



Impact of grid resolution on the abyssal ocean representation in numerical models

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Abstract. Accurately representing abyssal water masses and their inter-basin pathways remains a challenge for global ocean models and reanalyses. In this study, we investigate how horizontal and vertical resolution influence the simulation of abyssal waters by first evaluating three ocean reanalyses and one forward ocean model, focusing on Antarctic Bottom Water pathways from the Weddell Sea to the Argentine and Brazil basins and through the Vema Channel. Model outputs are evaluated against WOA18 climatology and in situ observations from moorings and hydrographic sections. Building on the recurring limitations identified in this inter-comparison, we conduct four targeted experiments with the Finite-Volume Sea Ice–Ocean Model (FESOM 2), modifying horizontal and vertical grid resolution while keeping all other model components unchanged. The experiments show that increasing vertical resolution substantially improves the representation of cold and dense abyssal waters and their inter-basin connectivity, whereas horizontal refinement alone does not systematically improve the representation of abyssal properties and can even degrade it when mixing parameterizations are not adequately tuned. Combining vertical and horizontal refinement improves specific local features, including the structure of the abyssal flow and the realistic eastward deflection of the Antarctic Bottom Water core within the Vema Channel, but does not outperform vertical refinement alone at the basin scale.

1 Introduction

The lower limb of the Atlantic Meridional Overturning Circulation (AMOC) is occupied by the Antarctic Bottom Water (AABW), a water mass which originates from dense waters formed on the Antarctic continental shelf, primarily within the Weddell Sea sector (Solodoch et al., 2022). There, Dense Shelf Water (DSW) descends the continental slope while entraining mid-depth modified Warm Deep Water (mWDW), forming two distinct water masses: The Weddell Sea Deep Water (WSDW) and the Weddell Sea Bottom Water (WSBW) (Orsi et al., 1999). WSBW is commonly limited, on its top, by the potential temperature (θ) isotherm of -0.7°C (Fahrbach et al., 1995). It remains largely confined to the Weddell Sea, without crossing the South Scotia Ridge, although it can indirectly influence the properties of AABW exported to lower latitudes (Abrahamsen et al., 2019). The lighter WSDW overlies the WSBW within the Weddell Sea and is bounded by the $\theta = -0.7^\circ\text{C}$ (lower) and $\theta = 0.0^\circ\text{C}$ (upper) isotherms (Carmack, 1977). As WSDW overflows the South Scotia Ridge and enters the Scotia Sea, the ocean floor effectively becomes the lower boundary of WSDW outside the Weddell Sea. From the Scotia Sea, WSDW propagates through the Georgia and Northeast Georgia passages into the Georgia Basin, where it merges with waters entering through the South Sandwich Trench before continuing northward into the Argentine Basin (Fig. 1).

The AABW variant which occupies the western South Atlantic is supplied precisely by the fraction of the WSDW that flows from the Georgia Basin into the southern Argentine Basin. Within the Argentine Basin, AABW is characterized by core properties of $\theta = -0.10^\circ\text{C}$ and salinity = 34.67 (Valla et al., 2018). Its upper limit is commonly identified

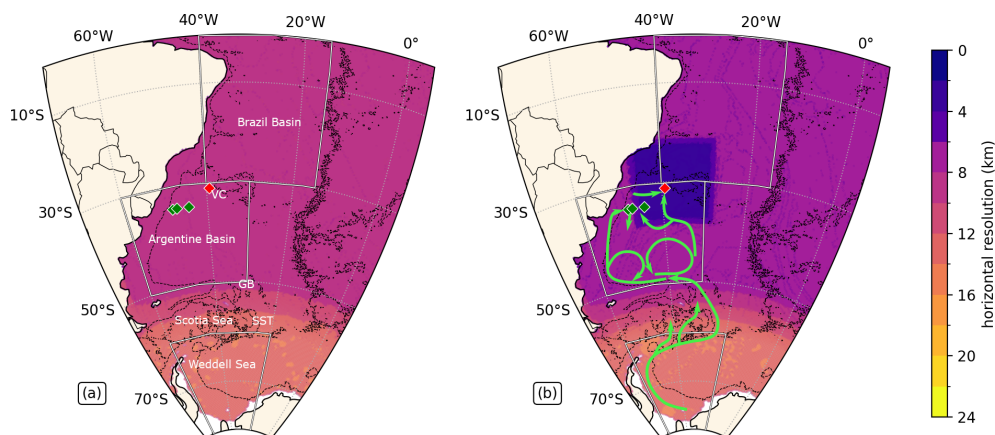


Figure 1. (a) Square root of grid-cell area (FESOM R and FESOM V) of the study region. (b) Same as (a), but of FESOM H and FESOM VH. Green diamonds mark CTD sites BB, C, and D and red diamond marks the approximate location of the three moorings within the Vema Channel. Rectangles represent, from north to south, the Brazil and Argentine basins and the Weddell Sea, while VC marks the Vema Channel, GB the Georgia Basin, and SST the South Sandwich Trench. Dashed black contour marks the isobath of 3000 m and solid black contour the continents. Green arrows are a schematic of the main pathways of AABW.

by the potential density referenced to 4000 m depth (σ_4) isopycnal of 46.06 kg m^{-3} (Arhan et al., 1999), which corresponds to the $\theta = 0.0^\circ \text{C}$ isotherm. After entering the Argentine Basin, AABW spreads along the seafloor following several intricate and connected pathways and continues its northward propagation toward lower latitudes through the Vema Channel (Santos et al., 2026a; Coles et al., 1996). This narrow passage acts as the principal conduit for AABW leaving the Argentine Basin and entering the Brazil Basin (Hogg et al., 1982; Morozov et al., 2018) before crossing the equator towards the North Atlantic Ocean. Due to the logistical complexity and high operational costs associated with sampling abyssal waters along deep boundary currents, basin interiors, and narrow passages such as the Vema Channel in a coordinated and simultaneous manner, sustained observations of this sector of the ocean are limited in both space and time.

Hence, despite substantial advances in the observational monitoring of the AMOC over the past decades, direct observations of its abyssal limb are sparse. The existing observational network relies on a combination of repeated full-depth conductivity–temperature–depth (CTD) sections and moored arrays. Ship-based hydrographic sections provide high-accuracy, full-depth snapshots of water mass properties, but they are intrinsically limited in time. In contrast, moored arrays offer continuous measurements, but their geographic coverage is limited, with most arrays concentrated near continental boundaries and restricted to a small number of latitudes.

Currently, three trans-basin moored arrays exist: the SAMoc Basin-wide Array (SAMBA; Meinen et al., 2012) at 34.5°S , the TRopical Atlantic Circulation and Overturning (TRACOS; Schott et al., 2005) array at 11°S , and the Rapid Climate Change–Meridional Overturning Circulation and Heatflux Array (RAPID–MOCHA; Cunningham et al.,

2007) at 26.5°N . Repeated CTD lines are available at the latitudes of 34.5°S , 32°S , 30°S , 24°S , 11°S , and 24°N (Chidichimo et al., 2023). As a result, integrating information from fewer than ten transoceanic sections across the entire Atlantic basin poses fundamental challenges. Key questions remain regarding the connectivity between these isolated arrays: how do changes observed at one latitude relate to those detected elsewhere, what pathways link abyssal water masses between sections, and to what extent do observed signals reflect local processes versus basin-scale adjustments. Moreover, combining heterogeneous datasets from different observational initiatives, each with distinct sampling strategies and uncertainties, adds an additional layer of complexity. Together, these limitations hinder a comprehensive assessment of abyssal water mass pathways, variability, and basin-scale connectivity based solely on observations.

To overcome these observational limitations, numerical models and ocean reanalyses are widely used to complement in situ measurements and to provide a spatially and temporally continuous description of the ocean circulation. However, despite their widespread use, global ocean models and reanalyses exhibit important limitations in their representation of the abyssal ocean, which is often poorly resolved in state-of-the-art modeling systems. For example, Bailey et al. (2023) showed that the relatively coarse resolution of the Estimating the Circulation and Climate of the Ocean (ECCO), Simple Ocean Data Assimilation (SODA), and Southern Ocean State Estimate (SOSE) models does not realistically capture AABW formation, export, and variability in the Weddell Sea. Similarly, Heuzé (2021) argued that, although Climate Model Intercomparison Project phase 6 (CMIP6) models exhibit substantial improvements compared to earlier generations, further developments are still required to correctly reproduce AABW formation rates, prop-

erties, and transports. More recently, Noro et al. (2025) assessed the representation and variability of the WSDW and WSBW in the 1/12° Global Ocean Physics Reanalysis (GLORYS12v1), finding that it overestimates warming and salinification trends in both water masses.

Dedicated studies have identified grid resolution as one of the factors controlling the representation of the abyssal ocean. Multi-model assessments such as the Ocean Model Intercomparison Project phase 2 (OMIP-2; Chassignet et al., 2020) have shown that increasing horizontal resolution alone does not necessarily improve the representation of deep-ocean thermohaline properties and may even degrade them in some regions. Conversely, Xu et al. (2023) and Stewart et al. (2017) have shown that enhanced vertical resolution improves the representation of dense water masses and large-scale deep circulation, highlighting the need to better understand how resolution choices affect abyssal processes.

