



# Wide-swath satellite altimetry and novel subsurface observations improve predictions in a dynamic western boundary current: Resolving complex fine-scale structures.

Colette Kerry<sup>1</sup>, Moninya Roughan<sup>2</sup>, and Shane Keating<sup>1</sup>

<sup>1</sup>School of Mathematics and Statistics, UNSW Sydney Australia, Sydney, NSW, Australia 2052.

<sup>2</sup>Coastal and Regional Oceanography Lab, School of Biological, Earth and Environmental Sciences, UNSW Sydney Australia, Sydney, NSW, Australia 2052.

**Correspondence:** Colette Kerry (c.kerry@unsw.edu.au)

## Abstract.

Eddyding oceanic regions adjacent to continental shelves typically exhibit complex flow structure and, while the broad-scale ocean surface is well observed by satellites, the ocean's fine-scale flows and complex vertical subsurface are typically undersampled. The combination of oceanographic observations and numerical models, through data assimilation, produces data-constrained, four-dimensional fields that support a range of ecological and economic needs. Data assimilation makes use of a numerical model to place observations in dynamical context, yet it is particularly challenging for highly variable oceanic flows with sharp spatial gradients and where observations are sparse in space and/or time relative to the ocean's scales of variability. Here we use observing system experiments to assess the impact of recently-available observations from the Surface Water Ocean Topography satellite (SWOT, observing the ocean's fine-scale height structure) and from the Fishing Vessel Observation Network (FVON, providing wide spread high-resolution crowd sourced temperature data below the surface) on regional ocean model estimates in an eddy-dominated western boundary current region, the East Australian Current. In our companion paper, we used temporally and/or spatially averaged statistics to describe model-observation differences and show that SWOT substantially improves sea surface height representation across scales and FVON data strongly improves subsurface temperature representation in coastal and shelf regions. While these averaged statistics are useful to demonstrate overall impact of various observation platforms, they often do not capture the detail of how data assimilation reproduces fine-scale dynamical features — precisely the features that are resolved by SWOT and FVON. Here we present select case studies to demonstrate the specific time and space structure of observation impacts. Using independent cruise, glider, drifter and FVON observations, we show that SWOT and FVON can provide significant improvement in the representation of complex fine-scale oceanic structure. The results demonstrate that wide-swath altimetry and fishing-vessel subsurface observations provide complementary constraints: SWOT data improves the surface expression and evolution of eddies, while FVON data constrains the vertical thermal structure that surface observations alone cannot resolve. The case studies also reveal that small errors in feature placement can lead to large subsurface errors, underscoring the need for sustained subsurface observing and uncertainty-aware state estimation. Our results demonstrate that integrating SWOT and FVON observations into regional prediction systems



offers a pathway toward more reliable ocean state estimates (essential for navigation, fisheries, marine heatwave monitoring, ecosystem applications, and coastal management) in an energetic boundary current system.

**Keywords:** East Australian Current (EAC), Four-Dimensional Variational (4D-Var) Data Assimilation, mesoscale, submesoscale, prediction, Western Boundary Current, ROMS, subsurface, SWOT, Fishing Vessels as Ships of Opportunity (FishSOOP), Fishing Vessel Observation Network (FVON), Observing System Experiments, OSEs

## Key Points:

1. Specific case studies directly demonstrate the positive impact of SWOT and FVON data on model estimates of complex fine-scale flows and highlight the challenges of producing accurate ocean state estimates at and below the surface.
2. Subsurface temperature data collected from fishing vessels (FVON) provides essential subsurface constraint that surface observations cannot supply, with impacts projected in time and space
3. Wide-swath satellite altimetry (SWOT) improves the geometry and evolution of eddies, with effects that propagate below the surface and beyond the observation location and times.
4. Small horizontal misplacements of surface features can generate large subsurface temperature errors, motivating sustained subsurface observing and uncertainty-aware state estimation

## 1 Introduction

Understanding and predicting regional and coastal ocean dynamics requires the effective combination of observations and numerical models that resolve key processes at suitable time and space scales (Jacobs et al., 2021; Edwards et al., 2024). By representing the observations within the dynamical context of the model, through data assimilation, the ocean model can provide an improved estimate of the ocean state (e.g. Martin et al., 2024). A well configured numerical model, observations at suitable scales, and an effective data assimilation system to combine them are essential. These data-constrained, four-dimensional oceanographic fields provide key information to support a range of ecological and economic needs (e.g. Cetina-Heredia et al., 2019), and are crucial to update model initial conditions in operational forecasts (e.g. Masina et al., 2026). Data assimilation is particularly challenging for highly variable oceanic flows with sharp spatial gradients where observations are sparse in space and/or time relative to the ocean's scales of variability (e.g. Walstad and McGillicuddy, 2000; Edwards et al., 2015, 2024). Consequently, the representation of fine-scale features, rapidly evolving flows, sharp spatial gradients and complex subsurface structure remains a key source of uncertainty in coastal and regional models (Gwyther et al., 2022a, 2023a, b; Kerry et al., 2026a).

Advanced data assimilation methods (e.g. 4-Dimensional Variational data assimilation (4D-Var) and the Ensemble Kalman Filter (EnKF), Moore et al., 2020a) make use of the time-variable dynamics of the model, allowing the observations to be assimilated over a time interval given the temporal evolution of the circulation. Key to effective combination of the model and observations are prior assumptions around the uncertainty associated with each. Observation uncertainty estimates prevent



‘over-fitting’ the solution to uncertain observations or observed processes that are unresolved by the model. The model background uncertainty estimate carries the statistical information of the model prior and is key to accurately projecting the information contained by the observations onto the model state estimate (Moore et al., 2019). With 4D-Var, the objective is to generate a new time-varying ocean state estimate that is a complete solution of the ocean model equations and better fits the observations, taking into account the uncertainties of both the observations and the model background state. This means that a balance must be achieved between matching the observations and representing them within the dynamical context of the model, to generate dynamically consistent state estimates and enable stable forecasts.

Modern observation platforms provide an unprecedented view of the ocean’s fine-scale structure both at the surface with the Surface Water and Ocean Topography satellite mission (SWOT) and below the surface with the Fishing Vessel Observation Network (FVON, known as Fishing Vessels as Ships of Opportunity Program — FishSOOP in Australia). The SWOT mission provides the first-ever synchronous 2D maps of sea surface height (SSH) at ~2 km resolution, albeit at low temporal resolution (21-day repeat passes, Chelton, 2024; Morrow et al., 2019). FVON / FishSOOP has provided a step-change in the availability of subsurface temperature data (since 2022), providing high-resolution observations from sensors mounted on fishing equipment in coastal, shelf and open-ocean regions (Vranken et al., 2023; Jakoboski et al., 2024; Lago et al., 2025b). SWOT data has been shown to provide significant improvement in the quality of ocean analyses and forecasts in a global data assimilation system (Benkiran et al., 2026), and FVON data assimilated into a regional model around New Zealand was shown to significantly improve subsurface temperature representation, especially in coastal regions (Azevedo Correia de Souza and de Godoi Rezende Costa, 2026). Combining these newly available observations with high-resolution models provides a unique opportunity to develop ocean state estimates that represent finer scale oceanic features. However, challenges exist as fine scale features are typically rapidly evolving and intrinsically unpredictable, limiting the ability of a numerical model to ‘join the dots’ between sparse observations (e.g. Kerry et al., 2026a).

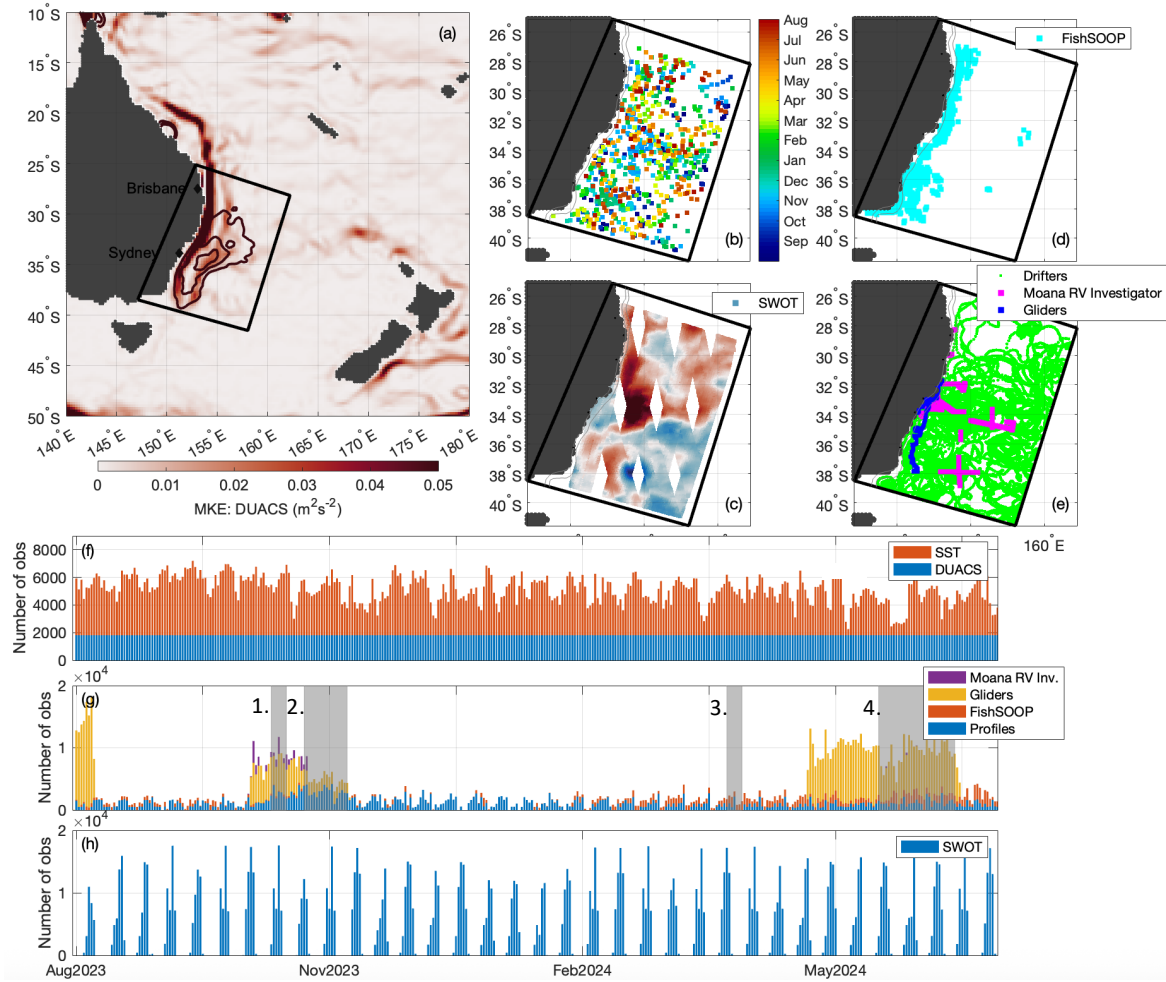
Data-assimilative systems are typically assessed based on temporally and/or spatially averaged statistics describing model-observation differences against assimilated and independent observations (e.g. Partridge et al., 2019; Chamberlain et al., 2021; Azevedo Correia de Souza and de Godoi Rezende Costa, 2026; Kerry et al., 2026c). While these statistics provide an assessment of overall performance, they lack detail of how data assimilation reproduces fine-scale dynamical features — precisely the features we aim to observe with SWOT and FVON. Specifically, temporally resolved assessment is useful to show details of data assimilation system adjustments (increments) and model estimate differences (e.g. Kerry et al., 2020; Janeković et al., 2022), and in the context of observing system experiments, can demonstrate the specific time and space structure of observation impacts. Furthermore, the actual surface and subsurface structure at specific times is relevant for many applications. For example, when using model state estimates or forecasts for navigation, the specific timing and location of fronts is important to guide the vessels towards an optimum route (Kalinichenko et al., 2025). Likewise, to understand or predict the interaction of fish (fisheries target species) or marine predators with dynamic seascapes, resolving the specific oceanic conditions that correspond with the ecological niche is needed (Scales et al., 2014b). Predictions of oceanic marine heatwaves require accurate representation of the specific subsurface structure of the temperature extremes (Elzahaby and Schaeffer, 2019; Elzahaby et al., 2021) and their spatio-temporal evolution.



