Response to reviewer comment RC2

Reviewer comments are presented first in *blue italics*, then followed by the author's response in normal font. Line numbers are referring to the original manuscript and are denoted as L145 for Line 145. For changes to text, we include the original in red and the changed version or new additions in green.

Major comments:

1. 1 L101- 102 "Further details of the free-running and DA configuration used in these OSSEs are given in Gwyther et al. (2022)." However, not much information has been provided in this present paper. It is simple to cite past work! However, such details, even in a summary format are very relevant to this paper, a table of differences between `ref' and `DA' model configurations would be most illustrative. Also a discussion of why those differences actually yield a "good" set-up to address the sub-surface impacts of data assimilation (discussed in the Introduction) is needed.

Following this comment, we have added the following table to the Appendix. This table shows the key differences between the ref state and OSSE configurations and points the reader to references which explain the model setup in greater detail.

Table 1. Key differences in model configuration are shown between the Free-running ref state and the 4D-Var OSSEs. Further details are given in Gwyther et al. (2022) and references therein.

Configuration	Free run	4D-Var OSSE
Lateral BCs	BRAN2020	BRAN2020
Surface BCs	BARRA-R	ACCESS with bulk flux parameterisation
Mixing schemes	Harmonic horizontal mixing coefficient is 40 $m^2 s^{-1}$ for tracers and 55 $m^2 s^{-1}$ for momentum. Background vertical mixing coefficient is 1×10^{-6} $m^2 s^{-1}$ for tracers and 2×10^{-5} $m^2 s^{-1}$ for momentum.	Harmonic horizontal mixing coefficient is 200 $m^2 s^{-1}$ for tracers and 300 $m^2 s^{-1}$ for momentum. Background vertical mixing coefficient is 1×10^{-6} $m^2 s^{-1}$ for tracers and 1×10^{-5} $m^2 s^{-1}$ for momentum.
DA background error	n/a	Decorrelation length scales are assumed to be homogenous and isotropic. Horizontal length scale is 100 km; Vertical length scale is 10 m.
DA observation error	n/a	SSH error is 0.04 m; SST error is 0.5°C; XBT has a depth-varying error profile with a subsurface max of 0.6°C at 300 m decreasing to 0.12°C at 1100 m.
DA 4D-Var loops	n/a	14 inner loops and 1 outer loop.
More details	See Gwyther et al. (2022) and Li et al. (2021).	See Gwyther et al. (2022) and Kerry et al. (2016).

We have add the following information about the initial perturbation of the OSSEs:

"The OSSE that is simulating the same period as the Ref state is perturbed to introduce error and initiate divergent evolution (see discussion below)."

To

"The OSSE that is simulating the same period as the Ref state is perturbed to introduce error and initiate divergent evolution through the use of different initial conditions. These initial conditions are similar to those used to initialise the Ref state but are extracted from a point 8 days later (the OSSE begins at 2 December 2011 with conditions from 10 December 2011).

This offset is chosen so as to fairly test the DA system (see Gwyther et al., 2022 for further information about this choice of perturbation)."

We have also added the following information, emphasising differences between the Ref state and the OSSE configurations, by changing:

"The DA configuration uses lateral forcing conditions from BRAN2020 and surface forcing conditions from a bulk flux formulation (Fairall et al., 1996) with daily atmospheric conditions from the Australian Bureau of Meteorology's ACCESS reanalysis (Puri et al., 2013). The different surface forcing conditions between the DA configuration and the free-running Ref state are appropriate, as they lead to an additional source of error that the DA system must reduce."

To:

"The DA configuration uses lateral forcing conditions from BRAN2020 and surface forcing conditions from a bulk flux formulation (Fairall et al., 1996) with daily atmospheric conditions from the Australian Bureau of Meteorology's ACCESS reanalysis (Puri et al., 2013). Vertical and horizontal mixing parameters have also been modified between the free-run and data-assimilating configurations. The different surface forcing conditions and mixing parameters in the assimilating and free-running configurations (see Table 1) are appropriate, as they lead to a source of error that the DA system must reduce, as required in an OSSE."

