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Impact of Argo, SST, and altimeter data on an eddy-resolving ocean reanalysis

Peter R. Oke[1] and Andreas Schiller[1]

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[1] We perform a series of Observing System Experiments (OSEs), where components of the Global Ocean Observing System (GOOS) are systematically withheld from a data assimilating ocean reanalysis. We assess the relative importance of Argo temperature (T) and salinity (S) profiles, sea-surface temperature (SST) and altimetric sea-level anomalies (SLA) for constraining upper-ocean T and S properties and mesoscale variability of SLA in an eddy resolving ocean reanalysis in the Australian region. Each OSE is assessed by comparing modelled fields with assimilated and withheld observations. We show that each observation type brings complementary information to the GOOS, and demonstrate that while there is some redundancy for representing broad-scale circulation, mesoscale circulation requires all observation types to be assimilated. **Citation:** Oke, P. R., and A. Schiller (2007), Impact of Argo, SST, and altimeter data on an eddy-resolving ocean reanalysis, *Geophys. Res. Lett.*, *34*, L19601, doi:10.1029/2007GL031549.

1. Introduction

[2] The past decade has witnessed dramatic advances in our ability to observe the oceans. Prior to the 1990s, ocean observations relied almost exclusively on ship-borne measurements and moored instruments. Today, most ocean observations are gathered by satellite-borne altimeters and radiometers, and by autonomous profiling floats. This advance has dramatically increased our capacity to monitor, forecast and reanalyse the ocean circulation. In this paper, we seek to assess the value of different observation types for constraining upper ocean T and S properties and SLA variability for short-range mesoscale ocean prediction. Specifically, we present results from a series of observing system experiments (OSEs), designed to assess the relative importance of Argo T and S profiles, satellite SST and altimetric SLA in an eddy-resolving ocean reanalysis in the Australian region. Along with XBT observations and the moored buoy network (e.g., TAO/PIRATA) that are not considered here, these observations comprise the foundation of the Global Ocean Observing System (GOOS) and are routinely assimilated into numerical models for research and operational applications.

[3] This paper is organised as follows. The components of the reanalysis system are described in section 2. The experiment design is presented in section 3, followed by the results in section 4 and the conclusions in section 5.

2. Reanalysis System

[4] The ocean model and data assimilation system used in this study were developed under the Bluelink project (www.bom.gov.au/bluelink/). Bluelink was established to develop the first Australian operational forecast system of the mesoscale ocean circulation around Australia. As a consequence, the data assimilation system used in Bluelink and in this study is not optimal, but it represents the state of the art in operational oceanography. For this study we use the Ocean Forecasting Australia Model (OFAM) [*Oke et al.*, 2005], a global configuration of the Modular Ocean Model version 4.0d [*Griffies et al.*, 2004] with 1/10° resolution around Australia, 0.9° across the Pacific and Indian Oceans and 2° in the Atlantic Ocean. OFAM has 47 vertical levels, with 10 m resolution down to 200 m depth. OFAM is initialised with a blend of climatologies [*Levitus*, 2001; *Ridgway et al.*, 2002] before a 12-year spin-up run, with no data assimilation, where it is forced with surface fluxes from ERA40 (www.ecmwf.int/research/era/). For the runs considered here, OFAM is forced at the surface using 6-hourly fluxes of momentum, heat and freshwater from ECMWF forecasts.

[5] We use the Bluelink Ocean Data Assimilation System (BODAS) that is described by *Oke et al.* [2005]. BODAS employs an ensemble optimal interpolation (EnOI) scheme that uses a stationary, 72-member ensemble of intraseasonal model anomalies, obtained from a non-assimilating model run. Observations that can be assimilated by BODAS include along-track SLA (atSLA) from altimeters, in situ T and S observations and satellite SST.

[6] The OSEs presented in this paper are based on different configurations of the Bluelink ReANalysis (BRAN). BRAN experiments involve the sequential integration of OFAM and BODAS using a 7-day assimilation cycle. Specifically, OFAM is integrated for 7 days; BODAS computes an analysis by combining a daily mean field from OFAM with observations; OFAM T, S and sea-level is nudged towards the analysis for 1 day using a 1 day nudging time-scale; and the sequence is repeated. We do not explicitly compute or apply increments to velocity.