In this study, we focus on the western South Atlantic, a key region for the northward export of the AABW. We first examine outputs from ECCO, Simple Ocean Data Assimilation (SODA), Global Ocean Physics Reanalysis (GLORYS), and the Ocean General Circulation Model for the Earth Simulator (OFES), which were selected as widely used ocean simulations representing different model concepts, including ocean reanalyses with distinct data assimilation methods and a forward ocean model to identify limitations and biases in their depiction of abyssal water properties and inter-basin connectivity. The recurring weaknesses identified across these simulations motivate a set of targeted numerical experiments using the Finite-Volume Sea Ice–Ocean Model (FESOM 2) to investigate the extent to which horizontal and vertical grid resolution contribute to these limitations. Horizontal and vertical resolutions are modified independently and in combination, while all other model components are kept unchanged, providing a controlled framework to isolate their relative influence on the representation of abyssal water properties and inter-basin connectivity in the western South Atlantic.

2 Data and numerical simulations

The present study analyzes three ocean reanalyses and five forward model simulations, four of which were specifically designed and conducted for this work. Ocean reanalyses incorporate observations through data assimilation to constrain the simulated ocean state, whereas forward models evolve freely under prescribed atmospheric forcing without assimilating ocean observations. Consequently, comparisons between these simulations should consider that differences may arise not only from model formulation and resolution, but also from the influence of data assimilation on the simulated ocean state. The study also makes use of in situ data and climatological fields to support the evaluation of model performance.

2.1 In situ data

We used two in situ data sets. The first is a set of full-depth high-resolution CTD profiles of temperature from the trans-basin cruise aboard the R/V *Maria S. Merian* conducted in January 2017 (MSM60; Karstensen et al., 2019), and from thirteen years (2009–2022) of repeated cruises conducted in support of the maintenance of the western portion of the South Atlantic MOC Basin-wide Array (SAMBA-West). The cruises were typically carried out once per year, although the sampling month varied between years, as illustrated in Fig. 2 of Santos et al. (2026a). Both datasets were collected along 34.5° S. We analyzed the longitudes of 48.5, 47.5, and 44.5° W. These sites correspond to the CTD cast sites referred to as Sites BB, C, and D in the literature (Chidichimo et al., 2021; Valla et al., 2018), as illustrated in Fig. 1. For more information about the quality control and processing of the data, see Valla et al. (2018).

The second data set corresponds to three historic temperature time series sampled by sensors moored within the Vema Channel at nearby locations (Fig. 1). They were named: “CLIVAR mooring” (Zenk, 2008); “E2 mooring” (Zenk and Visbeck, 2013); and “SAMBAR mooring” (Campos et al., 2021). The main information about each mooring is reported in Table 1.

2.2 World Ocean Atlas 2018 (WOA18)

The WOA18 climatology contains a set of long-term mean fields of ocean properties (Zweng et al., 2019; Locarnini et al., 2018). The data set consists of fields obtained through optimal interpolation of historic oceanographic data from different sources such as ship-deployed CTD, moored and drifting buoys, expendable bathythermographs (XBT), and gliders. The spatial distribution of the available hydrographic profiles within the study region is shown in Fig. A1 in the Appendix to provide context for the observational support underlying the climatological fields. The 0.25° annual climatological fields of temperature and salinity averaged between 1994 and 2005 were used for validation of the ocean simulation outputs. These fields were also used to compute σ_4 using the Thermodynamic Equation Of Seawater – 2010 software (TEOS-10; IOC et al., 2010). All comparisons with this data set were made utilizing its grid as reference, and hence model outputs were interpolated accordingly.

2.3 Estimating the Circulation and Climate of the Ocean (ECCO)

We analyzed the outputs of ECCO Version 4 release 4 (v4r4), its latest product release and the first to include the Arctic Ocean. This reanalysis is produced with the MIT General Circulation Model (MITgcm; Marshall et al., 1997). ECCO uses a unique grid formulation, in which between 70° S and 57° N a simple latitude-longitude (LL) grid is adopted, but

Table 1. Summary of the mooring data sets used in this study.

Data set name	Location	Seafloor depth (m)	Sensor depth (m)	Pressure (bar)	Sampling period
CLIVAR	31.2383° S 39.3333° W	4580	4527	4612	21 Apr 1998 to 08 Mar 2000
E2	31.2547° S 39.3160° W	4544	4479	4557	31 May 2005 to 18 May 2007
SAMBAR	31.2333° S 39.3833° W	4630	4529	4610	1 Feb 2019 to 29 Aug 2020

out of this region a cubed-sphere grid (CS) is used; this configuration is known as the Lat-Lon-Cap (LLC) grid (Forget et al., 2015). Its horizontal resolution varies spatially from 22 km (high latitudes) to 110 km (mid-latitudes), and it has 50 vertical levels with different resolutions, varying from 10 m near the surface to 457 m between its two deepest levels. ECCO outputs are available from January 1992 to January 2018 with a temporal resolution of hours, days, and months, of which only the monthly fields were used in this study. The atmospheric forcing of this simulation is from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim; Dee et al., 2011).

ECCO assimilates data from Argo floats, CTDs, XBTs, marine mammals, gliders, Ice-Tethered Profilers, moorings, and satellites (Fukumori et al., 2017). ECCO utilizes the adjoint method which simulates what is observed in the ocean based on the governing equations of motion (Forget et al., 2015; Thacker and Long, 1988), therefore the model conserves heat, salt, volume and momentum (Wunsch and Heimbach, 2007, 2013).

2.4 Simple Ocean Data Assimilation (SODA)

We used SODA version 3.4.2 (Carton et al., 2018), downloaded from <https://dsrs.atmos.umd.edu/DATA/soda3.4.2/> (last access: 2 February 2025). It is built on the Modular Ocean Model, version 5, ocean component of the Geophysical Fluid Dynamics Laboratory Coupled Model (GFDL CM2.5; Delworth et al., 2012). SODA's native horizontal grid is a tripolar Arakawa-B grid, which varies from $0.1^\circ \times 0.25^\circ$ resolution at high latitude to $1/4^\circ \times 1/4^\circ$ in the tropics, with 1440×1070 grid points. In the present study, we used the interpolated $1/2^\circ$ product. SODA spans the period 1980–2020 with monthly outputs and has 50 vertical levels, ranging from 10 m resolution in the upper 100 m to much coarser resolution in the deep ocean. Bottom topography is based on the NOAA/NCEI ETOPO5 bathymetric dataset, with modifications to improve the representation of narrow passages. The model uses the GFDL Sea Ice Simulator with the dynamics and thermodynamics of Winton (2000). The atmospheric forcing of this simulation is the ERA-Interim (Dee et al., 2011).

The main data sets that SODA assimilates are the World Ocean Database of historical hydrographic profiles (Boyer et al., 2013) and in situ and remotely sensed sea surface temperature. SODA assimilates data through the usage of an optimal interpolation method, in which the ocean state is constructed from a forecast based on the difference between the model and the observations (Carton et al., 2018).

2.5 Global Ocean Physics Reanalysis (GLORYS)

GLORYS is a global ocean and sea ice reanalysis developed by the Mercator Ocean operational oceanography center. The version used in this study features a LL quasi-isotropic horizontal grid with a resolution of $1/12^\circ$ and 50 vertical levels. The grid vertical spacing increases with depth, with resolution of 1 m near the surface and 450 m at 5000 m depth (Lellouche et al., 2021). Bottom topography is based on ETOPO1 (Amante and Eakins, 2009) and coast and continental shelf are based on GEBCO8 (Becker et al., 2009). The simulation is conducted using the NEMO platform (Madec, 2008) and uses the ERA-Interim fields as atmospheric forcing (Dee et al., 2011). The vertical mixing is parameterized according to a turbulent closure model (order 1.5) and sea ice is simulated using the LIM2 model (Lellouche et al., 2018). The reanalysis spans the period from 1993 onward at a monthly resolution. For this work we used outputs from 1993 to 2020. The model assimilates satellite-derived sea level anomaly, sea surface temperature, and sea ice concentration, along with in situ temperature and salinity vertical profiles, using a reduced-order Kalman filter.

2.6 Ocean General Circulation Model for the Earth Simulator (OFES)

OFES version 2 (Sasaki et al., 2020) is a forward ocean model based on version 3 of the Modular Ocean Model (MOM) (Pacanowski and Griffies, 1999). It features a LL grid system with a horizontal resolution of 0.1° , which covers the global ocean from 76° S to 76° N. The model has 105 vertical levels extending from the surface to 7500 m depth. The top 21 levels are uniformly spaced at 5 m, while the last

6 are spaced at 300 m. Bottom topography is based on the ETOPO1 bathymetric dataset.

The simulation was initialized using temperature and salinity fields from OFES version 1 and covers the period 1958–2016, with monthly outputs. (Sasaki et al., 2020). A sea-ice component (Komori et al., 2005) is included to simulate conditions in the Antarctic and subarctic seas. Atmospheric forcing is provided by the JRA55-do dataset (Tsujiro et al., 2018), which is based on the JRA-55 reanalysis (Kobayashi et al., 2015). Horizontal mixing is represented using a biharmonic operator, while vertical mixing follows the Noh and Jin Kim (1999) parameterization.