The East Australian Current (EAC) system is a dynamic oceanic region where the eddying western boundary current (WBC) interacts with a narrow continental shelf along Australia's most populated coastline (Figure 1a). Complex eddy dynamics and interactions with the continental shelf and coastal waters make the EAC system a challenging region to predict, providing an ideal test-bed for assessing the ability of an ocean model to represent fine-scale flows and complex subsurface structure. This study is based on series of observing system experiments that demonstrate the impact of SWOT and FVON observations on a high-resolution regional model of the EAC, using a proven 4D-Var data assimilation infrastructure (Kerry et al., 2016, 2018, 2024b, 2025). The experiments cover a 1-year period (Aug 2023-Jul 2024) due to the concurrent availability of SWOT and FVON data as well as a unique set of independent observations including data from gliders, surface drifters and a research cruise (Figure 1).

In Kerry et al. (2026c) we assessed model performance using a typical approach; average statistics over the 1-year period that compare the model solutions with assimilated surface and subsurface observations and independent in situ observations. We presented an optimization strategy for the advanced data-assimilation configuration through adjustments to prior observation and model background uncertainty estimates and demonstrated that the updated configuration achieves an improved fit to assimilated and independent observations. We then used the updated configuration to assess the impact of SWOT and FVON observations in addition to the traditionally assimilated data streams (satellite-derived sea surface temperature and sea surface height from legacy altimeters, and temperature and salinity from Argo profiling floats). We showed that inclusion of SWOT data improved model representation of sea surface height across scales, subsurface temperature in the coastal and shelf regions, and surface velocities. Assimilation of FVON data significantly improved subsurface temperature representation in coastal and shelf regions.

Here we extend the system-wide assessment of SWOT and FVON observing system experiments (Kerry et al., 2026c) by examining four targeted case studies that diagnose how these observations improve the representation of complex fine-scale structures in the EAC. Specifically, we explore: (1) an independently observed research-cruise transect through a warm-core and cold-core eddy to assess whether different observing configurations produce consistent subsurface eddy structure; (2) an independent off-shelf glider transect to test whether FVON observations have impacts beyond the periods and locations in which they are assimilated; (3) a sharp temperature-front to evaluate whether high-resolution FVON profiles improve vertical structure that is poorly constrained by surface observations alone; and (4) a 30-day evolution of interacting eddies to determine whether SWOT improves eddy geometry and subsequent evolution. Together, these case studies demonstrate how SWOT and FVON observations provide complementary constraints on surface and subsurface ocean structure, with observation impacts projected across both time and space, while also highlighting the continuing challenges of accurately estimating fine-scale three-dimensional ocean states in an energetic western boundary current system.



**Figure 1.** (a) Mean Kinetic Energy from DUACS, with mean Eddy Kinetic Energy contours, showing the circulation in the EAC system and the EAC-ROMS model domain. (b) Location of assimilated Argo profile observations colour-coded by date. (c) Example of SWOT coverage for a 6-day period (6-12 Oct 2023). Note not all 6-day periods have such complete domain-wide SWOT coverage. (d) Location of assimilated FVON/FishSOOP observations. (e) Location of drifters, Moana sensors aboard the RV Investigator and glider observations used for independent verification. (f) Number of DUACS SSH and daily SST observations (after processing), (g) number of in situ observations (after processing), and (h) number of SWOT observations (after processing) per day. Case studies are shown by the grey boxes in (g): Case study 1.) 18-24 Oct 2023, Section 3.1, Case study 2.) 31 Oct-17 Nov 2023, Section 3.2, Case study 3.) 15-21 Apr 2024, Section 3.3, and Case study 4.) 14 Jun- 14 Jul 2024, Section 3.4. Figure modified from Kerry et al. (2026c), Figure 1.

## 2 Model and Data Assimilation System Configuration

Here we present a brief summary of the model and data assimilation methodology, which has been described more fully in Kerry et al. (2026c). For reference, in this paper we use only the updated/improved model configurations resulting from the



observing system experiments (from Kerry et al., 2026c, and described below) to explore the case studies (times shown in  
125 Figure 1g).

## 2.1 Study Region

The EAC, the WBC of the South Pacific subtropical gyre, advects warm water poleward along the southeastern coast of Australia (Figure 1a). The system is unique (compared to other WBCs) in that eddies often form along the latitudinal extent of the EAC while it is still attached to the coast, allowing eddies to directly influence shelf circulation (Schaeffer et al., 2014;  
130 Schaeffer and Roughan, 2015; Malan et al., 2023). The southward-flowing current is most coherent off 27° S (Sloyan et al., 2016), intensifies at around 31° S (Kerry and Roughan, 2020), before separating from the coast typically between 31° S and 32.5° S (Cetina Heredia et al., 2014). Upon separation, large warm-core eddies are shed and cold-core eddies are generated between them (Oke and Middleton, 2000; Cetina Heredia et al., 2014; Oke et al., 2019), forming an energetic eddy field in the Tasman Sea where eddies propagate and evolve (Pilo et al., 2015b, a). EAC eddies can display complex vertical structures,  
135 including tilting and stacking, as they interact with each other and with the continental shelf (Oke and Griffin, 2011; Macdonald et al., 2013; Roughan et al., 2017; Pilo et al., 2018; Rykova and Oke, 2022).

## 2.2 The Regional Ocean Modeling System Configuration

We use the Regional Ocean Modeling System (ROMS) to simulate the ocean circulation off the southeastern coast of Australia (EAC-ROMS, Figure 1a) between August 2023 - July 2024 as part of the South East Australian Coastal Ocean Forecast  
140 System (SEA-COFS, Roughan and Kerry, 2023). ROMS is a widely used free-surface, hydrostatic, terrain-following, primitive equation ocean model and is described by Haidvogel et al. (2000); Shchepetkin and McWilliams (2005). The model configuration used in this study has been used in various past studies of the EAC and is described in detail in Kerry et al. (2016, 2020, 2026a). The domain covers the latitudinal extent of the EAC system including the five core dynamical regimes from where the current jet is most coherent, the EAC separation region, the EAC retroflection, the region of high eddy activity associated with the  
145 EAC eastern extension, and the EAC southern extension (Oke et al., 2019).

The cross-shore horizontal resolution varies from 2.5 km over the continental shelf and gradually increases to 6 km offshore. The horizontal resolution is 5 km in the along-shore direction. Higher resolution over the shelf allows the steep topography to be maintained while minimizing pressure gradient errors that emerge in terrain-following coordinate schemes (Haney, 1991; Mellor et al., 1994). The model has 30 vertical *s*-layers with higher resolution in the upper 500 m to resolve mesoscale  
150 dynamics, a near-constant-depth surface layer to better resolve surface currents (De Souza et al., 2015), and higher resolution near the seabed for improved representation of the bottom boundary layer.

Initial conditions and boundary forcing are derived from the Bureau of Meteorology (BOM) Ocean Model Analysis and Prediction System (OceanMAPS) forecasts (Brassington et al., 2023). The boundary forcing is applied daily and misfits in baroclinic energy to the OceanMAPS condition are absorbed at the boundary via a flow-relaxation scheme. The model is  
155 forced at the surface with realistic atmospheric forcing derived from BOM's Australian Community Climate and Earth-System Simulator - Regional (ACCESS-R) atmospheric forecast. The atmospheric forcing fields are applied every 6 hours and used



to compute the surface wind stress and surface net heat and freshwater fluxes using the bulk flux parameterisation of Fairall et al. (1996). A longterm free-running configuration has been shown to accurately represent the mean dynamical features of the EAC and its surface and subsurface variability (Kerry and Roughan, 2020; Li et al., 2021, 2022).

## 160 **2.3 Observations**

Here we combine the EAC-ROMS hydrodynamic model with observations using four-dimensional variational data assimilation (4D-Var, Section 2.4) over a 1-year period (August 2023 - July 2024). The assimilated observations include a combination of the observations described in Sections 2.3.1-2.3.5 (refer to Table 1). Model experiments are compared to all observations, including observations that are independent to all experiments (Section 2.3.6).

### 165 **2.3.1 Nadir altimeter derived Sea Surface Height**

Along-track satellite altimetry data are merged to produce a global, daily, gridded ( $1/4^\circ \times 1/4^\circ$ ) mean sea level anomaly (SLA) product, computed with respect to a seven-year mean, using the Data Unification and Altimeter Combination System (DUACS). We use the level 4 gridded Near Real Time (NRT) product (CMS, 2024) which is produced for operations, delivered every day and uses a non-centered processing time-window with a 6-day delay (as future data is not available). We add the DUACS  
 170 SLA data to the dynamic sea surface height (SSH) mean from a longterm free running model such that the sea level data is consistent with the ROMS model configuration (a standard procedure shown to be effective in numerous studies, e.g., Moore et al., 2011a; Matthews et al., 2012a; De Souza et al., 2015; Kerry et al., 2016; Wilkin et al., 2022). As the DUACS gridded product poorly resolves continental shelf processes, we exclude SSH observations over water depths less than 1000 m.

### **2.3.2 Satellite-derived Sea Surface Temperature**

175 Four different sea surface temperature (SST) products are ingested for this study (VIIRS, VIIRS2, NAVO and AMSR2). For assimilation, we average all SST data to a grid of  $\sim 15$  km resolution (approximately 3 model grid cells by 3 model grid cells) and to daily intervals, and assimilate the data at midnight every day. This data thinning approach is employed such that the number of SST observations is of similar order of magnitude to the number of SSH observations (Figure 1f), ensuring that SST does not overly dominate the cost function (e.g. Kerry et al., 2016). SST data is removed inside the 300 m bathymetry contour.

### 180 **2.3.3 Argo floats**

Argo free-drifting profiling floats measure pressure, temperature and salinity of the upper 2000 m of the global ocean (www.argo.ucsd.edu, Figure 1b). The Argo data points are averaged to the model grid (in the horizontal and vertical) and a 5-minute time-step. Following Wilkin et al. (2022), we repeat the profiles every 2 hours within a two-day time interval (at actual time  $\pm 1$  day).



### 185 2.3.4 SWOT Sea Surface Height observations

The Surface Water and Ocean Topography (SWOT) mission uses both a Nadir altimeter and a Ka-band Radar Interferometer (KaRIN) to measure ocean surface topography. SWOT measurements are at a resolution of 2 km over a 130 km wide swath with near-global spatial coverage every 21 days. Here we use the noiseless SSH anomaly (SSHA) from the Level 3 v102 expert data (AVISO/DUACS, 2024; Tréboutte et al., 2023; Dibarboure et al., 2025). As with the gridded DUACS data (Section 2.3.1),  
 190 we add the SWOT SLA data to the dynamic SSH mean from a longterm free running model for assimilation. Six-day windows allow for several swath passes to be assimilated in each window (e.g. Figure 1c). SWOT data is used over shallow water depths.

### 2.3.5 Fishing Vessels as Ships of Opportunity (FishSOOP) subsurface temperature observations

Australia's Fishing Vessel Observation Network (FVON, known as FishSOOP in Australia) is a collaborative project between research and industry, initially co-funded by the Fisheries Research and Development Corporation (FRDC) and Australia's  
 195 Integrated Marine Observing System (IMOS), to install temperature sensors on commercial fishing vessels around Australia (Lago et al., 2025b). FishSOOP is a founding partner of the International Fishing Vessel Observation Network (FVON). Low-cost and robust temperature sensors (Zebratech Moana TD 200 m, 1000 m, or 2000 m sensors) are installed on the fishing equipment and collect data during routine fishing operations. The collaborative data collection has provided a step-change in the availability of in-situ temperature observations, primarily on and near the continental shelf (Figure 1c). Data are processed  
 200 using IMOS standards and quality control flags applied as per Lago et al. (2025a). The FVON observations will be hereafter referred to as FishSOOP in this paper.