[7] A comprehensive assessment of a 3.5 year BRAN experiment (P. R. Oke et al., The Bluelink ocean data assimilation system (BODAS) submitted to *Ocean Modelling*, 2007) showed that when assimilating atSLA, SST and in situ T and S, BRAN provides a realistic representation of the mesoscale ocean circulation around Australia. In that experiment BRAN SLA and SST fields have root-mean-squared (RMS) errors of 4–10 cm and 0.4–1°C respectively;

[1]Commonwealth Scientific and Industrial Research Organisation Marine and Atmospheric Research, and Wealth from Oceans Flagship Program, Hobart, Tasmania, Australia.

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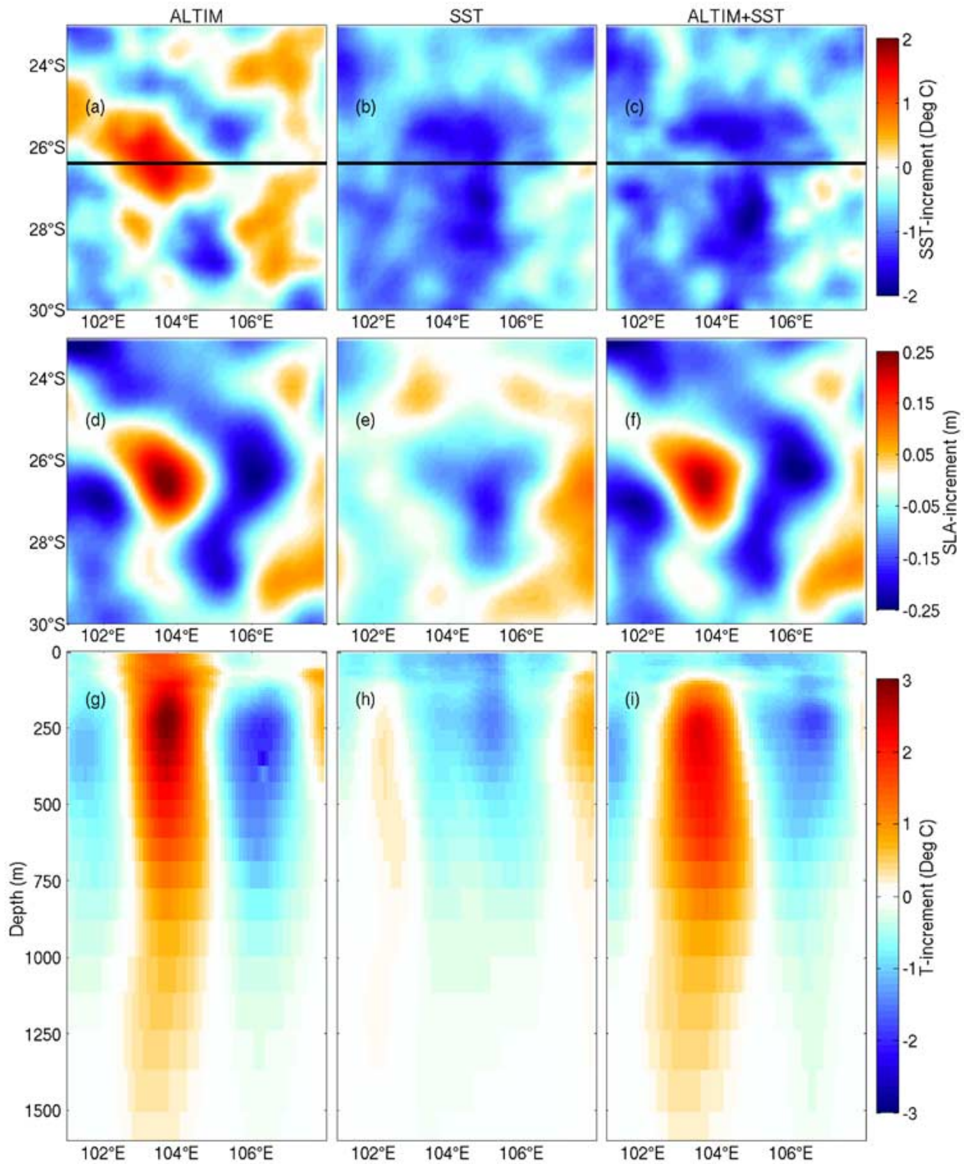