2.7 FESOM 2 simulations

The Finite-Element Sea Ice–Ocean Model (FESOM) (Wang et al., 2014) is the first fully developed global multi-resolution model specifically designed to simulate large-scale ocean dynamics. Its next-generation counterpart, the Finite-volume Sea ice–Ocean Model (FESOM 2), adopts a finite-volume discretization approach in place of the finite-element discretization used in the original model. This shift significantly enhances efficiency, making FESOM 2 at least nine times faster than its predecessor (Danilov et al., 2017).

FESOM 2 utilizes a horizontal triangular mesh with horizontal velocity components defined at the centers of the triangles, while scalar variables are positioned at its vertices. The vertical grid adopts the Lagrangian–Eulerian (ALE) vertical coordinate system (Donea and Huerta, 2003), with both horizontal velocities and scalar variables defined between vertical levels, whereas inter-layer exchange velocities are located at the layer interfaces and aligned with scalar positions. The bathymetry is derived from global RTopo-2 dataset (Schaffer et al., 2016). FESOM 2 contains a sea-ice component that has been derived from the Finite-Element Sea Ice Model (FESIM) (Danilov et al., 2015).

The simulations use a default model configuration in which each experiment is forced with the JRA55 atmospheric reanalysis and is initialized from the Polar Science Center Hydrographic Climatology (PHC; Steele et al., 2001). We use the Gent–McWilliams eddy parameterization (Gent and McWilliams, 1990) and the Redi (1982) isoneutral diffusion. Diffusivity is scaled linearly with resolution, with a reference diffusivity of $2000 \text{ m}^2 \text{ s}^{-1}$ at 100 km horizontal resolution. As the vertical mixing scheme, we employ the K-profile parameterization (KPP; Large et al., 1994). No additional calibration was applied to tailor the model to specific regions or processes of interest.

The reference simulation, hereafter referred to as FESOM R was designed to replicate results from existing numerical simulations, such as ECCO, SODA, OFES, and GLORYS. To achieve this, we adopted the exact vertical levels used in OFES, as it includes the highest number of vertical levels among the evaluated simulations. Hence, FESOM R employs 105 vertical levels that extend from the surface to 7350 m,

with five levels distributed between 3800 and 5350 m. The horizontal resolution is approximately 110 km in the northern parts of the Pacific and Indian Oceans, 30 km over most of the global domain, and 10 km in the South Atlantic Ocean. In addition, the mesh is progressively refined toward higher latitudes (Fig. 1a; Fig. A2a).

The vertical-refinement experiment, hereafter referred to as FESOM V was designed to evaluate the impact of vertical resolution. It retains all configurations of FESOM R but increases the number of vertical levels from 105 to 125, all additional levels concentrated between 3800 and 5350 m. While shallower than FESOM R (5350 vs. 7350 m), this configuration provides ~ 50 m resolution near the seafloor, compared to ~ 300 m in FESOM R over a much larger depth range (3800–7350 m). Above 3800 m both simulations share the same vertical structure.

The horizontal-refinement experiment, hereafter referred to as FESOM H, was designed to evaluate the impact of horizontal resolution. This experiment retains all configurations of FESOM R, but increases the horizontal resolution in key regions relevant to the northward flow of abyssal waters in the Atlantic Ocean, with FESOM H maintaining the original 105 vertical levels while increasing the horizontal resolution in the South Atlantic sector to 7.5 km and further refining it to 4 km in the Vema Channel and its surrounding area (Figs. 1b; A2b).

The combined-refinement experiment, hereafter referred to as FESOM VH, was designed to evaluate how the two previous configurations work together. FESOM VH enhances both vertical and horizontal resolution. This experiment uses the same vertical resolution as FESOM V and the same horizontal resolution as FESOM H. The main characteristics of the numerical simulations are reported in Table 2.

3 ECCO, SODA, GLORYS, and OFES results

In the following section, we first evaluate the representation of abyssal water masses in ECCO, SODA, GLORYS, and OFES by comparing model outputs with in situ observations and WOA18 climatology. The temporal evolution of the simulated density fields is also assessed to determine whether the models consistently represent the cascading of dense waters to the abyssal ocean and its propagation between basins. This analysis allows us to quantify both common and model-specific biases and to identify key deficiencies in the simulated abyssal representation.

3.1 Abyssal properties

We constructed horizontal maps of abyssal water properties (θ , salinity, and σ_4), covering the Antarctic continental shelf and slope, the central Weddell Sea, and the western South Atlantic. The latter includes the Argentine and Brazil basins, defined as follows: the Argentine Basin spans 50–30° S and

Table 2. Summary of the main characteristics of the ocean numerical simulations evaluated in this study.

System	Model	Grid	Resolution	Max depth (m)	Levels (3800 m–max depth)	Vert. spacing below 3800 m	Atmospheric forcing	Assimilation method	Period
ECCO	MIT_gcm	LLC	110–22 km (50 lev.)	5906	6	~ 350–445 m	ERA-Interim	Adjoint	1992–2018
SODA	GFDL CM2.5	Arakawa-B	1/4–1/10° (50 lev.)	5395	8	~ 210 m	ERA-Interim	Optimal Interpolation	1980–2020
GLORYS	NEMO	LL	1/12° (50 lev.)	5275	4	~ 410–440 m	ERA-Interim	Reduced-order Kalman	1993–2026
OFES	MOM	LL	1/10° (105 lev.)	7350	13	~ 267–300 m	JRA55	–	1958–2016
FESOM R	FESOM 2	Triangular	110–10 km (105 lev.)	7350	13	~ 267–300 m	JRA55	–	1958–2020
FESOM V	FESOM 2	Triangular	110–10 km (125 lev.)	5350	31	~ 50 m	JRA55	–	1958–2020
FESOM H	FESOM 2	Triangular	110–4 km (105 lev.)	7350	13	~ 267–300 m	JRA55	–	1958–2020
FESOM VH	FESOM 2	Triangular	110–4 km (125 lev.)	5350	31	~ 50 m	JRA55	–	1958–2020

Resolutions are given in the native units of each model. SODA resolution ranges from 1/4° in the tropics, corresponding to ~ 28 km, to 1/10° at 65° S, corresponding to ~ 12 km. GLORYS resolution is 1/12°, corresponding to ~ 9.3 km at the equator and ~ 4.5 km at subpolar latitudes. OFES resolution is 1/10°, corresponding to ~ 11.1 km at the equator and ~ 5.5 km at subpolar latitudes.

60–30° W, while the Brazil Basin extends from 30° S to 0° and from 40 to 15° W (Fig. 1, white boxes). Data were extracted from the deepest valid level at each horizontal grid point over the same period as the WOA18 dataset (1994–2005) at monthly resolution. For each simulation, we calculated the time-averaged field and the mean bias (simulation minus reference).

The reference θ field (Fig. 2a) shows cold waters below -0.7°C on the Antarctic continental shelf (Fig. 2, white contours), characteristic of DSF. Along the continental slope, temperatures increase, forming a band of relatively warmer water that separates the shelf from the central abyssal Weddell Sea, consistent with the presence of the mWDW (Fahrbach et al., 2011). In the central Weddell Sea, temperatures drop below -0.7°C again, indicating the presence of WSBW, which does not penetrate into the Scotia Sea, where higher temperatures prevail due to the presence of WSDW only (Fig. 2, red contours). In the Argentine Basin, waters with $\theta \leq 0^{\circ}\text{C}$ are observed, corresponding to AABW, which enters the Brazil Basin through the Vema Channel and progressively modifies its properties as it flows northward.

ECCO, SODA, GLORYS, and OFES all depict cold waters ($\theta < -0.7^{\circ}\text{C}$) over the Antarctic continental shelf (Fig. 2b, c, d, and e). In the central Weddell Sea, ECCO, GLORYS, and OFES also reproduce waters colder than -0.7°C , although the cold region in ECCO is spatially limited. SODA is the only simulation that fails to reproduce this feature, with central Weddell Sea bottom temperatures of approximately -0.35°C . OFES, at the other extreme, depicts waters colder than -1.4°C .

The northward spreading of cold waters from the Weddell Sea is limited in ECCO, SODA, and GLORYS (Fig. 2b, c, and d). OFES (Fig. 2e) is the only simulation that reproduces the presence of WSBW in the South Sandwich Trench, a deep channel located east of the South Scotia Ridge. ECCO, GLORYS, and OFES capture cold waters with $-0.7^{\circ}\text{C} < \theta < 0.0^{\circ}\text{C}$ in the Argentine Basin, but only OFES represents their further northward spreading through the Vema Channel into the Brazil Basin. SODA again stands out as an exception, with relatively warm waters in both the Argentine and Brazil Basins.

The results above describe the spatial extent of cold waters exported from the Weddell Sea. However, the bias fields reveal important regional contrasts throughout the study area. Despite the persistence of cold waters along the continental shelf, all simulations exhibit positive temperature biases, particularly along the eastern sector of the southern continental shelf (Fig. 2f, g, h, and i). In contrast, the eastern shelf of the Antarctic Peninsula, located to the west of this region, shows negative temperature biases, with the exception of ECCO, which exhibits a warm bias. In the abyssal central Weddell Sea (depths $> 3000\text{ m}$), ECCO, SODA, and GLORYS are warmer than the reference, whereas OFES shows colder values.