Further we have included the following discussion in the associated Appendix section:

"Key configuration settings and differences between the ref state and the OSSE model configuration are shown in Table 1. The decorrelation length scales are set following Kerry et al. (2016; section 3.5), and are consistent with estimates used elsewhere (e.g. Zhang et al., 2010; Zavala-Garay et al., 2012; Kerry et al 2018; Siripatana et al 2020; Gwyther et al., 2022). Observation error covariances (see Table 1) are applied for each observation type. Further discussion of the preparation of the observations, the choices of error, and the minimization scheme is discussed further in Gwyther et al. (2022)."

With regards to demonstrating that this DA setup is a 'good' setup: All of the choices made in configuring the DA system were made following extensive research. This DA system has also been shown to produce accurate estimates and forecasts of the EAC when assimilating observations (as shown in Kerry et al., 2016 and subsequent publications e.g. Kerry et al., 2018; Siripatana et al., 2020). However, we could emphasise that further, and so we have added the following to L100, by changing:

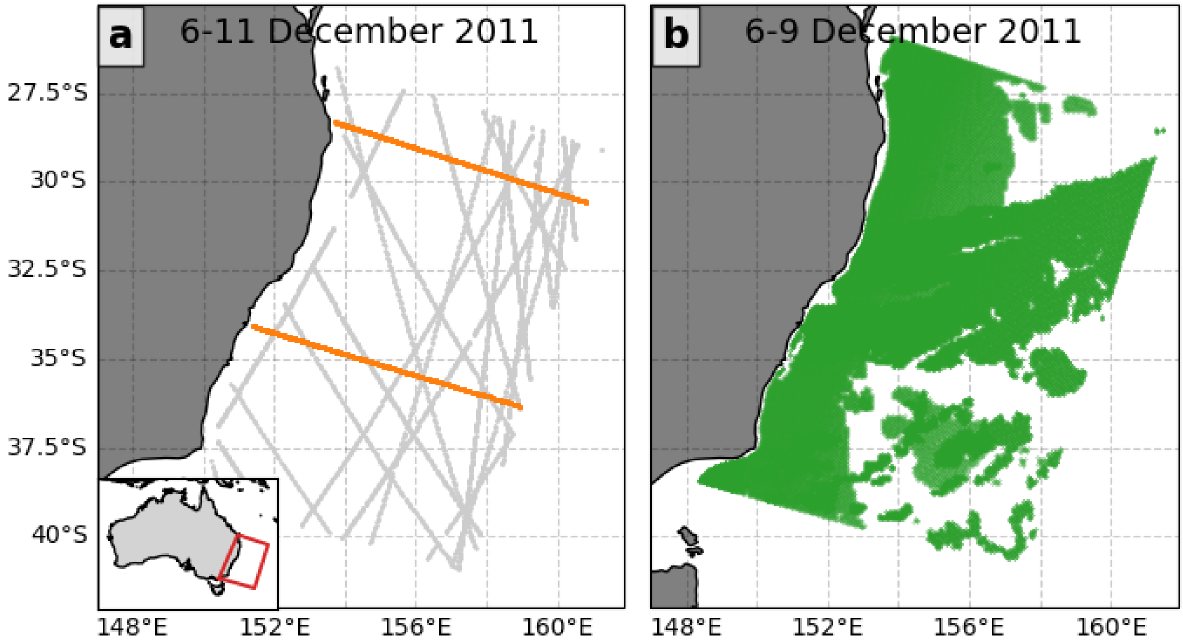
"Further details of the free-running and DA configuration used in these OSSEs are given in Gwyther et al (2022)."

To:

"The performance and configuration options of the DA system were extensively tested and were shown to produce relatively low error in estimates and forecasts of the EAC (Kerry et al, 2016). The system uses 14 inner loops with one outer loop, set following testing of how many loops were required to achieve acceptable reduction in the cost function (see Gwyther et al,. 2020; Kerry et al., 2016). The background error covariances are static and computed by factorisation based on Weaver and Courtier 2001, as described in detail in Kerry et al 2016."