### 2.3.6 Independent Observations

A suite of additional observations were also available over the simulation period that are not assimilated in any of the experiments. These provide independent observations against which we assess the performance of the model experiments  
 205 and allow us to objectively compare model representation of specific case studies across different experiments.

A 3-week research cruise aboard Australia's Marine National Facility, the RV Investigator, took place in Oct 2023. The cruise provides detailed 3-dimensional observations of oceanic eddies and fronts in the EAC (Azaneu et al., 2026), delivering a unique opportunity to comprehensively validate our subsurface ocean state estimates. Here we make use of data from Moana temperature sensors that were deployed on equipment during the research cruise (Figure 1e,h). In Section 3.1 we present these  
 210 observations through a cold-core eddy and across the eastern edge of a warm-core eddy.

Temperature and salinity data from ocean gliders, operated by IMOS, was available in Aug 2023, Oct 2023 and May-June 2024 (Figure 1e,g). Gliders are intended to measure across the continental shelf and most glider observations are confined to the shelf (water depths <1000 m) between 32-34°S. However, one mission extended off the shelf from 34-38°S from 31-Oct-2023 to 17-Nov-2023 before recovery (Figure 1e,g). This off-shelf glider transect is presented in Section 3.2.

215 Twenty-six Surface Velocity Program drifters (SVPs) from the Global Drifter Program (GDP; ) entered the model domain between August 2023 and July 2024 (Figure 1e), including 19 deployed during the 2023 research voyage. SVPs are satellite-



tracked buoys drogued at 15 m depth that measure surface current velocities, which are interpolated to six-hourly intervals in the GDP dataset. Drifter quality control follows the method described in Elipot et al. (2016). Surface velocities are low-pass filtered using a second-order Butterworth filter with a 25 hour cut-off to remove tidal and inertial oscillations (as in Tranchant et al., 2025). In Section 3.4 we present two drifters in a cold-core eddy and a warm-core eddy adjacent to the continental shelf at 34-36°S.

## 2.4 Data Assimilation Methodology

4D-Var data assimilation uses variational calculus to solve for increments in model initial conditions, boundary conditions, and forcing such that the differences between the observations and the new model trajectory is minimised – in a least-squares sense – over a specific assimilation window (Moore et al., 2004, 2011c). The goal is for the model to represent all of the observations in time and space using the physics of the model, and accounting for the uncertainties in the observations and background model state, producing a description of the ocean-state that is dynamically balanced and a complete solution of the nonlinear model equations. This is achieved by minimizing an objective cost function that measures normalized deviations of the modeled ocean state (given the increment adjustments to model initial conditions, boundary conditions, and forcing) from the observations as well as from the modeled background state (the model prior).

The minimization is performed through subsequent iterations of the tangent linear and adjoint models. Because we use the linearized model equations, the assimilation window length is limited by the time over which the tangent linear assumption remains reasonable. Here we assimilate observations over a 6-day window (refer to Kerry et al., 2026a, c), and the new ocean state estimate (the analysis) provides an improved estimate of the initial conditions for the next assimilation window.

To solve for the nonlinear ocean solution that better represents the observations, we must take into account the uncertainties in the system. As such, the background (prior model) uncertainty covariance matrix and the observation uncertainty covariance matrix are important scaling factors in the cost function. The background uncertainty covariance matrix should represent the expected uncertainties in the model initial conditions, surface and boundary forcings. The observation uncertainty should represent both the instrument error and errors of representativeness, which account for unresolved processes and scales in the model (Oke and Sakov, 2008). An iterative approach was used to determine appropriate prior assumptions of the background and observation uncertainties to produce improved analyses (refer to Section 2.5 of Kerry et al., 2026c). A detailed description of the assimilation methodology and configuration, including the specific prescribed prior observation and background uncertainties for the model experiments, is given in Kerry et al. (2026c).

The ROMS 4D-Var formulation and implementation is well described by Moore et al. (2011c, a, b), and it has been used successfully in many applications (e.g. Di Lorenzo et al., 2007; Powell et al., 2008; Powell and Moore, 2008; Broquet et al., 2009; Matthews et al., 2012b; Zavala-Garay et al., 2012; Janeković et al., 2013; Souza et al., 2014; Kerry et al., 2016; Gwyther et al., 2022b; Wilkin et al., 2022).



## 2.5 Model Experiments

We use the EAC-ROMS data-assimilating model configuration previously described in Kerry et al. (2016, 2018, 2020, 2026a).  
 250 For Kerry et al. (2026a, c) and this study, the model was configured over Aug 2023- Jul 2024 and used an updated ROMS  
 4D-Var algorithm (the Restricted B-preconditioned Lanczos). We adjust the model initial conditions only (boundary and  
 surface forcing are not included in the control vector) such that the new model solution (the analysis) better represents the  
 observations over the 6-day assimilation interval. The analysis then provides the initial conditions for the subsequent forecast  
 (model background estimate).

255 Here we make use of four experiments presented in Kerry et al. (2026c) with the improved data assimilation configuration  
 (refer to their Section 4, Table 1). The TRADshortTS experiment assimilates the ‘traditionally’ available observations: DUACS  
 SSH, SST and Argo profiling floats (Section 2.3.1 - 2.3.3). TRAD+FishSOOP assimilates the same observations as TRADshortTS  
 and also includes the FishSOOP observations (Section 2.3.5), TRAD+SWOTsh assimilates the ‘traditionally’ available observations  
 in concert with the SWOT SSH observations (Section 2.3.4), and TRAD+SWOT+FishSOOP assimilates the ‘traditionally’  
 260 available observations, SWOT SSH and the FishSOOP observations.

The spatial- and year-averaged mean absolute difference (MAD) for the observation platforms (Table 1) show the overall  
 average fit between the model experiments (sampled at the observation times and locations) and the observations. In Kerry et al.  
 (2026c) we used spatial- and year-averaged model-observation comparisons to provide an overall view of model performance  
 and the impact of SWOT and FishSOOP observations. The FishSOOP and drifter observations are independent to TRADshortTS  
 265 and TRAD+SWOTsh and, over the 1-year period, provide widespread coverage in space and time making them representative  
 independent observations for objective model assessment. Spatial- and year-averaged comparisons to the independent glider  
 and cruise observations provide less clear results as the independent observations are more isolated in time and space and  
 measure specific features. By presenting specific case studies below, we are able to reveal the complexities of the ocean  
 circulation and how the different model experiments represent these. This demonstrates specific, flow-dependent examples of  
 270 observation impact and provides a deeper understanding of the challenges faced in generating ocean state estimates and the  
 associated uncertainties.

## 3 Case Studies

We present four selected case studies to illustrate the impact and limitations of SWOT and FVON observations in resolving  
 complex fine-scale structures. These case studies are intended to complement the space-and-time averaged error statistics  
 275 (presented in Kerry et al., 2026c, summarized in Table 1) and provide further context.

### 3.1 Case study 1: Eddy structure observed by independent observations from a research cruise

Here we show an independently observed research-cruise transect through a warm-core and cold-core eddy to assess whether  
 different observing configurations produce consistent subsurface eddy structure. This case demonstrates that small horizontal



**Table 1.** Model experiments showing the spatial- and year-averaged MAD for the observation platforms and whether the observation platform is assimilated (✓) or not (×). For Argo temperature and salinity the MAD is given for the upper 1000 m.

| Model experiment:                                          | TRADshortTS          | TRAD+<br>FISHSOOP    | TRAD+SWOTsh          | TRAD+SWOT<br>+FISHSOOP |
|------------------------------------------------------------|----------------------|----------------------|----------------------|------------------------|
| Window length                                              | 6 days               | 6 days               | 6 days               | 6days                  |
| Initial conditions                                         | Previous<br>analysis | Previous<br>analysis | Previous<br>analysis | Previous<br>analysis   |
| Observation platforms:<br>MAD (whether assimilated or not) |                      |                      |                      |                        |
| DUACS SSH (cm)                                             | 5.6 (✓)              | 6.3 (✓)              | 4.5 (✓)              | 5.0 (✓)                |
| SWOT SSH (cm)                                              | 7.0 (×)              | 7.6 (×)              | 3.1 (✓)              | 3.4 (✓)                |
| Midnight SST (°C)                                          | 0.35 (✓)             | 0.37 (✓)             | 0.36 (✓)             | 0.37 (✓)               |
| Argo temperature (°C)                                      | 0.38 (✓)             | 0.36 (✓)             | 0.37 (✓)             | 0.38 (✓)               |
| Argo salinity                                              | 0.032 (✓)            | 0.033 (✓)            | 0.039 (✓)            | 0.039 (✓)              |
| FishSOOP temperature (°C)                                  | 0.92(×)              | 0.51(✓)              | 0.88(×)              | 0.54(✓)                |
| Moana temperature - Cruise (°C)                            | 0.73(×)              | 0.80(×)              | 0.79(×)              | 0.87(×)                |
| Glider temperature (°C)                                    | 1.40(×)              | 1.41(×)              | 1.67(×)              | 1.27(×)                |

misplacements of surface features can generate large subsurface temperature errors, motivating sustained subsurface observing  
 280 and uncertainty-aware state estimation.

Over the 6-day window from 18-24th Oct 2024 we compare the four model experiments (Table 1) to independent subsurface  
 temperature observations collected during the research cruise (Section 2.3.6). The assimilated and independent observations  
 available over the 6-day window are shown in Figure 2a. The independent observations collected during the research cruise  
 285 measure a section across the eastern edge of an anticyclonic warm-core eddy (WCE) at  $\sim 35^\circ\text{S}$  and through a cyclonic cold-  
 core eddy (CCE) at  $\sim 38^\circ\text{S}$  (Figure 2c). The assimilation period corresponding to this case study (18-24th Oct 2024) occurs 78  
 days (13 6-day windows) after the beginning of the experiment period, with the four model experiments evolving differently  
 due to assimilation of different data streams (in concert with the ‘traditionally’ available observations). The overall structure  
 of the SSH, SST and mixed layer depth (MLD) fields appears similar across the four experiments (Figure 2b-d).