Figure 1. Examples of (a, b, c) SST increments, (d, e, f) SLA increments, and (g, h, i) T increments for a longitude-depth section at 24.4°S (sections denoted in Figures 1a–1c) when only altimetry (Figures 1a, 1d, and 1g) only SST (Figures 1b, 1e, and 1h) and both altimetry and SST (Figures 1c, 1f, and 1i) observations are assimilated. For this region, the RMS differences between observed and analysed SST (SLA) are 0.9° (4.4 cm), 0.02° (11.5 cm), and 0.05° (4.8 cm) for cases ALTIM, SST, and ALTIM+SST respectively. For comparison, the RMS difference between the observed and background SST (SLA) is 0.9° (13.1 cm).

and that sub-surface T and S are typically within 1°C and 0.15 psu of observations around Australia.

[8] The EnOI scheme used here is well suited to OSEs. EnOI is multivariate, using observations of one type to update variables of all types, and readily assimilates observations of different types in a single step. An example of the multivariate nature of EnOI is presented in Figure 1 showing the SST, SLA and sub-surface T increments when different observations are assimilated. For this example, a series of warm-core and cold-core eddies are evident in the SLA observations, but only a cold-core eddy is evident in the SST observations. This can occur when, for example, the warm-core eddies are capped by cold near-surface waters. As a result, we find that when only altimetry is assimilated (Figures 1a, 1d, and 1g) the increments reflect both the warm-core and cold-core eddies, with a clear surface-expression of the eddies in the SST increments. By contrast, when only SST is assimilated (Figures 1b, 1e, and 1h), the increments reflect only cold-core eddies, plus a general T decrease over most of the region shown. However, when both altimetry and SST are assimilated (Figures 1c, 1f, and 1i), the increments reflect both the warm-core and cold-core eddies, as well as the surface T decrease. This example demonstrates both the multivariate

Table 1. Area-Averaged RMS Residuals Between Observed and Modelled SLA, SST, and All T and S Profiles Over the Top 500 m[a]

	RMS Residuals					
Experiment	SLA	cSLA	SST	cSST	T (z)	S (z)
ALL	7.9	4.9	0.66	0.69	0.80	0.14
NONE	14.9	6.1	1.8	1.7	1.60	0.21
Argo+SST	10.8	6.0	0.67	0.68	0.87	0.14
ALTIM+SST	7.7	5.1	0.66	0.69	1.33	0.22
ALTIM+Argo	8.1	5.4	1.2	1.7	0.90	0.15
Obs. S. Dev.	9.8	5.8	0.88	1.1	0.83	0.12

[a]SLA, cm; SST, °C; T, °C; S, psu. Coastal SLA (cSLA) is based on comparisons with tide gauges and coastal SST (cSST) is based on comparisons where the bottom depth is less than 200 m. The observed standard deviation is shown for each variable. Area averages are computed for the region 90–180°E and 60°S–10°N.

nature of the EnOI system used here and the importance of different types of observation for assimilation.

3. Experiment Design

[9] The OSEs we present here involve the systematic denial of different observation types [e.g., *Vidard et al.*, 2007]. Using the same initial conditions, we integrate each experiment for the period December 2005 to May 2006. The control experiments for this study are a run with no data assimilation (denoted NONE or No Assimilation) and a BRAN experiment that assimilates atSLA from altimetry, including Jason, Envisat and GFO, in situ T and S from Argo and SST from AMSR-E (denoted ALL, or ALTIM+Argo+SST). We also integrate 3 OSEs, including an OSE that assimilates only Argo and SST (denoted Argo+SST), only altimetry and SST (denoted ALTIM+SST) and only altimetry and Argo (denoted ALTIM+Argo). For each assimilating OSE, we use a time window of 1-day for SST, 7-days for Argo and 11-days for altimetry; and assimilate observations from within these time windows. These time windows yield near-global coverage from each observation type.