1.2 Table 1 "Along-track satellite-observed sea surface height altimetry and sea surface temperature." A plot is needed here to show the data coverage.

We have added a supplementary figure with example coverage of SST and SSH observations, as shown below:



Supplementary Figure 2. Example coverage of (a) along-track SSH (grey dots) and XBT (orange dots) over the period 6-11 December 2011, and (b) SST (green dots) over the period 6-9 December 2011. A shorter window is selected to show the typical spatial coverage of the SST, which, due to the high resolution and daily imaging, often covers the whole domain. Gaps in SST coverage are usually due to low surface winds or high cloudiness. These gaps are simulated using thresholds of 2m/s and 0.75 (for low wind and cloudiness, respectively) using daily fields from the BARRA-R reanalysis. Methods for masking and preparation of the SST and other observations are given in detail in Gwyther et al., (2022).

This figure is now referenced in the methods section:

"Example coverage from SSH, XBT and SST are shown in Supplementary Figure 2."

1.3 Figures such as 2 and 3 are time-averaged. But given the eddying flow, the errors are expected to vary in time, therefore a time-series plot or Hovmoller plot of error (with respect to `ref') standard deviations would be best.

At the suggestion of the reviewer we experimented with a time-varying versus a time-averaged plot. However, we believe that a time-varying plot is not insightful. This is because the eddies in each different model are not exactly at the same location and time, the comparison with the truth (e.g. an RMS plot) can have a large difference even if the fields aren't that dynamically different (e.g. an eddy is slightly misaligned). We feel this would be misleading. Our focus here is the time mean differences in subsurface structure hence we have not changed the plot.

1.4 L 223 "The XBT-N+S OSSE has a slightly higher EKE difference than XBT-N or XBT-S but performs better than Surf (cf. Fig.3j and Fig.3g)" Why so? The authors do not explain this counterintuitive result though more observations have been added in XBT-N+S than XBT-N or XBT-S.

We have changed:

"The XBT-N+S OSSE has a slightly higher EKE difference than XBT-N or XBT-S but performs better than Surf (cf. Fig.3j and Fig.3g)."

To

"The XBT-N+S OSSE has a slightly higher EKE difference than XBT-N or XBT-S but performs better than Surf (cf. Fig.3j and Fig.3g). As discussed in Gwyther et al., (2022), the XBT-N+S OSSE sometimes displays higher error than the single XBT transect OSSEs, which is likely because the DA scheme is forced to minimise errors at both the northern and southern subsurface observation locations. This leads to a degraded fit to either observation transect individually. This has also been demonstrated by others, for example, Siripatana et al., (2020), who found that additional data streams (mooring data and HF radar currents) degraded representation of SSH and SST; and Zhang et al., (2010), who showed that assimilating HF radar currents increased the error in the subsurface temperature forecast."

1.5 L377 "DA simulations will potentially struggle to generate representative baroclinic mode structure." The authors generalize their conclusions without demonstrating how does the model used for DA performs without any assimilation (see comment above 1.1). They haven't shown the nature of errors that this model has without any observations - unless those are described, how can one draw conclusions whether assimilating observations helps or not? It is important to design the experiments properly, by making sure the model used for DA is different from that to generate the `ref' trajectory.

We acknowledge that we omitted to show a free-running configuration of the data-assimilating configuration. So, we have run the free-running model with the same forcing conditions and mixing parameters as the OSSE configuration. This 'baseline' run shows the bias in the integration resulting from the different surface forcing and mixing parameters. We have included a new figure and section in the Appendix.

