation mis-fits for SLA increase by 29.5% and the model-observation correlation for SLA decreases by 0.22. Moreover, we find that the neglect of one altimeter, from a constellation of three altimeters, increases the model-observation mis-fits by about 3.5%; the neglect of a second altimeter increases the model-observation mis-fits by an additional 6.5%, and the neglect of a third altimeter increases the model-observation mis-fits by an additional 19.5%. In regions of strong mesoscale variability, the results are even more striking, with the neglect of three altimeters increasing the model-observation mis-fits by 39.5%. In high-variability regions the neglect of one altimeter, from a constellation of three altimeters, increases the model-observation mis-fit by 3.5%, the neglect of a second altimeter increases the mis-fits by 7%, and the neglect of a third altimeter increases the mis-fit by a further 29%.

We quantify the impact of with-holding each altimeter on the sub-surface temperature and salinity and show that the RMS difference of the sub-surface temperature between the OSEs with zero and 1 altimeter is in excess of 1.5°C, with average differences of 0.9°C. The difference in sub-surface temperature between the OSEs with 1 and 2 altimeters, or 2 and 3 altimeters exceeds 1°C in some locations, with average differences of about 0.5°C. We find that the RMS difference of the sub-surface salinity between the OSEs with zero and 1 altimeter is sometimes over 0.4 psu, with average differences of 0.2 psu; and the difference in sub-surface salinity between the OSEs with 1 and 2 altimeters, or 2 and 3 altimeters can exceed 0.15 psu, with average differences of about 0.08 psu.

We supplement the statistical analysis of our OSEs, reported above, with a series of qualitative comparisons between the modelled near-surface circulation and the circulation inferred from the trajectories of surface drifting buoys. In general, we find that the modelled circulation in the OSE with three altimeters consistently produces mesoscale variability that agrees with the circulation inferred from surface drifting buoys. Further, we show that in regions of strong mesoscale variability (specifically the western Tasman Sea) the OSE with no altimeter data sometimes generates large eddies that are similar to those generated in the OSE with three altimeters. This indicates that observations of SST and in situ temperature and salinity profiles provide some constraint on the eddy field. However, the performance is inconsistent, and it is more common for the eddy fields in the OSE with no altimeter data to be quite different to the OSE with three altimeters. Similarly, we find that the fields in the OSE with one altimeter sometimes closely resembles the fields in the OSE with three altimeters - but again, the performance is inconsistent. By contrast, in regions of weaker mesoscale variability (e.g., off south-west Western Australia), we find that the OSE with zero or one altimeter consistently produce results that differ significantly from the OSE with three altimeters and that do not reflect the circulation inferred from surface drifting buoys.

We have shown that multiple altimeters are needed to constrain the circulation in an eddy-resolving ocean general circulation model. We find that when data from three altimeters are assimilated, a 1/10°-resolution model produces flow fields that are consistent with independent observations. By contrast, when fewer than three altimeters are used, the model sometimes generates realistic circulation, but often generates fictitious eddies.

ACKNOWLEDGMENTS

Funding for this research was provided by CSIRO, through the Wealth from Oceans National Research Flagship, and from the Royal Australian Navy; and from the Office of Naval Research through Grant number N62909-10-1-7068. The authors gratefully acknowledge comments from D. A. Griffin that led to improvements in this study. Satellite altimetry is provided by NASA, NOAA and CNES. SST observations are provided by NOAA (www.nodc.noaa.gov) and Remote Sensing Systems (www.remss.com) and data from surface drifting buoys is provided by NOAA-AOML.

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