[10] We assess the performance of each OSE by comparing the daily mean reanalysed fields with observed SLA, SST, in situ T and S and coastal SLA (cSLA). Recall that we assimilate data once every 7-days. Therefore we only assimilate SST from 1 day in 7; so data from 6 days in 7 are independent. Similarly, even in those OSEs that assimilate Argo we do not assimilate all T and S profiles available. We simply thin out the profiles so that there is no more than one profile for every 5-grid points. This data thinning reduces the computational expense of the assimilation step. The cSLA observations are from 39 tide gauge stations around Australia that are not assimilated. Throughout this study, model sea-level is converted to SLA by removing the long-term mean obtained from the last 9 years of a 12 year non-assimilating model run.

4. Results

[11] In this section, we present RMS residuals between the observed and modelled SLA, SST, sub-surface T and S and cSLA for each OSE. These variables quantify most of the variability of interest for eddy-resolving reanalyses or forecasts, namely mesoscale (eddy) variability, mixed layer fluctuations and changes to upper-ocean properties. For each variable, we restrict our comparisons to the Australian region, where the model is eddy resolving, and to the period January–May 2006. Area-averages of RMS residuals are shown for each variable in Table 1. This includes statistics for cSLA and coastal SST (cSST), where the SST comparisons are restricted to locations where the water depth is less than 200 m.

[12] The RMS difference between the observed and reanalysed SLA and SST for each OSE is presented in Figure 2. Reanalysed SLA fields are compared to atSLA from all available altimeters (Jason, Envisat and GFO). Reanalysed SST fields are compared to SST from AMSR-E. For comparison, the observed standard deviations are also shown in Figures 2k and 2l (for SST, this is based on anomalies from the seasonal cycle).

[13] The area-averaged RMS difference between observed and reanalysed sub-surface T and S in the Australian region for each OSE is presented in Figure 3. We present residuals from the 3159 profiles that are assimilated and the 600 profiles that are withheld, separately.

[14] Figures 2 and 3 and Table 1 show that the residuals for all variables are largest for the experiment with no assimilation. The OSE that assimilates altimetry, Argo and SST performs the best overall, with small residuals for all variables. By contrast each OSE that assimilates only two of the three observation types considered here performs poorly for at least one variable. For example, when only Argo and SST are assimilated, the residuals of SLA and cSLA are significantly larger than ALL. Similarly, when only altimetry and SST are assimilated, the residuals in sub-surface T and S are large compared to ALL (Table 1, Figure 3); and when only altimetry and Argo are assimilated, the residuals for SST become comparable to those in NONE (Table 1).

[15] It is interesting that when only Argo and SST are assimilated the SLA residuals are much smaller than NONE (Figure 2, Table 1). This indicates that some of the information in altimetry is also represented by the SST and in situ T and S observations. This is expected, based on the well understood dynamical relationship between SLA and sub-surface T and S, but it also demonstrates the power of the multivariate EnOI scheme that we use here. The SLA residuals are noticeably smaller when altimetry is assimilated, particularly in the regions of energetic mesoscale variability like the Tasman Sea, along the path of the Antarctic Circumpolar Current (ACC) and off Western Australia, where the Leeuwin Current frequently sheds eddies (Figure 2). This suggests that while SST and Argo represent the broad-scale SLA features, they do not adequately resolve the details of the mesoscale.

[16] When SST is not assimilated (Figures 2b and 2j) the errors in SST are greater than the observed standard deviation (Figure 2l) indicating that SST is poorly represented in those OSEs. By contrast, when SST is assimilated the errors in SST are small compared to the observed standard deviation, indicating that the SST in those OSEs is well constrained.