Assimilation of SWOT data improves the fit to SWOT data by 52% (for TRAD+SWOTsh compared to TRADshortTS)  
 290 and 50% for (for TRAD+SWOT+FishSOOP compared to TRAD+FishSOOP, Figure 3a-d), computed based on the domain-  
 averaged MAD between the models and the SWOT observations for the 6-day window. FishSOOP observations were available  
 on the continental shelf at  $\sim 37^\circ\text{S}$  (Figure 2a, bottom panel) and the assimilation of FishSOOP data gives reduced bias and  
 MAD at the FishSOOP observation locations (compare Figure 3g and h, and Figure 3i and j). TRAD+SWOT+FishSOOP gives

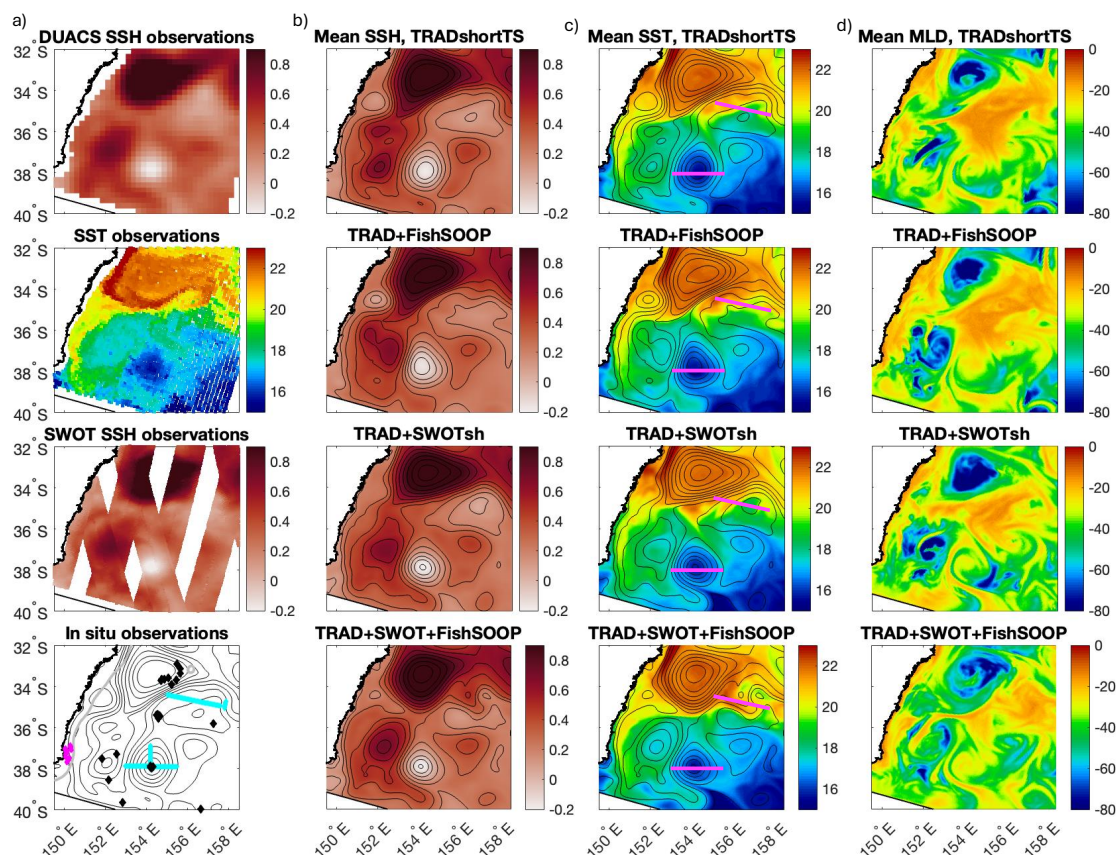


an absolute improvement of 89% in bias and a 45% improvement in MAD compared to TRAD+SWOTsh for the FishSOOP  
 295 observations available over the assimilation window, and TRAD+FishSOOP gives an absolute improvement of 51% in bias  
 and an 18% improvement in MAD compared to TRADshortTS.

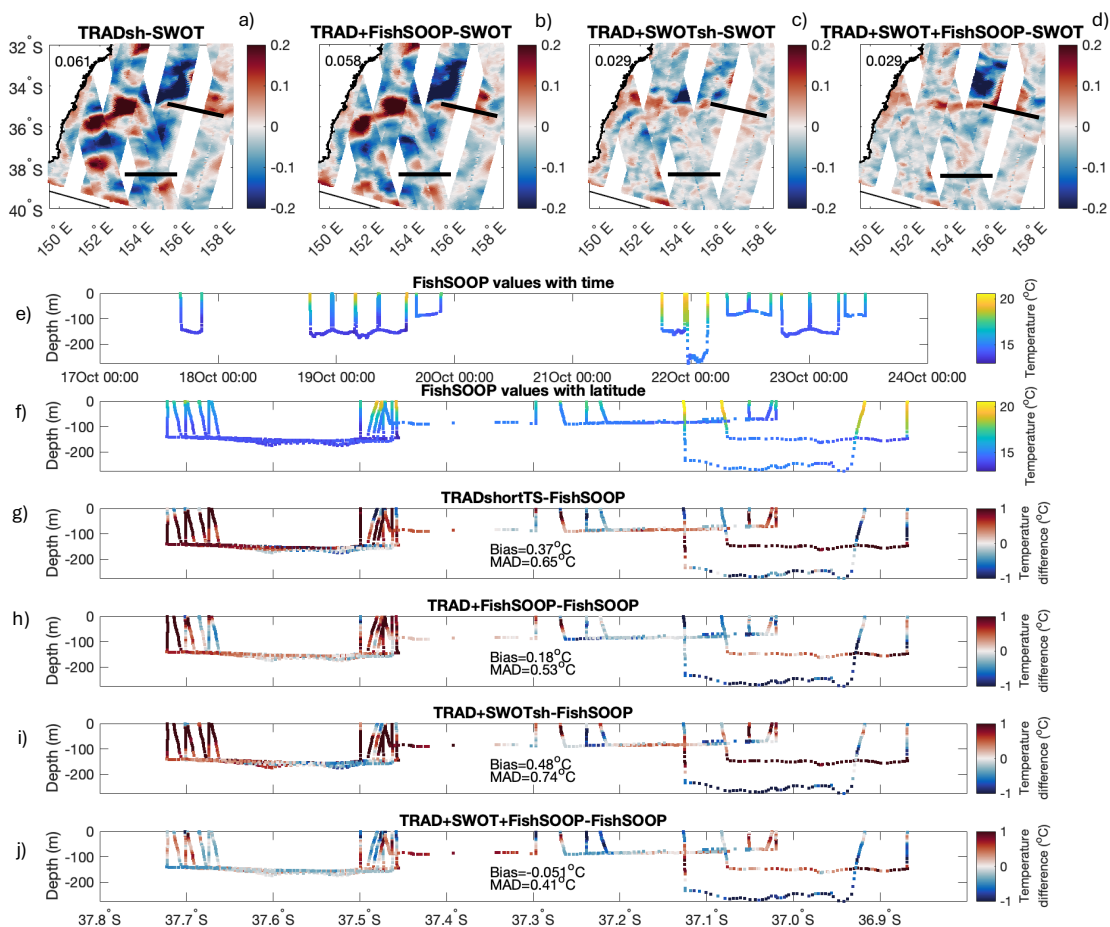
The structure across the edge of the WCE shows overall agreement to the observations for the TRADshortTS, TRAD+FishSOOP  
 and TRAD+SWOTsh experiments, with upward tilting isotherms at the edge of the WCE into the adjacent cyclonic eddy, and  
 MAD to the independent observations of 0.82-0.89°C (Figure 4, top panels for the WCE). TRAD+SWOT+FishSOOP has  
 300 a warmer surface layer due to slight misplacement of the feature extending east of the WCE (Figure 2c, bottom panel, and  
 Figure 3d) and a subsequent MAD of 1.71°C when compared to the cruise observations in the WCE (92-108% higher than  
 for the other experiments). The cruise section that observed the edge of the WCE took place on 23-24 Oct (the final day  
 of the 6-day assimilation window), while SWOT observed the feature 3 days earlier (20-21 Oct). This notable difference in  
 TRAD+SWOT+FishSOOP compared to the other experiments highlights how small misplacement in an oceanic feature can  
 305 result in considerable misrepresentation when compared to independent observations.

The CCE structure is generally well represented across all four experiments with isotherms tilting upwards towards the  
 eddy centre, and MAD to the independent observations of 0.43-0.57°C (Figure 4, bottom panels for the CCE). Two SWOT  
 passes overlapped across the CCE on 20-21 Oct and the CCE was (intentionally) concurrently measured by the cruise on the  
 20 Oct. While the fit to SWOT over the CCE (and elsewhere) is considerably improved in the experiments that include SWOT  
 310 (TRAD+SWOTsh and TRAD+SWOT+FishSOOP, Figure 3c,d), both experiments that include SWOT have higher MAD  
 against subsurface observations across the CCE collected on the cruise than their counterpart without SWOT (TRAD+SWOTsh  
 has a 32% higher MAD than TRADshortTS and TRAD+SWOT+FishSOOP has a 17% higher MAD than TRAD+FishSOOP).

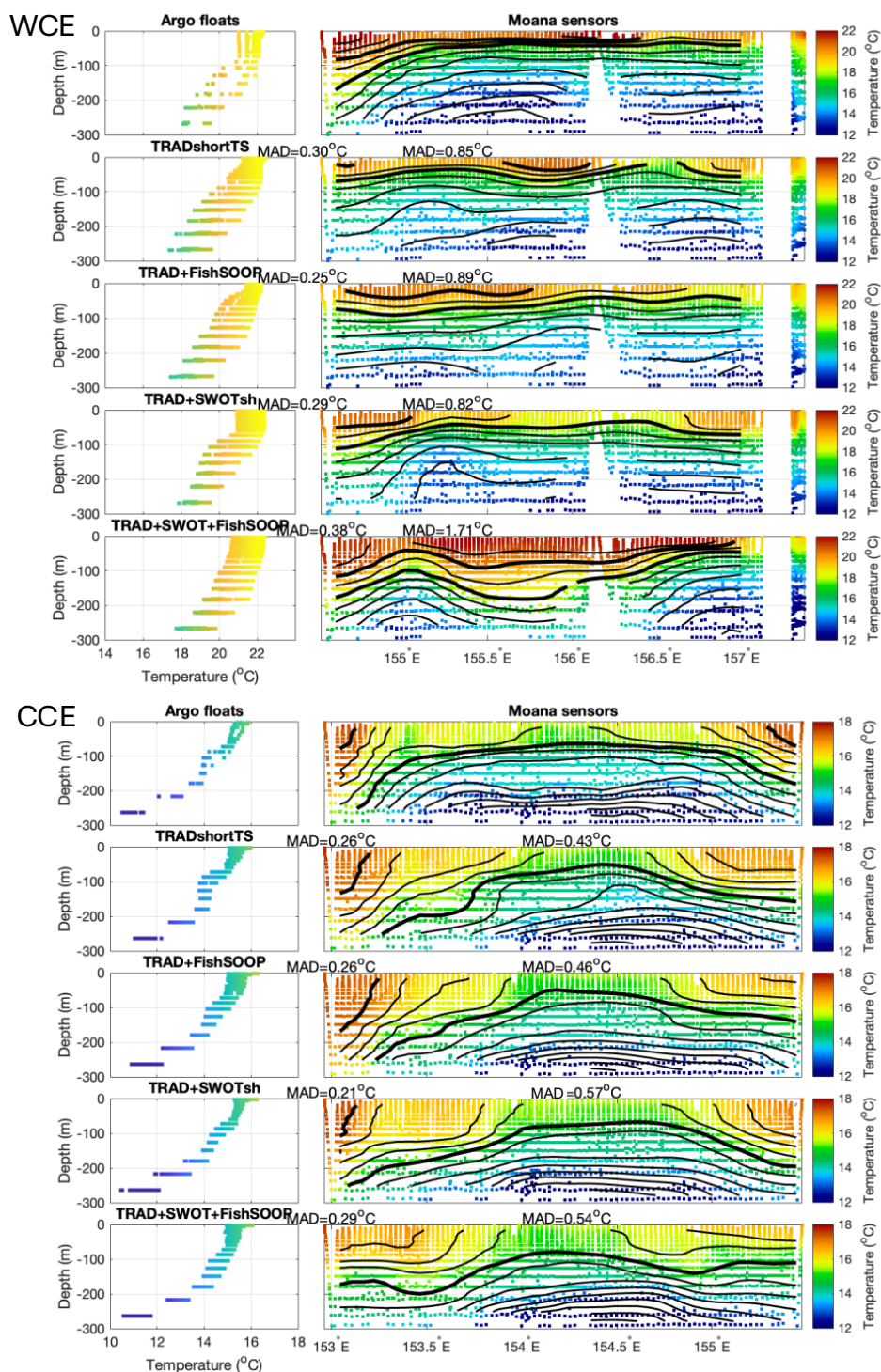
There is no clear improvement in the model representation of the WCE or CCE structures with the assimilation of SWOT or  
 the isolated FishSOOP observations (on the south-eastern continental shelf for this 6-day window and for previous windows  
 315 up until this time). This is in contrast to year-average statistics in Kerry et al. (2026c) which show overall improvement  
 in independently observed subsurface representation with assimilation of SWOT. This case study demonstrates that the model  
 experiments evolve differently as they attempt to best fit to the observations. The independent observations reveal the complexities  
 of subsurface structure and how different model experiments can represent different subsurface structures. Further, the results  
 motivate the need for subsurface observations to help constrain the surface adjustments. With 4D-Var, only a single model  
 320 state estimate is generated; however, the differences shown here and the considerable impact of a small misplaced oceanic  
 feature (in TRAD+SWOT+FishSOOP, Figure 2c, Figure 4) suggest an ensemble of solutions would be useful. This would  
 allow quantitative evaluation of the expected surface and subsurface structure and the associated uncertainty.