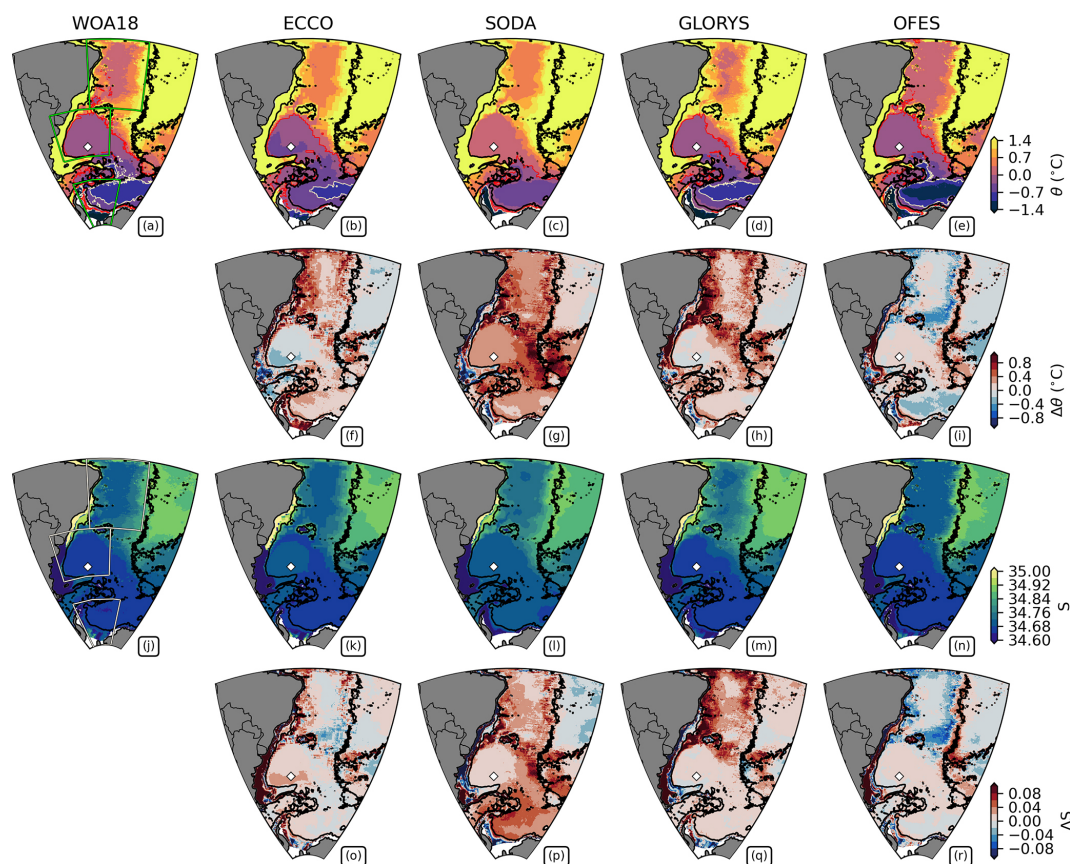


Figure 2. Mean potential temperature (θ ; a–e) and salinity (j–n) from 1994 to 2005 at the deepest valid level at each horizontal grid point, and the corresponding mean biases relative to WOA18 ($\Delta\theta$, f–i; ΔS , o–r). Columns correspond to WOA18 (reference), ECCO, SODA, GLORYS, and OFES, from left to right. The black contour indicates the 3000 m isobath, the red contour marks the $\theta = 0.0$ °C isotherm, and the white contour marks the $\theta = -0.7$ °C isotherm. White diamonds mark the position of the virtual profile depicted in Fig. A4. Rectangles in the WOA18 panels (a), (j) represent, from north to south, the Brazil Basin, Argentine Basin, and Weddell Sea.

In the Argentine Basin, abyssal waters are warmer than the reference in SODA and OFES. GLORYS exhibits localized colder patches in the southern and northwestern portions of the basin and warmer regions surrounding these patches. ECCO, by contrast, shows a consistent cold bias throughout this basin. In the Brazil Basin, ECCO, SODA, and GLORYS depict warmer conditions than the reference, while OFES shows a mixture of warm and cold regions, with the negative bias dominating over a larger portion of the basin. Notably, ECCO and OFES, the former more strongly, the latter more subtly, exhibit opposite bias signs between the Weddell Sea, the Argentine Basin, and the Brazil Basin, whereas SODA and GLORYS show consistently warm conditions across all three regions.

The reference salinity field (Fig. 2j) displays alternating regions of relatively high (> 34.84) and low (< 34.68) salinity on the continental shelf. In the central Weddell Sea, bottom salinities are approximately 34.68, and these values persist northward through the Argentine Basin. Within the

Brazil Basin, salinity increases from approximately 34.72 in the basin interior to 34.88 near its boundaries.

ECCO, GLORYS, and OFES correctly reproduce the alternating salinity bands on the Antarctic continental shelf (Fig. 2k, m, and n), whereas SODA does not cover this region (Fig. 2l). In the central Weddell Sea, ECCO, GLORYS, and OFES depict salinities near 34.68, while SODA shows comparatively higher values. In the Argentine Basin, GLORYS and OFES also reproduce salinities near 34.68, although GLORYS exhibits saltier waters in the northeastern portion of the basin. ECCO displays the opposite pattern, with saltier waters in the central basin and fresher values toward its margins, while SODA shows the highest salinities of all simulations throughout the basin. In the Brazil Basin, SODA and GLORYS depict the saltiest conditions, OFES shows the freshest waters, and ECCO exhibits intermediate salinity values.

ECCO, GLORYS, and OFES generally exhibit positive salinity anomalies along the eastern side of the Antarctic Peninsula and fresh biases farther east on the Antarctic con-

tinental shelf, near the southern limit of each model domain (Fig. 2o, q, r). SODA, in contrast, shows a consistent fresh bias across these regions (Fig. 2p). In the central Weddell Sea, SODA and GLORYS display predominantly salty biases, with SODA presenting the largest deviations, while ECCO and OFES exhibit a mixture of positive and negative anomalies. In the Argentine Basin, all four simulations depict saltier-than-reference conditions. This signal extends into the Brazil Basin for ECCO (with some localized negative patches), SODA, and GLORYS, whereas OFES stands out by exhibiting predominantly negative anomalies across most of the basin, resulting in a marked basin-to-basin contrast, with fresher conditions in the Weddell and Brazil Basins and saltier waters in the Argentine Basin.

The reference σ_4 field (Fig. A3a) shows high-density waters ($\sigma_4 > 46.3 \text{ kg m}^{-3}$) over the Antarctic continental shelf. In the central Weddell Sea, bottom densities are slightly lower ($\sigma_4 \approx 46.2 \text{ kg m}^{-3}$) and extend toward the South Scotia Ridge without crossing it, as well as eastward into the South Sandwich Trench. In the Argentine Basin, lighter bottom waters are found ($\sigma_4 \approx 46.1 \text{ kg m}^{-3}$). Farther north, these waters leak through the Vema Channel into the Brazil Basin, where densities decrease slightly as they progress northward ($\sigma_4 \approx 46.04 \text{ kg m}^{-3}$). The spatial patterns described for θ are largely mirrored in the σ_4 field (Fig. S4, first row). As a consequence, the latter displays positive (negative) biases where the former shows negative (positive) anomalies, indicating that density variations are primarily controlled by temperature rather than salinity in these simulations.

Dense and cold waters are present along the Antarctic continental slope in all simulations. However, none of them show clear evidence of DSW plumes cascading downslope to form new WSBW and WSDW (see video supplements, <https://doi.org/10.5281/zenodo.19699061>, Santos et al., 2026j). In ECCO, the central Weddell Sea is initially occupied by relatively light waters that gradually become denser over time. SODA shows episodic pulses of denser waters in this region, and the basin as a whole becomes denser by the end of the simulation relative to its initial state, with periods of rapid water mass transformation also occurring. GLORYS, in contrast, exhibits comparatively little temporal variability. However, its temporal evolution is characterized by intermittent pulses rather than a smooth progression, as seen in the video supplements (Santos et al., 2026j).

In the Argentine and Brazil Basins, the simulations also exhibit distinct temporal evolutions. In ECCO, SODA, and OFES, the long-term trends in these basins differ from those observed in the Weddell Sea. While the Weddell Sea tends to become denser over time in ECCO and SODA, the Argentine and Brazil Basins show a general lightening trend. OFES presents a similar inter-basin contrast but with the opposite sign: the Argentine and Brazil Basins show an initial increase in density followed by a gradual decrease, yet abyssal waters remain denser at the end of the simulation than at the begin-

ning. This contrast between the Weddell Sea and the adjacent basins in ECCO, SODA, and OFES may indicate limitations in the representation of deep-basin connectivity. GLORYS, in contrast, shows relatively small temporal changes and a similar pattern across all three basins, although the lack of temporal continuity in its outputs complicates the interpretation of its variability.