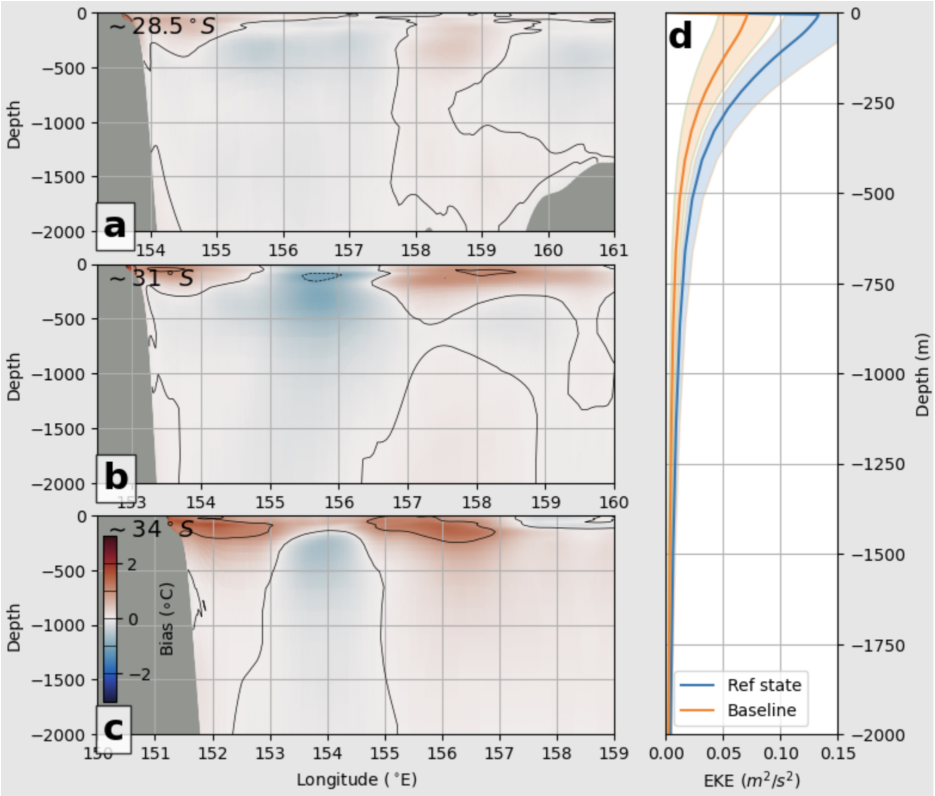


Figure A1. The temperature bias between the baseline and the ref state is shown at three transects, (a) 28.5S, (b) 31S and (c) 34S. In (d), the depth profile of EKE, averaged over the high EKE box (see box in Figure 3a), for the ref state and baseline experiments.

To explain this figure, a new section has been added to the appendix.

“Appendix A: The `baseline’: Bias in the OSSE configuration

As described in Section 2.2, we employ a fraternal twin approach, where the ref state and the OSSE are simulated by the same model, but with different configurations. These differences, such as parameterisations and boundary conditions, should produce errors that are similar in nature (i.e. have similar magnitude and properties) to the initialisation error present in a true ocean DA system. However, the errors introduced through differences in configuration should not result in such a large impact, that the long-term representation is no longer realistic. If this occurs, it is difficult to separate out the error resulting from the difference in configuration (the bias), and what is the difference resulting from the DA process itself. Consequently, the free-running and data-assimilating simulations must have different configurations but without a large mean bias.

To quantify this bias, we run a ‘baseline’ experiment, using the free-running model but with boundary conditions and parameterisations identical to the OSSEs. The bias is then calculated as the time-mean difference between the ref state and the baseline simulation.

Figure A1 shows the time-mean bias in temperature at three transects: 28, 31, 34 (Figure A1a-c). The surface region displays the greatest bias, of approximately 1.5C in the surface waters at 34S (Figure A1c), while at depth bias is negligible (close to 0C below 500m in all transects Figure A1a-c). The surface bias is very likely to be corrected for by the assimilation of SST observations. The depth profile of EKE for the ref state and baseline have similar shape: surface intensified with a gradual decrease with depth. Compare this to the same profiles for the OSSEs, which display subsurface maxima (Figure 3k).