**Figure 2.** (a) Observations for 18-24 Oct 2023 window, and (b-d) Mean modeled SSH (m), SST ( $^{\circ}$ C) and mixed layer depth (m) for 18-24 Oct 2023 window. Magenta lines show the WCE and CCE sections observed by the RV Investigator cruise, presented in Figure 4.



**Figure 3.** (a-d) SSH differences between the model values (extracted at SWOT observation times and locations) and the SWOT observations for 18-24 Oct 2023 window with domain averaged MAD in top left corner (m), and (e) FishSOOP observations with time and (f) with latitude for the 18-24 Oct 2023 window, and (g-j) model fit to FishSOOP observations over the 6-day window, with the model-observation bias and MAD given in the figure panels.



**Figure 4.** Model representation compared to independent Moana observations observed on the RV Investigator cruise of the WCE (top panels) and CCE (bottom panels) for the 18-24 Oct window. Bold contours in the WCE show the 18°C and 20°C isotherms, and in the CCE show the 15°C and 17°C isotherms. Argo floats shown are to the west of the WCE section, and in the centre of the CCE, respectively (refer to Figure 2a, bottom panel).



### 3.2 Case study 2: Independent glider observations reveal the sustained impact of FishSOOP data

Here we use an independent off-shelf glider transect to test whether FishSOOP observations have impacts beyond the time and locations in which they are assimilated. This case study shows that assimilating FishSOOP data over the preceding 90 days produces sustained improvements in subsurface temperature, reducing bias and MAD through the upper 200 m.

Glider observations are intended to routinely measure across the continental shelf along the inside edge of the EAC (e.g. as per Schaeffer et al., 2015), so most glider observations for the 1-year experiment period are confined to the continental shelf between 32-34°S. However, one mission extended off the shelf from 31 Oct 2023 to 17 Nov 2023 providing high spatial resolution independent observations to 200 m depth spanning a longitudinal section from 34-38°S (Figure 5). The glider deployment occurs 90 days (15 6-day windows) after the beginning of the experiment period. The subsurface temperature as measured by the glider, and the model realizations (at the corresponding glider times and locations) reveal differences across the model experiments (Figure 5, middle panels) as the four model experiments evolve differently due to assimilation of different data streams.

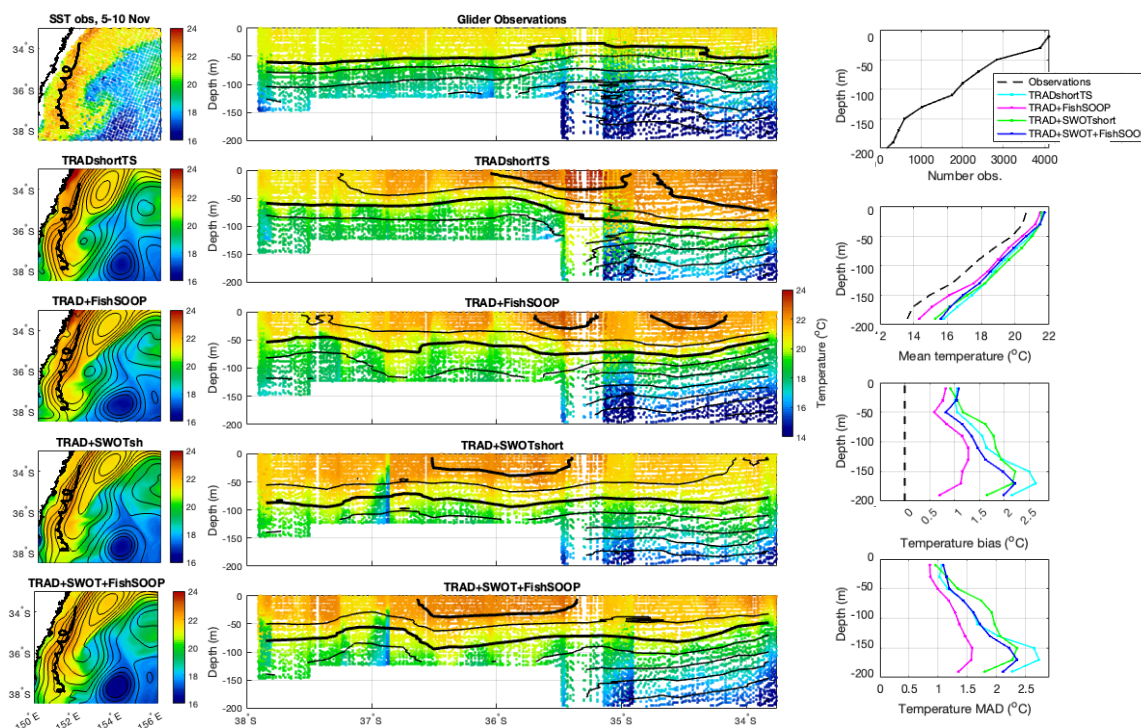
Averaged over all glider observations (the longitudinal transect) and binned with depth, the TRAD+FishSOOP experiment exhibits the lowest temperature bias and the lowest MAD (Figure 5, right panels), with the greatest improvement from 50-200 m. The assimilation of FishSOOP data in concert with the ‘traditionally available’ observations (TRAD+FISHSOOP compared to TRADshortTS) gives bias reduction of 20-60% and reduction in MAD of 15-42% throughout the observed depths (0-200 m). With the addition of SWOT data, the improvement against the independent glider observations with the inclusion of FishSOOP data (TRAD+SWOT+FishSOOP compared to TRAD+SWOTshort) is up to 30% for temperature bias and up to 18% for MAD.

Over the 90-day period leading up to the glider deployment (1 Aug - 30 Oct 2023), FishSOOP observations in the model domain were available over the south eastern region (Figure 6a). For the glider deployment period (31 Oct - 17 Nov) no FishSOOP observations were available within the model domain. The improvement (for TRAD+FishSOOP and TRAD+SWOT+FishSOOP) in both subsurface temperature bias and MAD as compared to independent glider observations taken directly after a 90-day period over which FishSOOP data was assimilated demonstrates the sustained positive impact of FishSOOP observations.

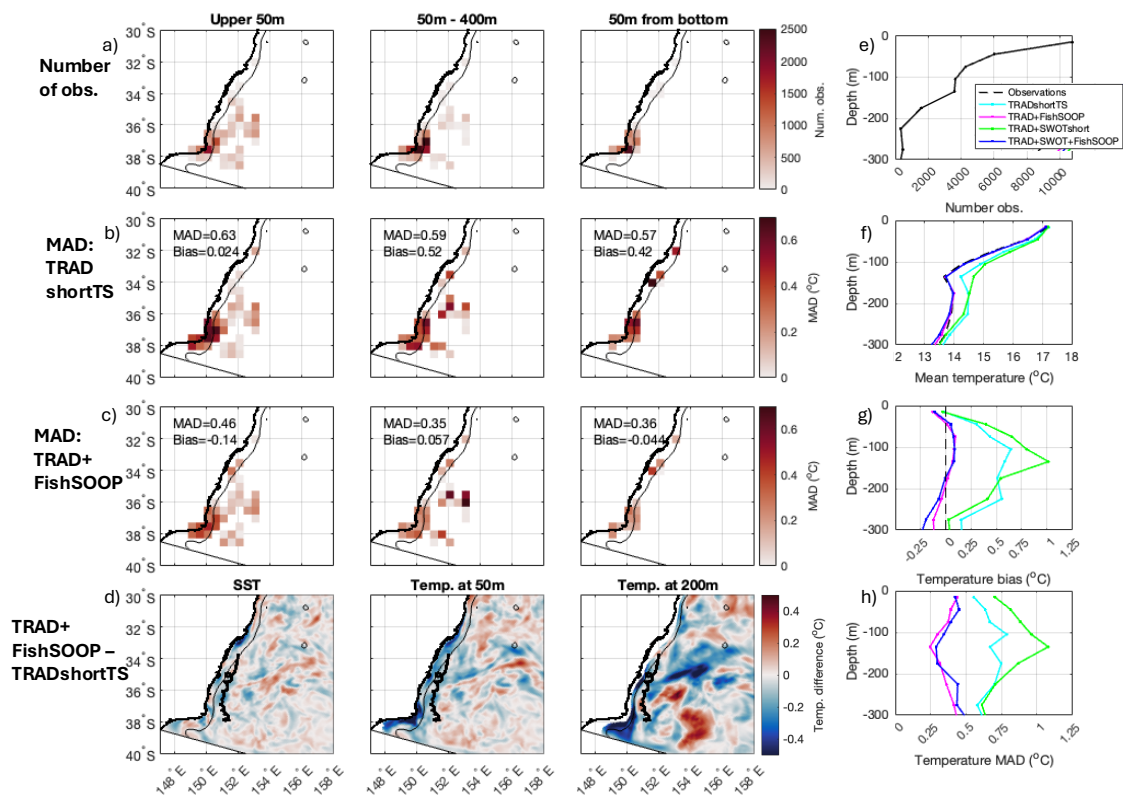
The spatial coverage of the FishSOOP observations (from 1 Aug - 30 Oct 2023) and the associated bias and MAD for the models compared to the FishSOOP observations for three chosen depth ranges (upper 50 m, 50-400 m and 50 m above the ocean bottom) are shown in Figure 6a-c. Temperature bias and MAD between the models and the FishSOOP observations is considerably reduced when the FishSOOP observations are assimilated (compare Figure 6b with 6c; also spatially-averaged and depth-binned profiles are shown in Figure 6f-h). With the assimilation of the FishSOOP data over the 1 Aug - 30 Oct 2023 period, the consequent differences in the mean modeled temperature fields are marginal for SST, and greater over the depth range of 50-200 m (differences at 0 m, 50 m and 200 m shown in Figure 6d) in line with the bias reduction (Figure 6g). These adjustments provide sustained improvement in model representation over the following 3-week period, as observed by the independent glider observations. Specifically, cooler subsurface temperatures (Figure 6d) contribute to reduced bias and MAD against glider observations, particularly from 50-200 m (Figure 5, right panels).



In Kerry et al. (2026c) we showed that on average (over the 1-year period) assimilation of observations from SWOT improved the fit to FishSOOP observations. However, for this 90-day period the bias and MAD are degraded with the inclusion of SWOT observations (in the absence of FishSOOP observations, TRAD+SWOTshort compared to TRADshortTS in Figure 6f-h).



**Figure 5.** (Left panels) SST observations for 5-10 Nov and mean modeled SST analysis fields for 5-10 Nov assimilation window. Black line shows the glider track from 31 Oct 2023 to 17 Nov. (Middle panels) Independent glider observations and the corresponding model analysis representation for 31 Oct 2023 to 17 Nov 2023 glider mission. (Right panels) Number of glider observations with depth for 31 Oct 2023 to 17 Nov 2023 glider mission, mean temperature from gliders and model analyses, temperature bias and temperature MAD.



**Figure 6.** a) Number of FishSOOP observations from 1 Aug 2023 up to Oct 30th 2023 for three depth ranges; the upper 50 m, 50-400 m and 50 m above the bottom, binned into  $0.5^\circ$  cells. b) MAD between FishSOOP observations and TRADshortTS model extracted at FishSOOP times and locations, binned into  $0.5^\circ$  cells. c) Same as b) but for TRAD+FishSOOP model. d) Average model field differences from 1 Aug 2023 - 30 Oct 2023 (TRAD+FishSOOP - TRADshortTS) for SST, temperature at 50 m and temperature at 200 m. (e) Number of FishSOOP observations with depth from 1 Aug 2023 up to Oct 30th 2023, (f) mean temperature from FishSOOP and model analyses, (g) temperature bias and (h) temperature MAD.