[17] The SST residuals in NONE (Figure 2b) are dominated by a bias error, where the model is systematically too cool off western Australia and along the ACC and is too warm off eastern Australia and off Antarctica. By contrast, ALTIM+Argo (Figure 2j) has no significant bias, indicating

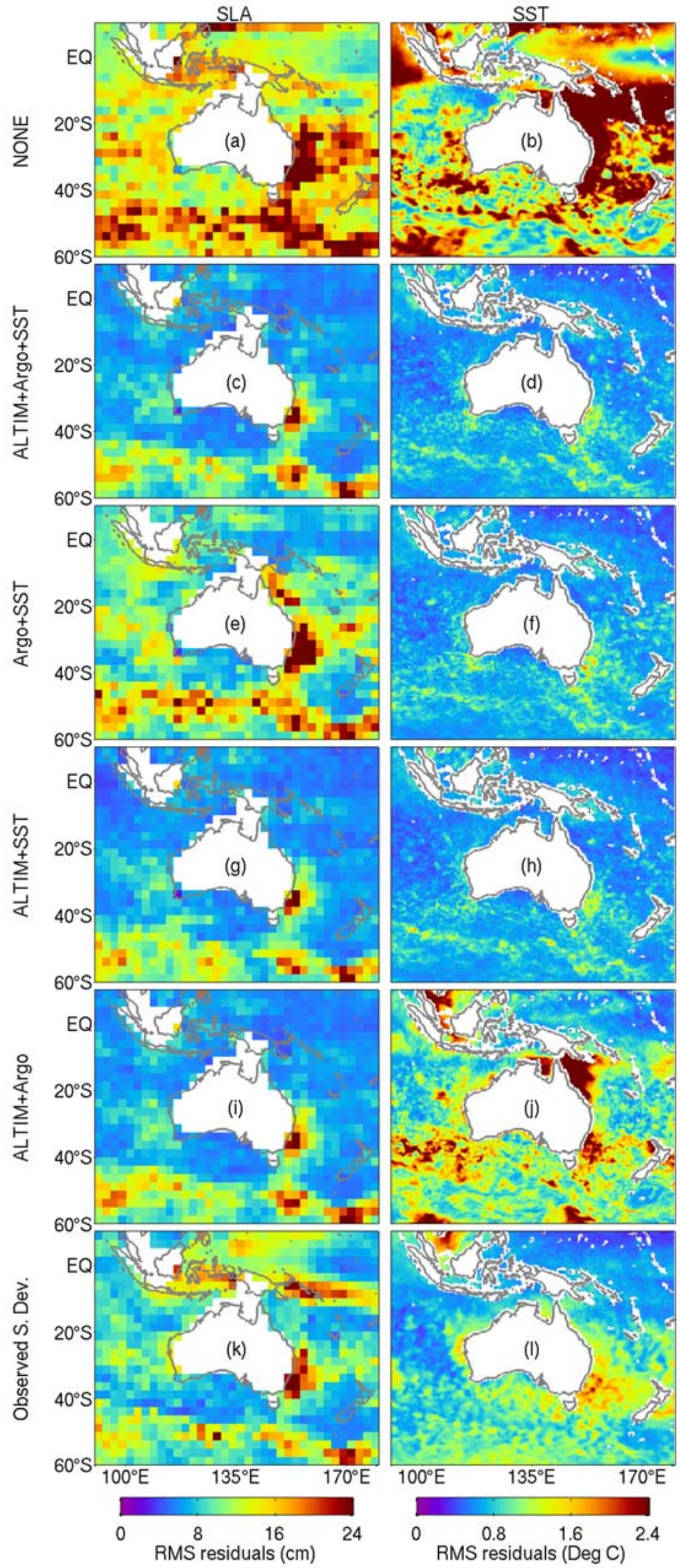

Figure 2. (a, b, c, d, e, f, g, h, i, j) RMS residuals between observed and modelled SLA (left column) and SST (right column) for each OSE; and (k, l) the observed standard deviation. Statistics are computed using atSLA observations from Jason, Envisat, and GFO (left column) and AMSR-E for the period January–May 2006.