The lack of strong (subsurface) bias with a consistent sign suggests that the differences in subsurface structure (e.g. Figure 2,4,5), mode structure (Figures 9 and 10), EKE distribution (Figure 3) and energy conversion rates (Figure 8) are principally a product of the DA system; they don't result from any consistent bias in the DA model forcing and configuration."

This appendix has also been introduced in the methods section:

"However, it is also important to ensure that the different configuration of the Ref state and OSSEs (e.g. in this case, surface forcing and some mixing parameters) do not cause such an impact as to introduce a large long-term bias. To assess this, a `baseline' experiment was conducted using the OSSE configuration, but without assimilating any observations. Comparison of this against the Ref state showed a warm bias in the surface waters, which is likely to be corrected by assimilating SST. More importantly, there is no strong bias in the subsurface ocean, which would otherwise be difficult to correct with assimilation (see Fig.A1)."

1.6 I enjoyed reading Sec 2.3.4 and 3.5; other sections/results identified problems with the data assimilation experiments, but never explained their causes. In the end, I am not what exactly sure what is the take home message? Every data assimilation scheme/implementation has a specific treatment of background errors. In this paper, there is no concrete evidence that it is the background errors that are to be blamed; mere speculations have been raised (L391, L418). It would be much better if there was a set of experiments with different B (formulation or changed values) that proved these speculations- even partly. Otherwise, what exactly is the contribution of this work? A diagnostic tool presented in Sec 2.3.4 and its use case in Sec 3.5? I hope some of this criticism helps improve this work on a very important topic.

We agree that a sensitivity study of DA parameters, like the background error covariance, would be interesting and very useful. To conduct such a sensitivity study, many new experiments would need to be simulated in order to thoroughly explore the parameter space and sensitivities of the parameter. This would completely change the scope of the paper. This manuscript is a case study of a particular DA configuration, where the goal is to assess in detail the subsurface representation of the EAC and its eddy field. We have demonstrated that assimilation of the different datasets changes the sub-surface structure of the eddies - which is often overlooked in the usage of data assimilating models. Indeed, few people look below the surface at dynamical features at all.

The goal of this paper is not to optimise (or improve) the representation of the background error covariances, but to assess the impact of hypothetical observing platforms and show how subsurface representation is impacted by data assimilation. However, we thank the reviewer for these comments - and we think they will be valuable for designing future research directions. Indeed, this study motivates our future research direction in which we hope to improve the specification of the background error covariances using hybrid Ensemble-Var methods, as discussed at lines 406-412.

Minor comments:

2. 1 L19 "they" deliver

Changed.

2.2 L68 "focus on two" ??

Changed to “focus on two manifestations of this impact:”

2.3 L340 "sim" should be "$\sim$"

Changed

2.4 Most figures do not have axes labeled (for e.g., "Latitude (deg N)"), same remark for colorbar - Fig.2

We have ensured that all latitude and longitude axis labels are marked with a °S or °E suffix. We hope this should negate the need to include the axis label, however we have also added to every caption which has this: “Axes with latitudes are labelled °S and axes with longitudes are labelled °E”

We have also added colorbar labels to Figure 2, and removed a degree symbol in the caption.

2.5 Most figures would be more readable if XBT-N, -S lines are superimposed.

Thank you for suggesting this. We have updated all spatial maps to have XBT-N and XBT-S lines in the appropriate panels.

2.6 L87 "surface forcing conditions from BARRA-R" Are they also daily?

Correct. Have changed to “daily surface forcing conditions from BARRA-R”

2.7 a. Fig.6(e) The transect line is further from XBT-S than in other panels. Is it same section?

As we describe at L270-272, the transect line has been shifted so as to pass through the centre of the eddy, which should allow for a more comparison between OSSEs when eddies may have a slightly different position. Otherwise the comparison would be between the centre of the ref state eddy and the edge of the OSSE eddy.

2.7 b. Fig 6(k), Fig. 7(k) What is the colorscale?

Thank you for pointing this out - we have corrected both of these figures.