### 3.3 Case study 3: FishSOOP observations reveal ocean structure across a sharp temperature front

Here a sharp temperature-front is observed by FishSOOP and we use the case study to evaluate whether high-resolution FishSOOP profiles improve modeled vertical structure (that is poorly constrained by surface observations alone). This case study presents an example where FishSOOP observations across a sharp temperature front provide valuable information on subsurface structure, that is not otherwise observed by Argo profiling floats or represented by the model with the assimilation of satellite-derived surface data and Argo floats alone. The case study shows that assimilation of in situ temperature data from FishSOOP sharpens the surface front in the model, improves mixed layer depth structure, and reduces model-observation differences across the front, providing wide spread changes to the subsurface ocean structure away from the observations.



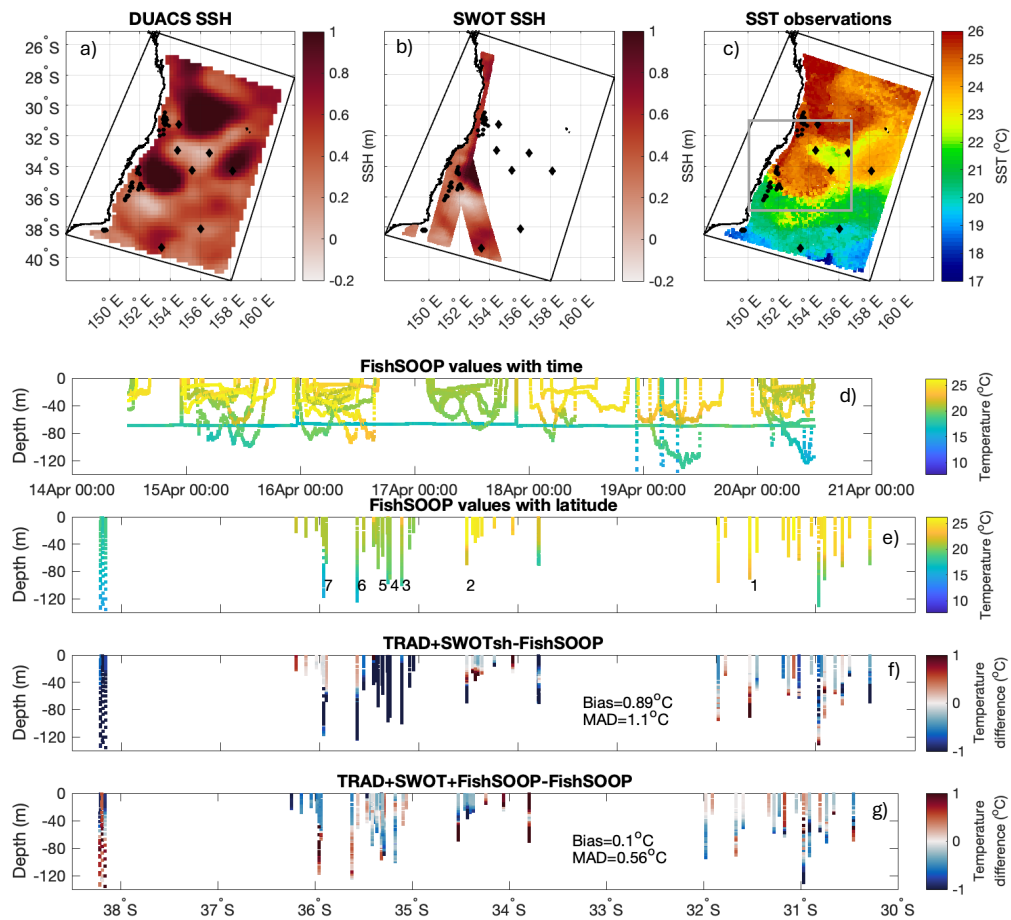
This case study focuses on a single 6-day window from 14-20 Apr 2024. We present a comparison of the TRAD+SWOTsh experiment and the TRAD+SWOT+FishSOOP experiments (refer to Table 1) to elucidate the impact of FishSOOP data. We use the experiments that assimilate SWOT data as SWOT data has been shown to provide better representation across fronts (Kerry et al., 2026a).

The surface observations (Figure 7a-c) reveal the EAC separating from the coast at  $\sim 35^{\circ}\text{S}$  forming a large WCE with a sharp temperature gradient along its southern flank. FishSOOP observations (small black dots in Figure 7a-c) provide in situ temperature data near the continental shelf (the structure in time and space shown in Figure 7d-e), including data that crosses the temperature front. Assimilation of the FishSOOP data provides an 11% improvement in bias and a 49% improvement in MAD between the models and the FishSOOP observations over the 6-day window (Figure 7f,g).

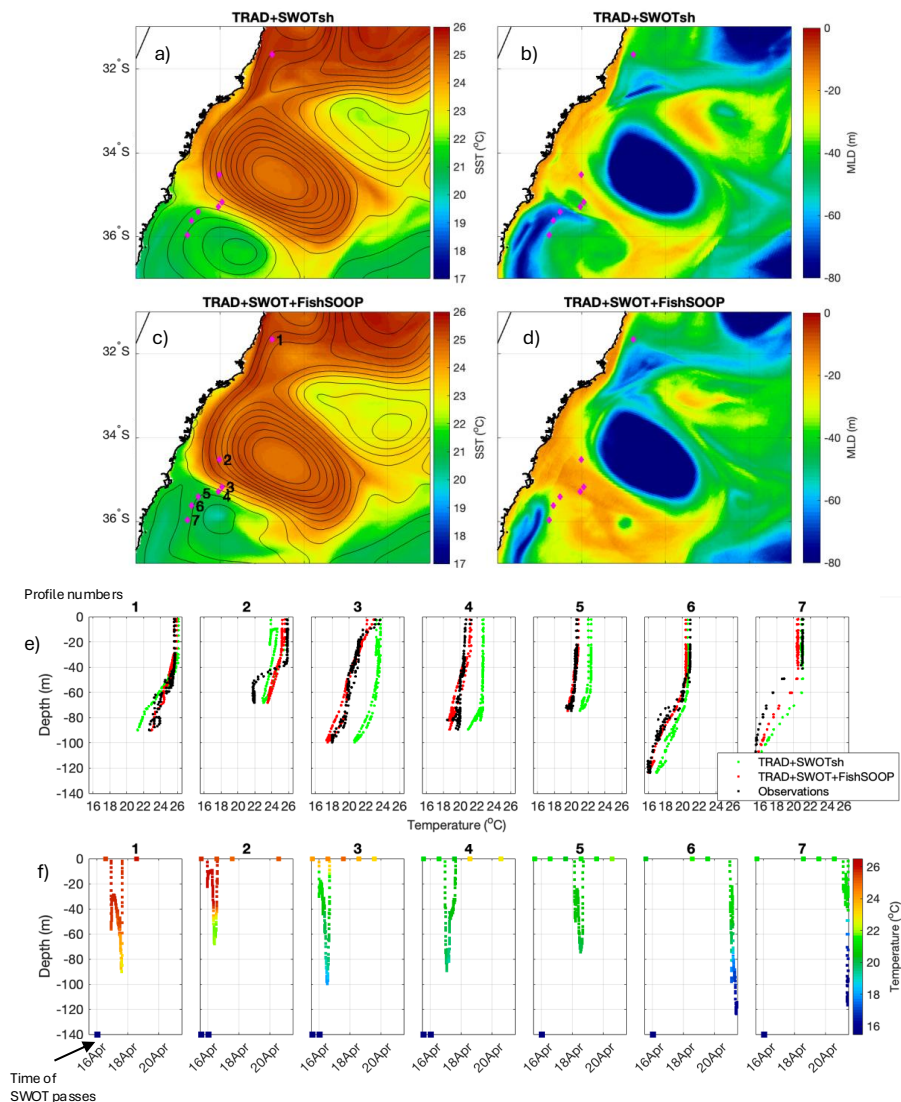
Specific FishSOOP profiles are presented here to reveal the observed and modeled representation of the subsurface structure upstream in the EAC (profile 1), inside the WCE (profile 2), across the front (profiles 3-5) and in the CCE (profiles 6-7, Figure 8). Upstream in the EAC jet (profile 1) both models represent the observed temperature structure well (Figure 8e, profile 1). As the EAC separates from the coast, on the western side of the WCE (Figure 8e, profile 2), FishSOOP data shows a distinct mixed layer and a sharp temperature gradient from 40-50 m; while assimilating FishSOOP data results in better representation of the surface layer, the sharp gradient is not represented in either model. Profiles 3 and 4 observe across the sharp temperature front at the southern edge of the WCE. In TRAD+SWOTsh the surface temperature changes more gradually across the front (profiles 3-5) and the mixed layer is deeper ( $\sim 60$  m). The TRAD+SWOT+FishSOOP model is constrained by the FishSOOP observations and considerably better represents the sharpness of the temperature front at the surface and the front's associated subsurface structure (Figure 8e, profiles 3-5).

Profile 3 is located directly on the southern edge of the WCE and the subsurface structure observed by FishSOOP reveals that the warm surface layer is thin as the WCE overwashes the cold water to the south (seen in Figure 8e,f, profile 3). While the TRAD+SWOTsh experiment correctly represents the SST at profile 3's location, the subsurface structure is not correctly represented (Figure 8e, profile 3). The overwashing results in a considerably shallower mixed layer (than was represented by TRAD+SWOTsh). By assimilating the FishSOOP data across the front (in TRAD+SWOT+FishSOOP) the information on mixed layer depth (observed by profile 3) is projected in space (compare Figure 8b and Figure 8d) to modify the model estimate of mixed layer depth and frontal structure beyond the observed locations. Further, the sharpness of surface temperature front (from profiles 3-5) is better represented when FishSOOP data is assimilated (TRAD+SWOT+FishSOOP, compared to TRAD+SWOTsh). The SWOT pass that observes the front (Figure 7b) is at the start of the assimilation window (Figure 8f), and while the front is sharper than without SWOT (TRADshortTS, not shown) it is still not as sharp as when constrained by the FishSOOP data. We note that the resolution of the available SST data was not fully exploited in this study (refer to Section 4).

In the CCE (profiles 6 and 7) the surface layer temperature is well represented in both models, but the below layer gradient is better represented with the assimilation of FishSOOP data. TRAD+SWOT+FishSOOP has a shallower mixed layer and a steeper gradient below the mixed layer (than TRAD+SWOTsh) that better matches observations (Figure 8e, profiles 6,7).



**Figure 7.** (a-c) Surface observations and locations of FishSOOP (black circles) and Argo (black diamond) insitu observations for 15-21 Apr 2024 window. (d) Representation of FishSOOP observations with time for the 6-day window. (e) Representation of FishSOOP observations with latitude, (f) difference between TRAD+SWOTsh model and FishSOOP observations, and (g) difference between TRAD+SWOT+FishSOOP model and FishSOOP observations. Bias and MAD are given in panels f) and g).



**Figure 8.** Model fields of SST and mixed layer depth (MLD) for TRAD+SWOTsh (a-b) and TRAD+SWOT+FishSOOP (c-d), with selected FishSOOP profiles shown and numbered in (c). (e) Selected FishSOOP profile observations and corresponding model values extracted at FishSOOP times and locations and (f) FishSOOP observation structure with time. SST observations within 2 grid cells of the FishSOOP profile location are shown at the surface, and times of the SWOT passes are shown at the bottom.