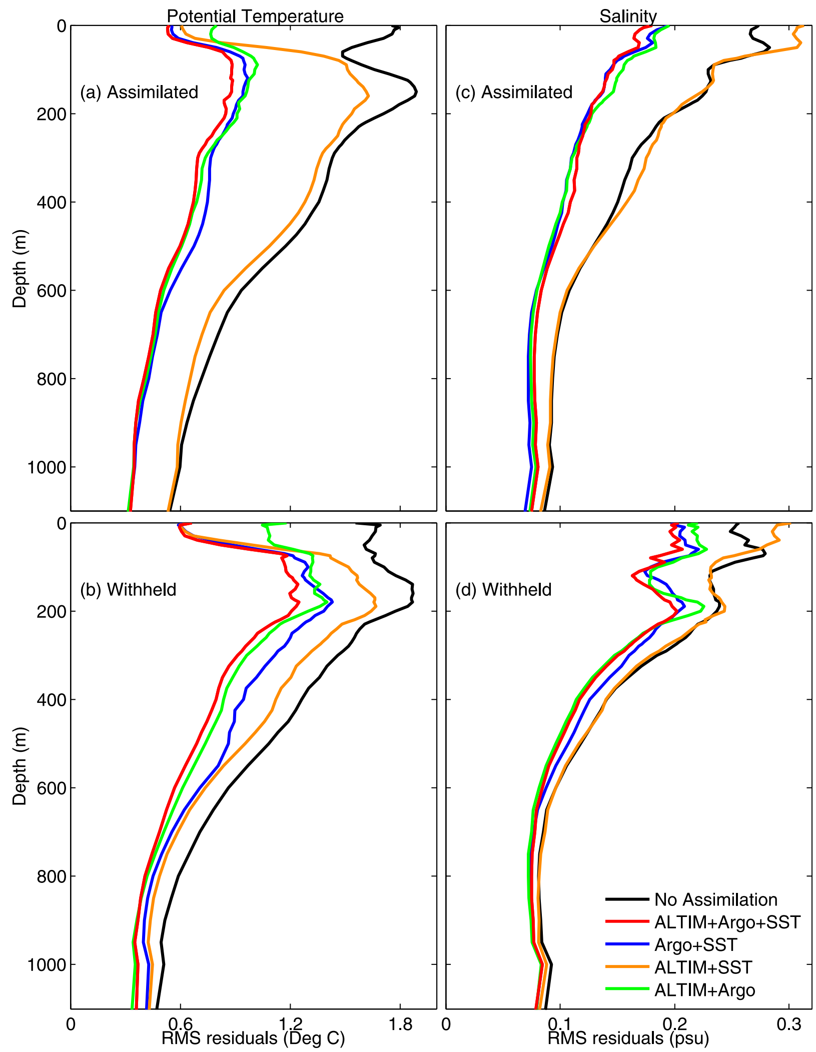

Figure 3. RMS residuals between observed and modelled (a, b) potential temperature and (c, d) salinity, using assimilated (Figures 3a and 3c) and withheld (Figures 3b and 3d) observations for each OSE. Statistics are computed for the region 90–180°E and south of the equator using 3159 assimilated and 600 withheld Argo profiles for the period January–May 2006.

that the in situ observations from Argo appropriately constrain the broad-scale T field over the upper ocean. However, in general, this OSE does not provide a good representation of the SST variability in the Australian region. Specifically, the SST residuals are very large in regions that are not directly observed by either altimetry or Argo, notably in the Coral Sea, in the Gulf of Carpentaria and off Antarctica. This is quantified in Table 1, where the area-averaged residuals for cSST is large compared to those OSEs that assimilate SST. SST residuals are also large in the Tasman Sea and south west of Australia (Figure 2j), where mesoscale variability is high (Figures 2k and 2l).