Overall, the comparison of θ , salinity, and σ_4 shows that all simulations broadly capture the large-scale distribution of abyssal water masses, but exhibit consistent limitations in their representation of abyssal properties and inter-basin connectivity. ECCO and OFES reproduce the general thermohaline structure but display contrasting bias patterns between basins, while SODA shows a more spatially uniform yet persistently warm and saline deep ocean. Across all simulations, density biases closely follow temperature errors, indicating that inaccuracies in the θ field are the primary driver of the discrepancies in the σ_4 field. Moreover, none of the simulations clearly represents dense shelf water cascading from the Antarctic continental shelf, and the inconsistent temporal evolution of abyssal density between the Weddell Sea and the Argentine and Brazil Basins further points to limitations in the representation of deep-basin connectivity.

3.2 TS diagram analysis

To further examine the discontinuities between connected basins, we focus on the Argentine and Brazil basins. While the pathways connecting the Southern Ocean to the Argentine Basin involve complex topographic features such as the South Scotia Ridge and multiple fracture zones, the Vema Channel provides a relatively direct and well-defined passage linking the Argentine and Brazil basins. We therefore analyze the θ – S relationship in each simulation and compare it with the corresponding reference (Fig. 3a and b). The diagrams use all grid points from the surface to the bottom within the Argentine and Brazil basins (the two northernmost white boxes in Fig. 1), binned into a 2D histogram. Model outputs were interpolated to match WOA18's horizontal resolution, and all datasets were then interpolated onto a uniform 50 m vertical grid from the surface to 6000 m. Figure 3 shows a zoom-in of the densest portion of the full θ – S diagram.

When comparing the two basins, WOA18 shows a well-defined θ – S curve in the Argentine Basin, with the coldest waters at approximately -0.5°C (Fig. 3a). In the Brazil Basin, this curve shifts toward warmer and lighter values, with no waters colder than 0.0°C (Fig. 3b). This occurs because a large fraction of the coldest waters does not reach the northern portion of the Vema Channel due to the existence of numerous sills along the channel, while part of this cold water also mixes with the overlying water masses (Morozov et al., 2018). As a result, abyssal waters within the Argentine Basin are noticeably colder and denser than those reaching the Brazil Basin.

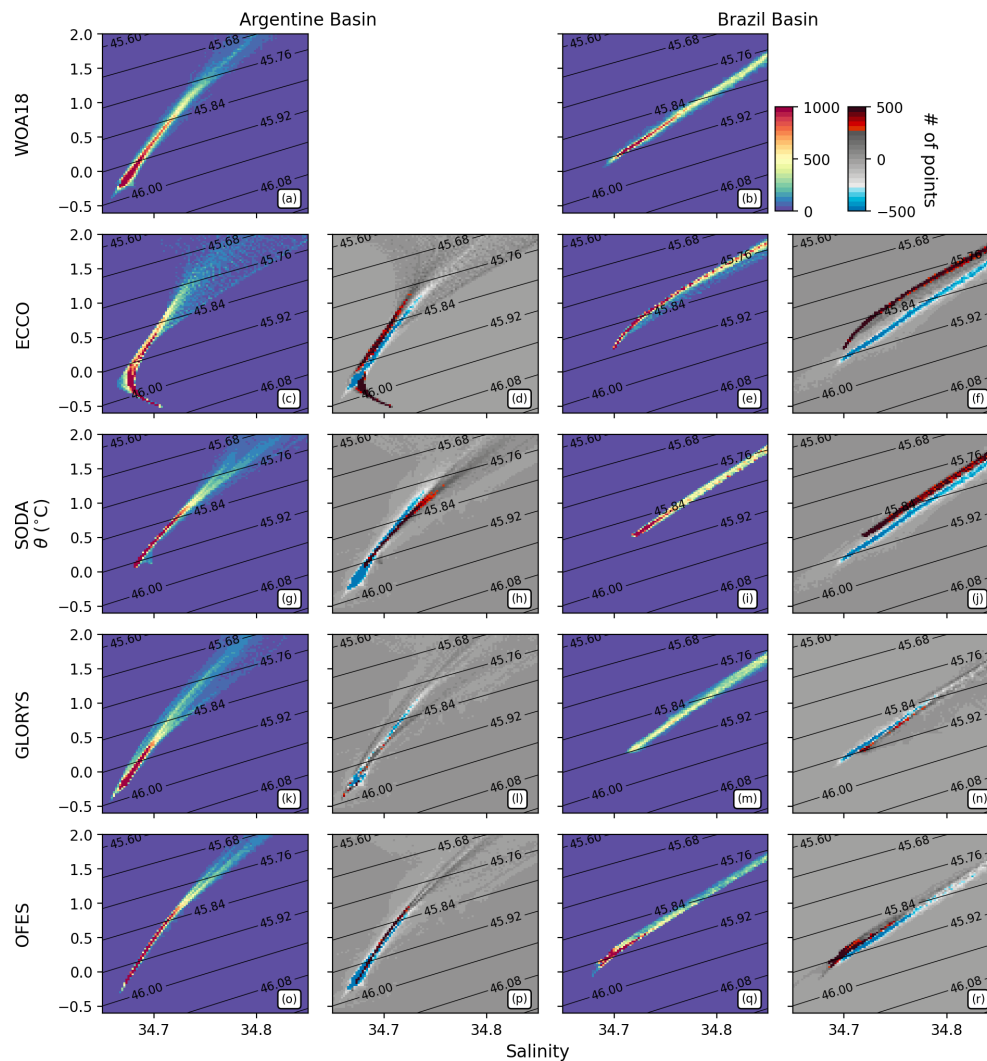


Figure 3. Time-averaged θ – S distribution of the Argentine Basin (first column) and of the Brazil Basin (third column). Averaged θ – S distribution of the difference between WOA18 and each simulation at the Argentine Basin (second column) and at the Brazil Basin (fourth column). The rows from top to bottom represent WOA18 (first row), ECCO (second row), SODA (third row), GLORYS (fourth row), and OFES (fifth row). Contour lines are σ_4 . The colorbar of the first and third columns indicates the number of grid points within each θ – S bin; the colorbar of the second and fourth columns indicates the difference in grid point counts between the simulation and WOA18, where positive (negative) values indicate bins where the simulation exceeds (falls below) the WOA18 reference count. The diagrams are zoomed at the abyssal layer ($-0.6^\circ\text{C} < \theta < 2.0^\circ\text{C}$; $34.65 < S < 34.85$).

In the Argentine Basin, ECCO exhibits a noticeable scattered dispersion of waters lighter than 45.84 kg m^{-3} and a tilt of the curve toward higher salinity values at densities above 45.92 kg m^{-3} (Fig. 3c), while SODA presents a shape closer to the reference, though lacking waters colder than 0.0°C (Fig. 3g). Despite these differences, both simulations share a common limitation when transitioning to the Brazil Basin: the θ – S distribution shows a marked reduction in the occurrence of the densest water classes and a systematic shift of the entire curve toward lighter densities relative to the reference (Fig. 3e, f, i, and j), indicating a discontinuity in abyssal water transport through the Vema Channel.

GLORYS closely follows the reference θ – S curve in the Argentine Basin, including waters colder than 0.0°C and with only minor deviations from the reference (Fig. 3k and l). OFES presents a similar overall shape but with a narrower salinity range (Fig. 3o and p). In the Brazil Basin, GLORYS shows a striking reduction in the number of θ – S occurrences for the density range of 45.84 – 45.92 kg m^{-3} (Fig. 3m), indicating a lack of the densest bottom water masses, though the overall shape of the curve still agrees with the reference (Fig. 3n). OFES, in contrast, exhibits a shift of the entire curve toward lighter densities, similar to ECCO and SODA,

but retains slightly denser waters at the very bottom of the basin (Fig. 3q and r).

The θ – S analysis reveals that, while the simulations differ in how they represent abyssal water properties in the Argentine Basin, they all exhibit a common artificial change in abyssal water properties when transitioning to the Brazil Basin. The way this artificial change manifests, however, differs between simulations: ECCO, SODA, and OFES show a systematic shift of the entire θ – S curve toward lighter densities, whereas GLORYS shows a volumetric reduction concentrated in the densest water classes while broadly preserving the overall shape of the curve. Together, these results point to a limitation in the representation of abyssal water mass connectivity across the Vema Channel.

3.3 Temperature distribution across Vema Channel

To investigate where and how the changes in abyssal water properties develop we next focus on the Vema Channel, the main passage connecting the two basins. Figure 4 shows temperature sections extracted at the nearest available latitude to 31.3°S in each model's native grid. To avoid artificial smoothing and loss of signal, no interpolation to a common latitude was applied to the different products. Examining the temperature structure within this region provides a direct way to assess how deep-water masses are represented as they flow from the Argentine to the Brazil Basin.

The WOA18 reference field reveals a discrepancy between the actual location of the Vema Channel and its representation (Fig. 4a). Only three vertical levels cover the channel, spanning a total of five grid points, none of which capture its full depth. Despite this, the reference field indicates the presence of waters colder than 0.0 °C in the region corresponding to the channel, suggesting that WOA18 captures at least the thermal signature of the abyssal flow, even if its spatial structure remains poorly resolved.