### 3.4 Case study 4: Assimilation of SWOT data improves eddy shape and subsurface structure

In this case study, we follow the 30-day evolution of interacting eddies to determine whether SWOT improves eddy geometry and subsequent evolution. This case study demonstrates that SWOT assimilation improves eddy shape even away from direct



SWOT observations, improves agreement with independent drifter trajectories, and reduces differences against independent  
 405 subsurface FishSOOP observations.

We follow a series of three eddies over a 30-day period from 14 Jun to 14 Jul 2024 (5 6-day assimilation cycles, Figure 1g, Figure 9). The WCE, centered on  $\sim 36^{\circ}\text{S}$ , is flanked by two cyclonic eddies (CCEs) to the north and south. Here we compare the evolution of the TRADshortTS and the TRAD+SWOTsh models to demonstrate the impact of SWOT data. Independent drifter observations (Section 2.3.6) observe both the WCE and the northern CCE. Argo profiling floats are assimilated into both  
 410 experiments and FishSOOP data is independent to both experiments (as per Table 1).

Over the first 6-day window of the period (14-20 Jun, Figure 9, row 1) SWOT observations provide very good spatial coverage of the eddies and there is a notable difference between the model that assimilates SWOT (TRAD+SWOTsh) and the one that does not (TRADshortTS). Specifically, SWOT data provides improved representation of the southern CCE and the shape of the WCE; the CCE is stronger in TRAD+SWOTsh and is pushing up against the southern edge of the WCE.

415 This has significant impact on the subsequent assimilation window (20-26 Jun, Figure 9, row 2) in which SWOT data is absent over the area of interest. The stronger CCE in TRAD+SWOT moves NW and squashes the WCE to form a stronger WCE whose position is considerably better represented (in TRAD+SWOTsh compared to TRADshortTS) even in the absence of SWOT data in this window. The improved representation of the WCE is evident by the trajectory of the independent drifter observations from 20-26 Jun that follow closely the shape of the WCE in TRAD+SWOTsh (Figure 9, row 2).

420 For the third and fourth windows (26 Jun - 2 Jul and 2-8 Jul, Figure 9, rows 3 and 4) the SWOT observations continue to constrain the shape of the eddies. The WCE (as observed by the independent drifter data) remains considerably better represented with the inclusion of SWOT data. For the fifth window (8-14 Jul, Figure 9, row 5), the WCE in TRADshortTS has evolved to a shape closer to the drifter observed shape; however, the southern CCE remains weaker (than in TRAD+SWOTsh) and the northern CCE is positioned too far to the west. In contrast, the position of the northern CCE in TRAD+SWOTsh  
 425 matches well with the independent drifter observations.

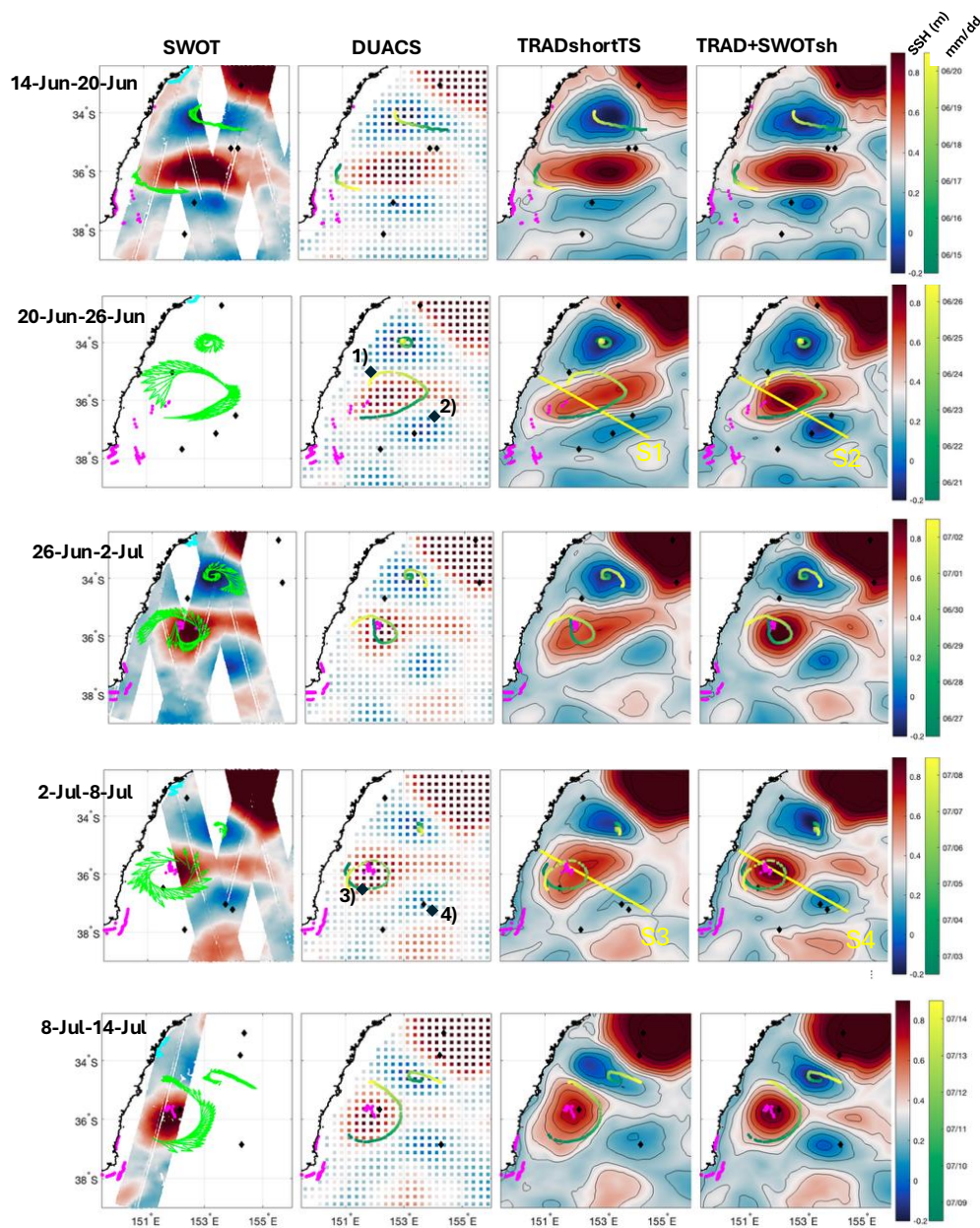
FishSOOP data over this 30-day period observed in situ temperature to  $\sim 150$  m depth over and directly offshore of the continental shelf between  $37-38^{\circ}\text{S}$ , and at the centre of the WCE at  $\sim 36^{\circ}\text{S}$  (magenta dots in Figure 9). FishSOOP data is independent to both TRADshortTS and TRAD+SWOTsh. The distribution of the FishSOOP data in time and space is illustrated in Figure 10a,b. By assimilating SWOT (in TRAD+SWOTsh), and therefore better representing the location, shape and strength  
 430 of the eddies, to fit to independent FishSOOP data is improved by 48% (improvement in MAD for all FishSOOP data available over the 30-day period, Figure 10c,d).

Comparison of model representation of cross sections through the eddies reveal the subsurface structure associated with the smaller, deeper and stronger WCE as a result of SWOT data assimilation (Figure 10, S2 compared to S1, and S4 compared to S3). For Argo float 2) (on the eastern side of the WCE on 20-26 Jun), TRADshortTS gives a surface layer that is too warm, as  
 435 the WCE spreads eastward without constraint from SWOT. Argo float 1) (on the western side of the WCE) and the FishSOOP data (also observing the western side of the WCE) are well represented in both TRADshortTS and TRAD+SWOTsh (Figure 10e). For the 2-8 Jul window (Figure 10f), the average temperature measured by the FishSOOP data at the centre of the WCE is better represented by TRAD+SWOTsh. Argo float 4) (in the southern CCE) is well represented in both models. Argo float

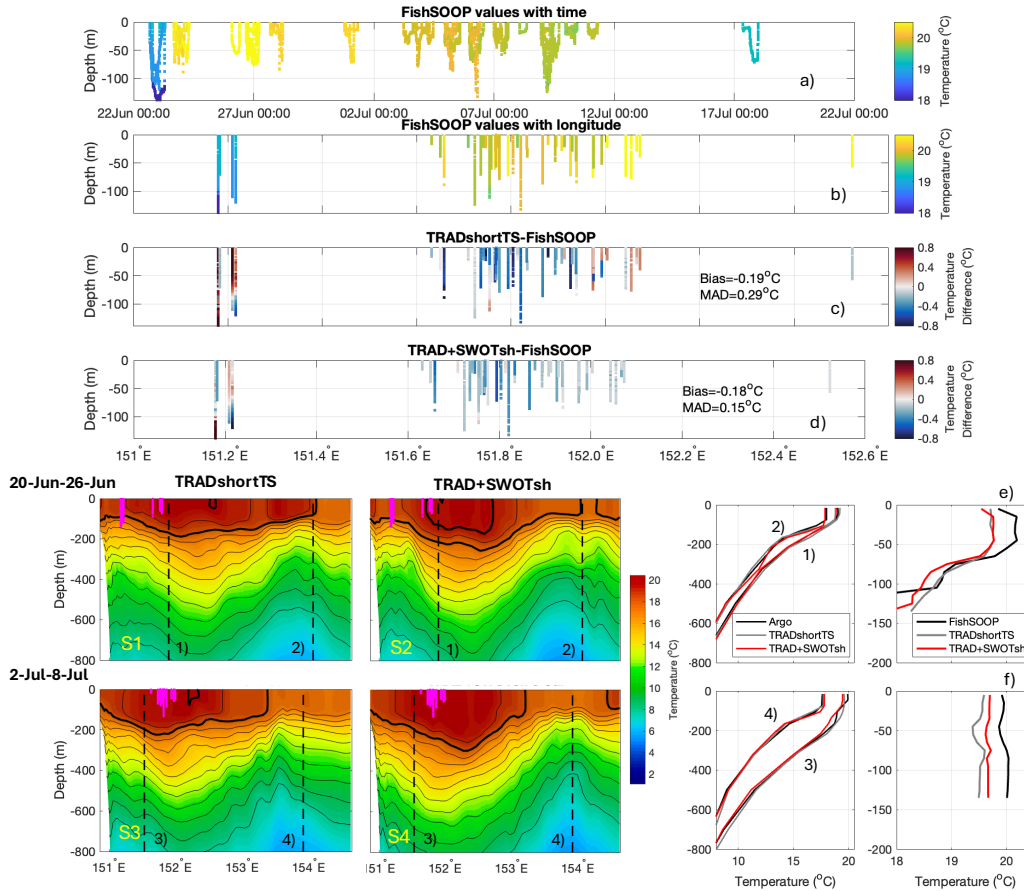


3) (at the southern edge of the WCE) observes some stacking and the structure is better represented by TRAD+SWOTsh.  
440 Specifically, the shallow mixed layer depth is well represented by TRAD+SWOTsh compared to TRADshortTS; however the  
step-like structure below 100 m is not represented and the profile shape from 150-250 m is better represented by TRADshortTS.

This profile (Argo float 3) demonstrates an example of complex subsurface structure and how this can be (mis)represented  
in model state estimates, where the data assimilation system attempts to provide a best-fit between the model and various  
data streams, taking into account the uncertainties associated with all of the observations and the model background. These  
445 necessary limitations are important to understand when interpreting model estimates, particularly when complex subsurface  
structure exists and can be significant (for example for subsurface marine heatwaves or understanding the subsurface distribution  
of biota).



**Figure 9.** SWOT SSH, DUACS SSH and modeled SSH for TRADshortTS and TRAD+SWOTsh for five consecutive 6-day assimilation windows from the 14 Jun 2024 through to the 14 Jul 2024. Argo floats are shown as black diamonds and FishSOOP observations as magenta dots. Drifter trajectories are shown as arrows in the left panels, and color-coded with time in the other panels. For the SWOT, Argo, FishSOOP and drifters, all observations over the 6-day window are shown. For DUACS and modeled fields, the middle time of the 6-day window is shown.