[18] Clearly the smallest sub-surface T and S residuals result from the OSEs that assimilate Argo profiles (Figure 3). While there is a significant reduction in the T residuals in ALTIM+SST, particularly near the surface, on average these observations have very little impact on the residuals for S. There is even a small increase in the S residuals near the surface in ALTIM+SST compared to NONE. This result demonstrates that without Argo observations, S is very poorly constrained in our reanalysis. The residuals for S are typically greater than 0.15 psu near the surface in all of the OSEs, even when Argo is assimilated (Figures 2c and 2d). These residuals are quite large compared to the expected errors of Argo observations, indicating that even when Argo is used, S is not well constrained by the assimilation. At least in part, this is likely to be because our assimilation system is not optimal. However, it leads us to the expectation that the assimilation of sea surface salinity (SSS) observations may be beneficial, although we have not explored this issue here. While a sparse network of SSS observations are routinely available from thermosalinograph measurements, we expect a significant improvement in our ability to constrain upper ocean salinity to result from the upcoming SSS satellite missions (SMOS and Aquarius).

[19] The impact of SST on the T residuals is also evident in Figure 3. Based on the differences in the T residuals from ALTIM+Argo and those that assimilate SST we conclude that in the Australian region, on average, the impact of SST observations is limited to the upper 50–100 m of the water column. This result has a clear latitude dependence that