The Vema Channel is poorly represented in both ECCO (Fig. 4b) and SODA (Fig. 4c). In ECCO, a single column of grid points is present in the region where the channel should be located, whereas the SODA grid contains no points in this region, despite being slightly deeper. In both simulations the channel is represented misaligned, wider and shallower than in reality. The temperature sections show waters warmer than the reference, with no waters colder than 0.0 °C. GLORYS provides a better representation of the channel (Fig. 4d), with two vertical levels inside it: the deepest containing two grid points approximately 300 m above the actual bottom, and the shallower containing four. Nevertheless, no waters colder than 0.0 °C are found within the channel. In OFES, the channel structure is slightly misaligned with its actual location (Fig. 4e). The number of grid points and vertical levels inside the channel matches those in GLORYS, but the abyssal waters are colder and less stratified than the reference.

In the region of the Vema Channel, ECCO, SODA, and GLORYS all exhibit positive temperature biases relative to

the reference, while OFES is colder. For SODA and GLORYS, this is consistent with the warm bias observed throughout the Argentine Basin (Fig. 2g and h). In ECCO however, this represents an inversion of the pattern seen in the Argentine Basin, where waters are significantly colder than the reference (Fig. 2f). This pattern is consistent with a bathymetric control imposed by the Vema Channel sill. Figure A4 shows that, although ECCO exhibits the coldest abyssal temperatures, these waters are confined below sill depth because of its relatively strong abyssal vertical temperature gradient, leaving warmer waters available at the sill. In contrast, OFES exhibits a weaker abyssal vertical temperature gradient. Although its deepest waters are warmer than those in ECCO, colder waters are already present at sill depth, explaining the opposite sign of the temperature anomaly within the Vema Channel and the Brazil Basin.

3.4 Comparison with in situ data

Here we compare simulation outputs with in situ observations from three moorings deployed within the Vema Channel (Table 1). Comparing OGCM outputs against pointwise in situ observations is an inherently demanding test, given that OGCMs are not designed to resolve variability at these small scales. Accordingly, this analysis should not be interpreted as a conventional validation, but rather as an exploration of model performance under such unfavorable conditions.

During the CLIVAR period, ECCO shows the highest correlation (≈ 0.50) among the four simulations but its mean temperature substantially deviates from the reference (Fig. 5a and d). SODA shows a weaker correlation (≈ 0.19) and a similarly large deviation from the reference mean. GLORYS achieves a small correlation (≈ 0.33), and a considerably greater variability (Fig. A5a), while its mean temperature is closer to the reference than ECCO and SODA. OFES exhibits a slightly negative correlation (≈ -0.05), but provides the closest representation of the reference mean among the four simulations.

During the E2 period, ECCO shows an improved correlation (≈ 0.66) relative to the CLIVAR period, but with increased variability, and its mean temperature remains similar to CLIVAR though slightly warmer than the reference (Fig. 5b and e). SODA exhibits a negative correlation (≈ -0.4) and a larger variability than in CLIVAR, with a mean temperature that deviates more from the reference. GLORYS shows a reduced correlation (≈ 0.22) and increased variability relative to CLIVAR (Fig. A5b), but its mean temperature remains closer to the reference than ECCO and SODA. OFES exhibits a more negative correlation (≈ -0.33) than in CLIVAR but improved variability, and again provides the closest representation of the reference mean among the four simulations.

During the SAMBA period, only SODA and GLORYS provide outputs. SODA shows a small but positive correla-

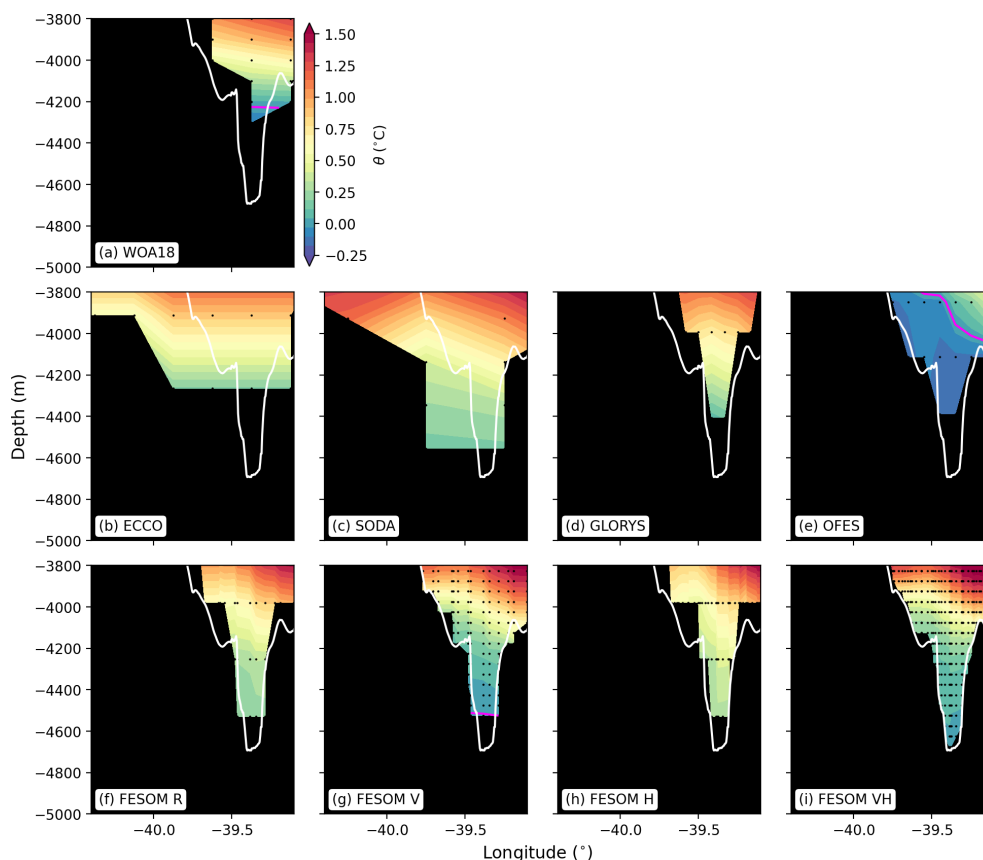


Figure 4. Time-averaged potential temperature (θ) from 1995 to 2004 across Vema Channel at the nearest available latitude to 31.3° S of: WOA18 (a), ECCO (b), SODA (c), GLORYS (d), OFES (e), FESOM R (f), FESOM V (g), FESOM H (h), and FESOM VH (i). Black dots are the grid points, white line is the bathymetry of the General Bathymetric Chart of the Oceans (GEBCO) and magenta line is the isotherm of 0.00°C .

tion (≈ 0.24) and statistical metrics similar to the CLIVAR period, but its mean temperature deviates even further from the reference, suggesting a possible overestimation of the abyssal ocean warming trend (Santos et al., 2026a; Johnson, 2022). GLORYS shows a correlation (≈ 0.34) similar to the CLIVAR period, but its variability remains excessive (Fig. A5c). Unlike SODA, GLORYS does not exhibit a pronounced warming trend.

In addition to the mooring records, the simulations were compared with CTD data from the SAMBA-West array, just south of the Vema Channel at Sites BB, C, and D (Fig. 1, green diamonds). We used the deepest bin of each CTD cast to construct the reference time series, shown as black stars in Fig. 6. Mean temperatures and linear trends for each simulation and site are summarized in Table 3.

At Site BB, all simulations produce temperatures warmer than the reference (Fig. 6a, Table 3). OFES is the only simulation with a mean temperature close to the reference, though still slightly warmer, whereas ECCO, SODA, and GLORYS substantially overestimate it, with GLORYS additionally exhibiting the largest uncertainty among the four simulations. The observed CTD trend at this site is not statistically signif-

icant, which excludes a meaningful comparison of warming trends with the simulations.

At Site C, ECCO and SODA overestimate the reference mean temperature, with SODA showing the largest deviation (Fig. 6b, Table 3). GLORYS is slightly below the reference while OFES is slightly above, both with the same absolute deviation, though GLORYS exhibits considerably larger uncertainty. Regarding trends, ECCO provides the closest match to the observed warming trend, while SODA substantially overestimates it. GLORYS shows a cooling trend in contrast to the observed warming, and OFES overestimates it moderately. Overall, OFES provides the best representation of the reference mean, while ECCO captures the observed trend most accurately.