**Figure 10.** FishSOOP observations inside the WCE that is observed by drifters in Figure 9, a) observations with time, b) observations with longitude, c) difference between TRADshortTS model and FishSOOP observations, d) difference between TRAD+SWOTsh model and FishSOOP observations. Subsurface structure for 20-26 Jun (e) and 2-8 Jul (f) time windows. Sections through the eddies (shown in Figure 9) are modeled temperature at the middle time of the window. Comparisons of two Argo profiles (shown in Figure 9) and the (average of all) FishSOOP data at the centre of the WCE are shown.

#### 4 Discussion and Conclusions

Here we presented a series of data assimilating experiments to demonstrate the impact of SWOT and FVON observations  
 450 on ocean state estimates of a dynamic western boundary current region. Combining traditionally-available observations and  
 novel SWOT and FVON data with a high-resolution regional model of the EAC, using a proven 4D-Var data assimilation  
 infrastructure, we previously assessed observation impact based on model-observation differences averaged over a 1-year  
 period (Kerry et al., 2026c). We showed that the inclusion of SWOT data improves model representation of sea surface  
 height across scales, subsurface temperature in the coastal and shelf regions, and surface velocities. Results also showed that



455 assimilation of FVON data significantly improves subsurface temperature representation in coastal and shelf regions. While such temporally and/or spatially averaged statistics are useful and commonly used to assess the overall performance of data-assimilative systems, specific case studies can demonstrate details of model estimate differences and provide specific examples of observation impact in time and space. In this manuscript, we presented select case studies that demonstrate the impact of SWOT and/or FVON observations in resolving complex surface and subsurface fine-scale structures.

460 A data assimilation system aims to reduce the difference between the ocean model estimate and a variety of observations, taking into account uncertainties associated with both the observations and the model background state. Different observing system experiments will evolve differently as the data assimilation system attempts to fit to different data streams, account for (prior specified) errors, and project information from the observations onto the new model state in time and space. Such differences are evident in Case study 1 (Section 3.1) where the surface fields and subsurface structures qualitatively  
 465 match across most experiments (Figure 2, Figure 4). The exception is an example of a small misplacement of a surface feature (in TRAD+SWOT+FishSOOP) resulting in considerable errors against independently observed subsurface temperature observations. This example shows that small horizontal feature misplacements can generate large subsurface temperature errors, demonstrating the value of additional subsurface data streams and the need for uncertainty-aware state estimation (such as from ensembles). Ensemble simulations to account for uncertainty in the locations of mesoscale features and to filter-out  
 470 unconstrained scales can provide significant benefit to mesoscale predictability and provide important uncertainty estimates for decision makers (Thoppil et al., 2021; Hoteit et al., 2025). Further, estimating uncertainty both at constrained and unconstrained scales is key to producing reliable and useful predictions while capturing the ocean's fine-scale dynamics (Jacobs et al., 2021).

With advanced time-dependent data assimilation, information contained in the observations is projected into model space to provide adjustments to the model state in both time and space. Within an assimilation window, observation information  
 475 is projected onto the model state directly via the data assimilation scheme. Improvements are also carried into subsequent assimilation windows due to the updated (improved) initial conditions. This sustained improvement in time is evident in Case study 2 (Section 3.2) where assimilation of FVON data over a 3-month period persisted for weeks after the observations were no longer available, reducing independent glider temperature bias by 20–60% and MAD by 15–42% through the upper 200 m. Improvement sustained across assimilation windows is also demonstrated in Case study 4 (Section 3.4) where SWOT data  
 480 improves the representation of small cyclonic eddy that subsequently improves the evolution of adjacent anticyclonic eddy (that is not constrained by SWOT). Over a 30-day period, SWOT assimilation improved eddy shape and subsequent eddy evolution, including during periods and locations without direct SWOT coverage, and improved agreement with independent drifter and subsurface temperature observations. The sustained improvement across windows obtained by SWOT and FVON data is promising, and contrasts the result of Gwyther et al. (2023b) who showed that subsurface observations at regular  
 485 frequencies (of the order of the assimilation window length) were required to achieve sustained depth-structure improvement.

Likewise, observation impact can be projected in space (horizontally and vertically) both within an assimilation window and across assimilation windows through improved initial conditions. Within a data assimilation window (in this case 6 days), adjustments are made over a region dynamically connected to the observations such that the model better fits the data while respecting the model dynamics. In Case study 2 (Section 3.2) the spatial impact is shown by the model adjustments



490 to subsurface temperature (Figure 6d). In Case study 3 (Section 3.3) FVON profiles improved the representation of a sharp temperature front and its associated mixed layer structure, reducing model–observation MAD by 49% over a 6-day window. This case study provides an example of a model adjustment to subsurface structure due to FVON observations that is projected in space; rather than a deep mixed layer associated with a WCE and a CCE at their boundary, the model (that assimilates FVON) represents the WCE overwashing the CCE with a shallower mixed layer over a dynamically connected region unobserved by the FVON data (Figure 8b and d). Other studies have demonstrated time-averaged observation impact projected in space; Siripatana et al. (2020) showed that a mooring array designed to observe the full depth structure of the EAC was able to constrain the current core over  $\sim 3$  degrees of latitude (the upstream, coherent EAC region), while downstream in the eddy dominated region further subsurface constraint was required to correctly represent current-core and eddy depth structure. Indeed, Gwyther et al. (2022b) demonstrated that observing downstream depth structure (in the eddy dominated region) was more impactful towards improving representation of domain-wide depth structure than observing the upstream coherent region.

The impact of FVON data across a sharp front (Case study 3, Section 3.3) shows the value of this emerging data network, an important point being that fishers often target fronts due to enhanced foraging behavior (Scales et al., 2014a), therefore collecting data where the models need it most; across regions of sharp spatial gradients and complex vertical structure. Indeed, the value of observing the ocean in regions of greatest variability was systematically shown using various observation impact assessment methods applied to the EAC (Kerry et al., 2025). We note that the resolution of the available SST data was not fully exploited in this study, as a data thinning approach was applied where the SST data was averaged to an  $\sim 15$  km grid (to avoid SST dominating the cost function, Section 2.3.2). Because the strategy is invariant across experiments, it is not critical in terms of assessing the impact of SWOT and FishSOOP observations; however, it removes some of the fine scale detail available in the SST observations. Future work could assimilate the infra-red (IR) platforms (VIIRS and NAVO) at the model grid resolution, and assimilate AMSR2 separately at the native 25 km resolution (with a higher observation uncertainty applied). This would exploit the fine scale detail observed by the high-resolution IR SST data and allow AMSR2 constrain the analysis in the absence of IR observations (to fill the gaps where IR observations are not available due to clouds). Care must be taken to ensure SST data does not dominate the cost function (due to large volumes of data), which could result in a degraded fit to the FishSOOP data and other data streams.

515 Our results demonstrate that wide-swath altimetry and fishing-vessel subsurface observations provide complementary constraints: SWOT improves the surface expression and evolution of eddies, while FVON constrains the vertical thermal structure that surface observations alone cannot resolve. In Kerry et al. (2026c) we showed that the assimilation of (surface) SWOT data improves the model fit to (subsurface) FVON data, on average over the 1-year period. Case study 4 (Section 3.4) provides an example of this impact; SWOT data assimilation over a selected 30-day period improves the fit to (independent) FVON observations by 48%, specifically associated with the improved location and strength of eddies. The value of subsurface observations in constraining surface features is demonstrated in Case study 3 (Section 3.3), where FVON data improve representation of a sharp SST front. Previous studies, using various methods to assess observation impact, have shown that subsurface observations are required, in concert with surface observations, to correctly represent oceanic subsurface structure (Zavala-Garay et al., 2012; Siripatana et al., 2020; Kerry et al., 2024a; Gwyther et al., 2022b, 2023a; Kerry et al., 2025).



Moreover, using observing system experiments, Pasmans et al. (2019) showed subsurface observations require constraint at the surface to produce a realistic ocean state estimate.

The projection of information from observed variables on to the unobserved ocean state, in space and time, is determined by the data assimilation methodology, and the prior assumptions around observation and model background uncertainty (e.g. Moore et al., 2019, 2020b; Wilkin et al., 2022). Specifically, data assimilation techniques take observation-forecast differences and determine a model increment, such that the new model solution better fits the observations. Indeed, the greatest knowledge gap associated with data assimilation methodologies remains the correct specification of the background error covariances ( $\mathbf{P}$ ) which control how information from observations is projected to the unobserved model state (the analysis increment must lie in the space spanned by  $\mathbf{P}$ , Moore et al., 2019). This is particularly challenging for assimilation of temporally and spatially sparse observations in dynamically active regions. Future work aims to explore the marriage of 4D-Var and EnKF to capitalize on the advantages of both (i.e., the dynamical interpolation properties of the adjoint, and the explicit flow-dependent error covariances) to improve the spatial and temporal projection of observation impact. Such ensemble-variational methods have shown improvements in forecast skill particularly in dynamically active atmospheric systems (Buehner et al., 2010; Raynaud et al., 2011; Lorenc and Jardak, 2018, e.g.) with implementation in the ocean requiring further work (Pasmans and Kurapov, 2019). Further, correct specification of observation uncertainty is key to prevent over-fitting (Oke and Sakov, 2008) and has shown significant improvements in system performance (e.g. Kerry and Powell, 2022; Kerry et al., 2024a, 2026c). Machine-learning techniques also offer potential to address flow-dependent covariances and model and observation uncertainty estimates.

Overall, the four case studies presented here demonstrate specific details of how SWOT and FVON data improve model state estimates, with improvements projected in time and space (away from observed times and locations). The case studies specifically show the spatial and temporal structure of observation impacts in resolving complex fine-scale features - precisely the features that we aim to capture with SWOT and FVON. This is crucial for a range of applications where the actual surface and subsurface structure is relevant (rather than time and space averages); for example, predicting marine heatwave subsurface structure, the locations of fronts and subsurface structure influencing the distribution of biota, and the locations of fronts for navigation. Further, the examples highlight the complexities of oceanic structure and the challenges of producing accurate ocean state estimates at and below the surface. The results motivate the sustained collection of novel observations and their integration into regional ocean models to provide advances in coastal prediction, key to supporting a range of ecological and economic needs.

## Data Availability

The experimental settings used for this study, including model forcing and configuration files, and a frozen version of the ROMS code used, are published to Kerry et al. (2026b) at <https://doi.org/10.5281/zenodo.20077064>.

The SWOT data is provided at <https://doi.org/10.24400/527896/A01-2023.018> by AVISO/DUACS (2024). DUACS SSH data is provided by E.U. Copernicus Marine Service CMS (2024). SST, Argo, FishSOOP and glider data sourced from



Australia's Integrated Marine Observing System

(<https://imos.org.au/data>). Data from the CSIRO Marine National Facility Voyage IN2023\_V06 is sourced from here:

560 [https://www.marine.csiro.au/data/trawler/survey\\_details.cfm?survey=IN2023\\_V06](https://www.marine.csiro.au/data/trawler/survey_details.cfm?survey=IN2023_V06). Drifter data was sourced from here:  
[https://osmc.noaa.gov/erddap/tabledap/OSMC\\_flattened.html](https://osmc.noaa.gov/erddap/tabledap/OSMC_flattened.html)

The Regional Ocean Modelling System (ROMS) is an open-source modelling framework available for download at  
<https://www.myroms.org>. This study uses version 4.2.

### Author contributions

565 CK developed the ROMS model configuration of the EAC system, processed the observations, developed and optimized the 4D-Var data assimilation configuration. CK analysed the results, generated the figures and wrote the manuscript. MR and SK secured the funding. MR played a key role in developing the FishSOOP program and led the research voyage. SK provided guidance on SWOT. All authors reviewed the analysis methods and contributed to the structure of the manuscript.

### Competing Interests

570 No competing interests are present.

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