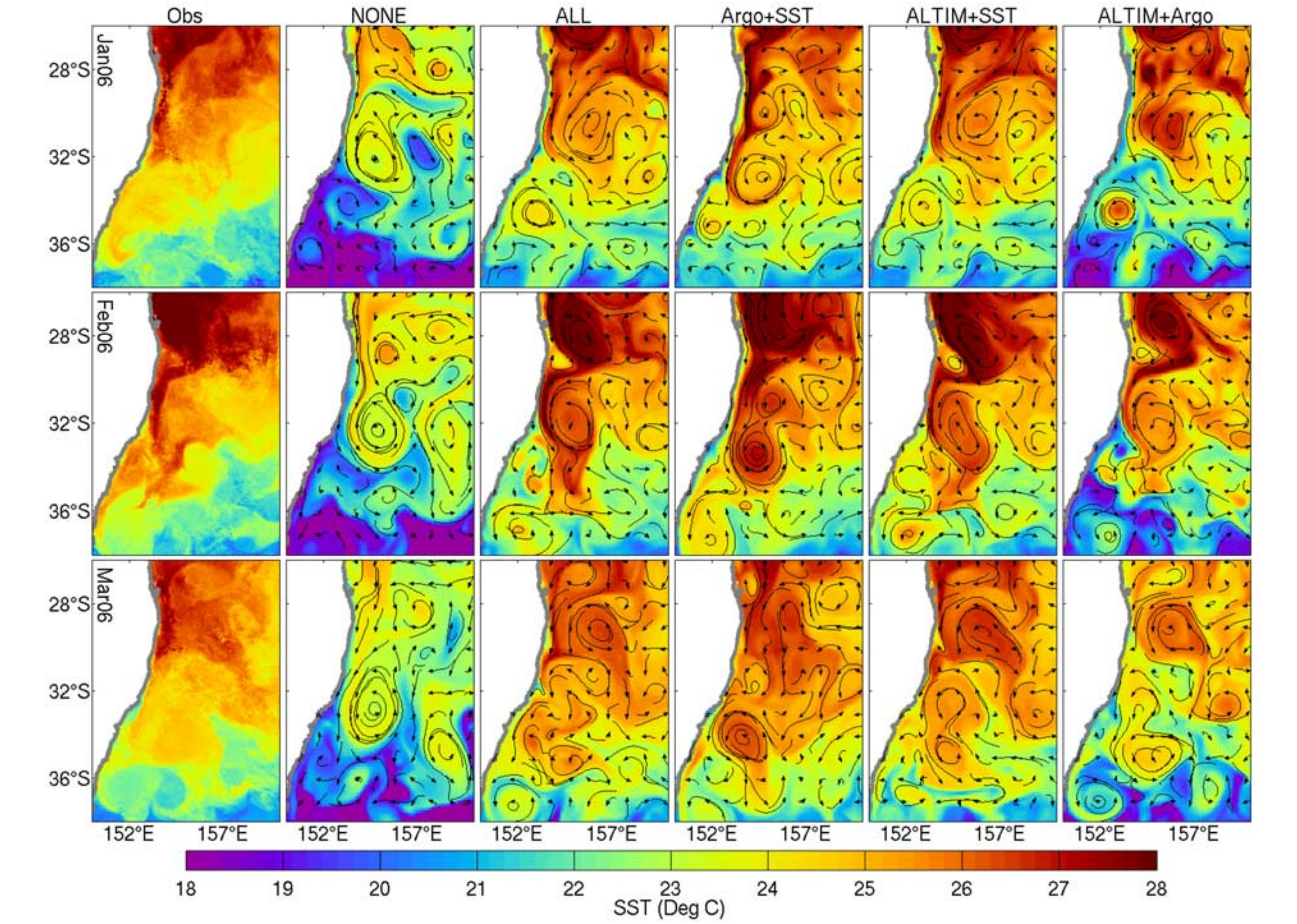

Figure 4. Observed SST from (left) 6-day composite AVHRR; and (columns 2, 3, 4, 5, 6) 6-day averaged SST with virtual drifter paths overlayed for each OSE in the Tasman Sea for (top) mid-January, (middle) mid-February, and (bottom) mid-March of 2006.

appears to be related to errors in mixed layer depth. We find that south of 45°S, assimilation of SST has a positive impact over the top 200–300 m, while in the tropics the impact of SST is limited to less than 50 m depth.

[20] To compliment the statistical analyses presented above, we also present a qualitative assessment of the impact of with-holding each data type in the Tasman Sea. The circulation in the Tasman Sea is dominated by the East Australian Current (EAC) and a rich field of mesoscale eddies. In Figure 4, we show 6-day composite SST from AVHRR measurements (first column) that are not assimilated, and 6-day averaged SST for each OSE (columns 2–6). The vector paths plotted in Figure 4 show Lagrangian trajectories over each 6-day period, computed from the time-dependent reanalysed surface currents. Fields are shown for each OSE in mid-January, mid-February and mid-March 2006.

[21] The fields in Figure 4 show that when SST is assimilated, the reanalysed SST is very similar to the observed SST. By contrast, when SST is not assimilated, the reanalysed SST differs significantly from observations. Consistent with the statistical analysis above, these differences are reduced in ALTIM+Argo, compared to NONE.

[22] It is clear from Figure 4 that the mesoscale circulation is qualitatively similar for each OSE when altimetry is assimilated, but is quite different otherwise. For example, the position of the Tasman front in January and February, denoted by the separation of the EAC from the coast around 32°S, is very similar in the OSEs that assimilate altimetry. Also note the robustness of the anti-cyclonic circulation around 152°E and 37°S in February and March; and the coastal meander near 29°S in February that is evident in the observations and the OSEs that assimilate altimetry. These considerations support our suggestion that altimetry is required for mesoscale circulation to be resolved.

5. Conclusions

[23] While we find that there is some redundancy in the GOOS for representing the broad-scale circulation, altimetry appears to be critical for representing mesoscale variability. Similarly we find that SST observations are particularly important for regions that are not well observed by Argo and altimetry, such as wide continental shelves and in shallow seas. We show that SST is important for constraining the near-surface temperature in all regions we consider. The impact of Argo is shown to be significant, representing the only component of the GOOS that positively impacts reanalyses of S. We conclude that Argo, SST and altimetry provide complementary information to the GOOS.

[24] While the conclusions about the relative importance of the different components of the GOOS presented here are valid for the model and data assimilation system that we use, the results might not be generally true for other systems. Clearly, the impact of different observation types depends on how those observations are assimilated, what errors are prescribed to them and how well the model is initialised. We expect that as long as improvements are made in these areas, there will be improvements to the impact of different observations on reanalyses and forecasts. The quality of ocean reanalyses and forecasts depend on the long-term sustainability of all components of the GOOS and is likely to benefit from enhancements, such as the availability of SSS observations and the completion of the Argo array.

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P. R. Oke and A. Schiller, CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, TAS, 7001, Australia. (peter.oke@csiro.au)