At Site D, SODA again shows the largest deviation from the reference mean, while OFES provides the closest representation with a mean temperature only slightly above the reference (Fig. 6c, Table 3). Notably, ECCO shifts from overestimating the reference mean at Sites BB and C to underestimating it here. This pattern is consistent with the bathymetric blocking hypothesis discussed in Sect. 3.3. In ECCO, Site C is represented by the 4264 m model level, correspond-

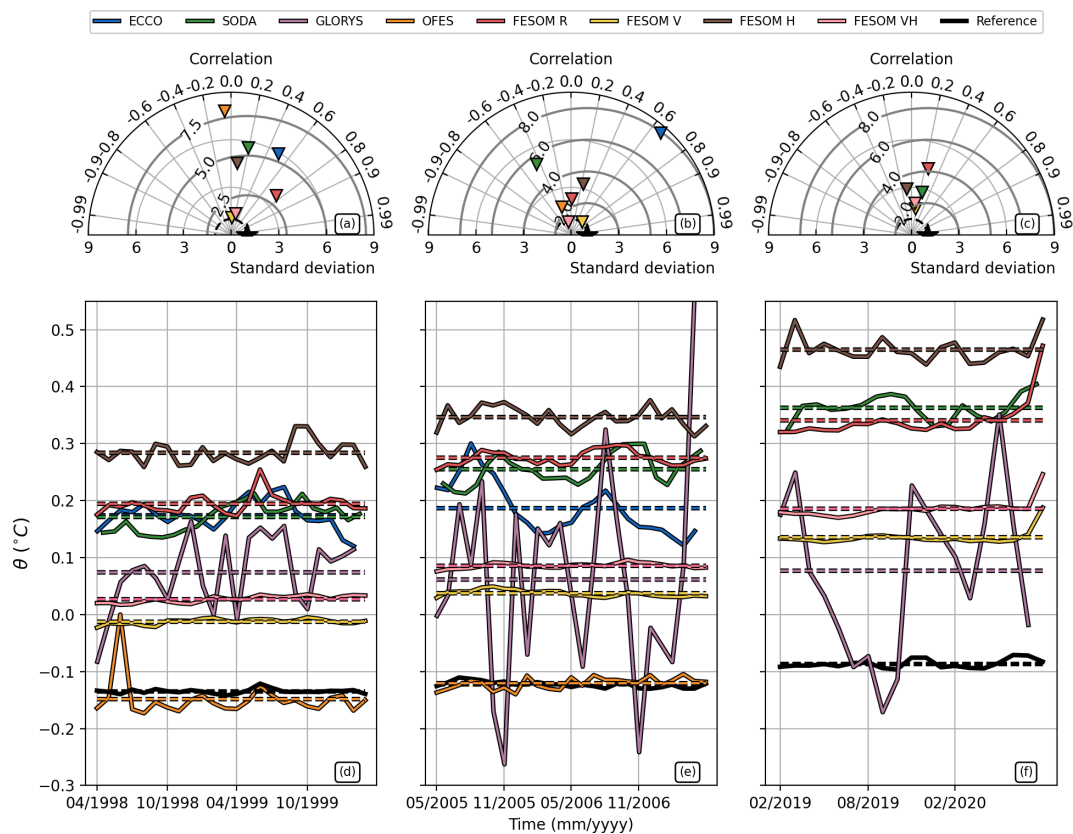


Figure 5. Taylor diagrams comparing simulation outputs with in situ temperature records from sensors moored within the Vema Channel (top row), and the corresponding temperature monthly time series (bottom row). In the Taylor diagrams, the standard deviation is normalized by the reference (mooring observation, black star), and gray arcs indicate the normalized RMSE. Dashed lines in the time series indicate the mean temperature for each dataset. Columns correspond to the CLIVAR (left), E2 (center), and SAMBA (right) mooring periods. Colors indicate: Reference (black), ECCO (blue), SODA (green), GLORYS (purple), OFES (orange), FESOM R (red), FESOM V (yellow), FESOM H (brown), and FESOM VH (pink).

Table 3. Mean temperature and linear trend derived from simulation outputs and CTD observations (reference) at Sites BB, C, and D along the SAMBA-West array. The reference corresponds to the deepest bin of each CTD cast. Trends are computed over the same period as the CTD observations at each site. Trend values are multiplied by 10^3 for display purposes.

	Site BB		Site C		Site D	
	Mean (°C)	Trend (10^{-3} °C yr $^{-1}$)	Mean (°C)	Trend (10^{-3} °C yr $^{-1}$)	Mean (°C)	Trend (10^{-3} °C yr $^{-1}$)
Reference	-0.10 ± 0.02	-0.8 ± 2.7	-0.12 ± 0.007	2.1 ± 1.2	-0.13 ± 0.008	1.9 ± 1.1
ECCO	0.54 ± 0.01	2.2 ± 0.2	0.09 ± 0.008	1.4 ± 0.1	-0.17 ± 0.003	0.5 ± 0.1
SODA	0.40 ± 0.05	7.6 ± 0.7	0.31 ± 0.03	6.9 ± 0.4	0.26 ± 0.027	7.6 ± 0.4
GLORYS	0.29 ± 0.24	-10.0 ± 3.2	-0.14 ± 0.10	-4.2 ± 1.4	-0.08 ± 0.080	-0.1 ± 1.0
OFES	-0.05 ± 0.04	4.4 ± 0.9	-0.10 ± 0.009	3.0 ± 0.2	-0.11 ± 0.009	3.8 ± 0.2
FESOM R	0.71 ± 0.05	1.5 ± 0.6	0.30 ± 0.026	5.6 ± 0.4	0.25 ± 0.02	4.9 ± 0.3
FESOM V	0.19 ± 0.05	9.7 ± 0.6	0.09 ± 0.02	5.6 ± 0.3	0.07 ± 0.02	6.3 ± 0.3
FESOM H	0.62 ± 0.05	2.5 ± 0.6	0.36 ± 0.03	7.6 ± 0.4	0.33 ± 0.03	8.1 ± 0.4
FESOM VH	0.25 ± 0.04	8.2 ± 0.5	0.15 ± 0.024	6.8 ± 0.3	0.12 ± 0.02	6.9 ± 0.3

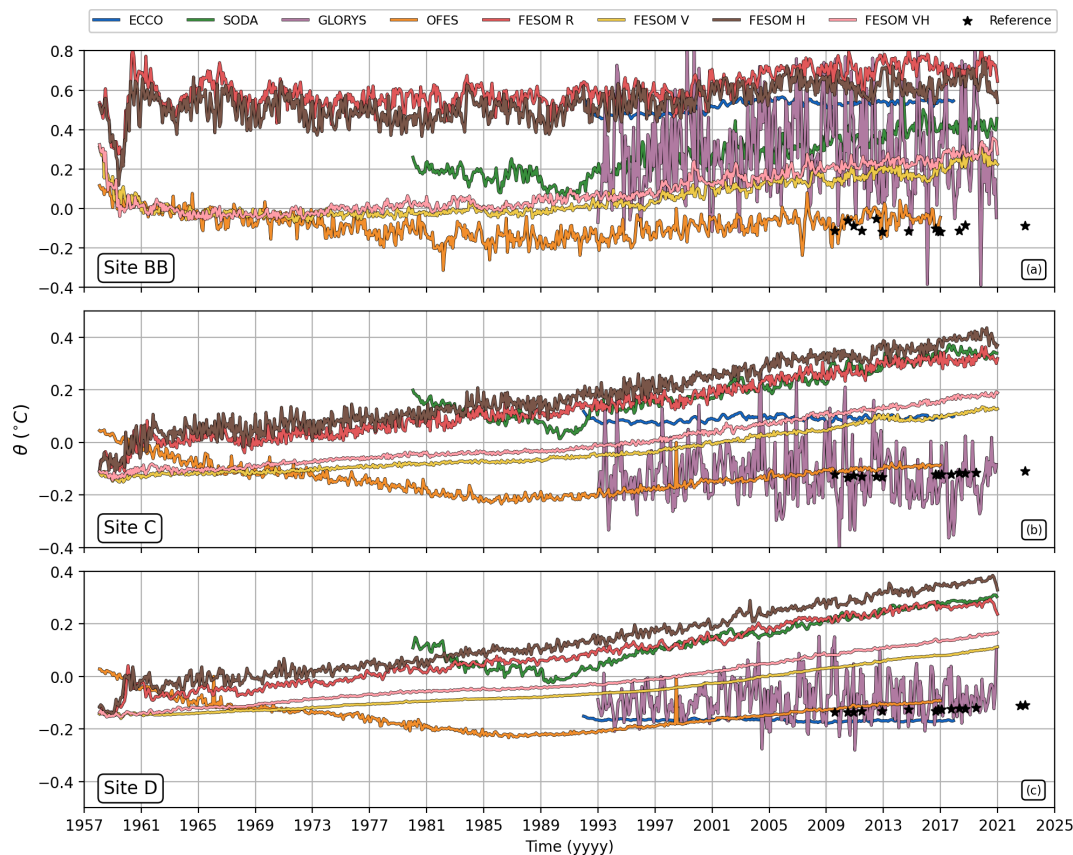


Figure 6. Time series of potential temperature (θ) at the grid point closest to Site BB (a), Site C (b), and Site D (c) for each simulation and for the reference (black stars), corresponding to the deepest CTD bin at each site. The color scheme follows Fig. 5.

ing to the deepest model level connected through the Vema Channel, whereas the deeper Site D is represented by the 4640 m level. The strong temperature contrast between these two levels suggests that the coldest abyssal waters remain below the deepest model level connected through the Vema Channel. GLORYS remains close to the reference mean but with large uncertainty. Regarding trends, ECCO again provides the closest match to the observed warming trend, while SODA substantially overestimates it. GLORYS shows a near-zero trend, and OFES moderately overestimates it.

In summary, the comparison highlights that model performance varies substantially across locations and periods, with no single simulation consistently outperforming the others. SODA consistently overestimates the reference mean temperature across all sites, while GLORYS, despite reproducing mean conditions reasonably well, exhibits excessive variability throughout. OFES generally provides the closest representation of the observed mean temperature, and ECCO captures the warming trends most accurately, but its mean temperature is highly sensitive to the model level representing each site due to the strong vertical temperature gradient. Together, these results reinforce the limitations identified in

the previous sections regarding the representation of abyssal water properties in the western South Atlantic.

4 FESOM results

The recurring limitations identified in the previous section, including the warm abyssal bias, reduced inter-basin connectivity, and discontinuities in the propagation of abyssal waters through the Vema Channel, suggest that common mechanisms may underlie the deficiencies shared by otherwise distinct ocean simulations. Because the evaluated simulations differ in several aspects, including grid resolution, atmospheric forcing, data assimilation, bathymetry, and sea-ice representation, the intercomparison alone cannot isolate the contribution of any individual model component to these biases. Using a common model configuration in which horizontal and vertical grid resolution are modified independently and in combination, the controlled FESOM experiments investigate whether differences in grid resolution can explain the recurring limitations identified across the different simulations. Therefore the reference experiment (FESOM R) provides the baseline against which the effects of the controlled resolution changes are assessed.

4.1 Abyssal properties

The bottom temperature distribution in FESOM R (Fig. 7b) reproduces several of the recurring limitations identified in Sect. 3, despite being based on an independent model formulation. Cold waters ($\theta < -0.7^\circ\text{C}$) occupy the Antarctic continental shelf, while only a limited area of the central Weddell Sea contains bottom waters colder than -0.7°C , similar to ECCO. These waters do not extend beyond the South Scotia Ridge, consistent with ECCO, SODA, and GLORYS. Waters with $\theta \leq 0.0^\circ\text{C}$ are exported into the Argentine Basin but remain confined to its southern part, allowing warmer waters to dominate most of the basin. As a result, the waters entering the Brazil Basin are markedly warm, closely resembling the distributions simulated by ECCO and SODA.

The bias field of FESOM R (Fig. 7f) further confirms that the reference experiment reproduces the large-scale deficiencies identified across the evaluated simulations. Although positive temperature biases are widespread throughout the study region, their spatial distribution is not uniform. The Brazil Basin exhibits substantially stronger warm anomalies than the Argentine Basin, producing an abrupt inter-basin transition similar to that identified in ECCO and OFES. Unlike these simulations, however, the discontinuity in FESOM R arises from a change in the magnitude of the warm bias rather than from a reversal of its sign, suggesting that the degradation of abyssal water properties increases downstream of the principal inter-basin pathways.

We now examine how controlled changes in horizontal and vertical resolution modify these patterns. FESOM V (Fig. 7c) shows a substantial improvement relative to FESOM R. A broader area of the central Weddell Sea is occupied by cold waters with $\theta \leq -0.7^\circ\text{C}$, though these waters still do not extend into the South Sandwich Trench. Waters with $\theta \leq 0.0^\circ\text{C}$ now span the entire Argentine Basin, and a colder class of waters flows from this basin into the Brazil Basin. The bias map (Fig. 7g) reflects this improvement, displaying reduced magnitudes and a more spatially uniform warm bias across the study region, without the basin discontinuities present in FESOM R.

FESOM H (Fig. 7d) exhibits the weakest performance among the four experiments. No waters colder than -0.7°C are present in the central Weddell Sea, and waters colder than 0.0°C are absent in the Argentine Basin, occupying just a small portion of the Georgia Basin. A warmer class of waters, relative to both FESOM R and FESOM V, is exported northward into the Brazil Basin. The bias field (Fig. 7h) displays spatial patterns similar to those of FESOM R but with substantially larger magnitudes, resulting in a poorer representation of inter-basin connectivity.

FESOM VH (Fig. 7e) performs better than FESOM R in some aspects but worse in others. Waters colder than -0.7°C occupy a broader area of the central Weddell Sea, and a colder class of waters flows from the Argentine Basin into the Brazil Basin, indicating an improved representation in

that region. However, the connection between the Weddell Sea and the Argentine Basin remains poorly represented, as waters colder than 0.0°C are not exported northward from the Georgia Basin, unlike in FESOM R and FESOM V. The bias field (Fig. 7i) shows a distinct pattern, with larger positive biases in the Argentine Basin and comparatively smaller biases in the Brazil Basin.

The spatial patterns described for θ are largely mirrored in the salinity fields (Fig. 7j–r), and as a consequence, the σ_4 field (Fig. A6) displays predominantly negative biases across most of the analyzed regions, indicating that density variations are primarily controlled by temperature rather than salinity. Over the Antarctic continental shelf, density biases are positive, in contrast to the negative values observed elsewhere. Despite the presence of relatively dense waters on the shelf, these waters are not sufficiently transferred to the abyssal Weddell Sea through downslope cascading, limiting the ventilation of the deep basin and contributing to the negative density biases observed in this region.

The video supplements (Santos et al., 2026j) support this picture, as no clear indications of denser waters reaching the abyssal Weddell Sea can be seen in any of the configurations. Unlike the previously analyzed simulations, the FESOM simulations do not exhibit inverse density trends between adjacent basins. Instead, all experiments display a general negative density trend across the Weddell Sea, Argentine, and Brazil Basins, though the rates of change differ among configurations. In the Weddell Sea, FESOM R and FESOM H lose all waters within the density range $46.16 < \sigma_4 < 46.20 \text{ kg m}^{-3}$ by 2019, whereas FESOM V and FESOM VH do not completely lose this density class, though its volume decreases over time. In the Argentine Basin, FESOM R loses all waters within $46.08 < \sigma_4 < 46.12 \text{ kg m}^{-3}$ by 1993, FESOM V by 2002, FESOM H by 1988, and FESOM VH by 1995. In the Brazil Basin, FESOM R and FESOM H lose all waters within $46.04 < \sigma_4 < 46.08 \text{ kg m}^{-3}$ by 1968, while FESOM V and FESOM VH retain this density class throughout the simulation. These results indicate that enhanced vertical resolution promotes a more coherent density evolution across connected basins.

The four FESOM experiments indicate that vertical resolution exerts a stronger control on the large-scale representation of abyssal water masses than horizontal resolution. In both pairs of experiments (FESOM R–FESOM V and FESOM H–FESOM VH), increasing the number of vertical levels consistently produces a colder abyssal ocean and enhances the northward propagation of colder and denser abyssal waters, thereby reducing the discontinuities in abyssal properties between the Weddell Sea, Argentine Basin, and Brazil Basin. The improved performance of the vertically refined configurations is consistent with previous studies showing that enhanced vertical resolution improves the representation of deep water masses and strengthens the deep overturning circulation (Xu et al., 2023; Stewart et al., 2017)

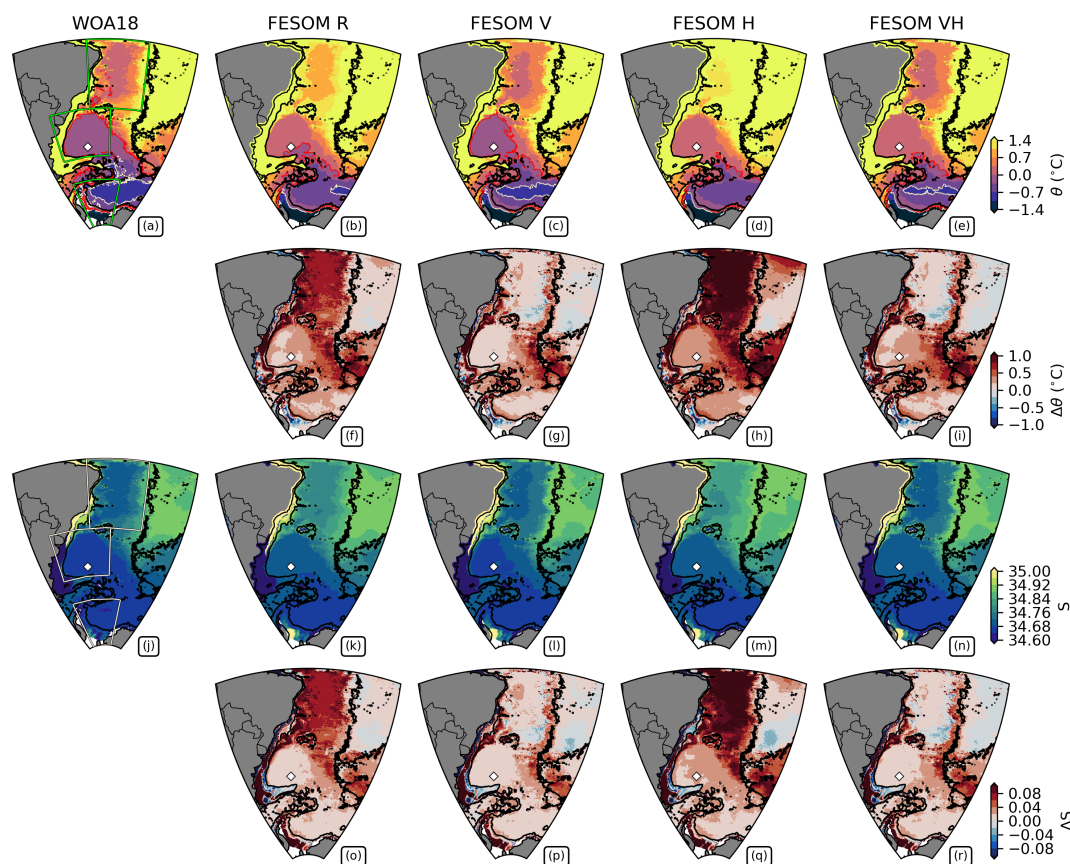


Figure 7. Mean potential temperature (θ ; a–e) and salinity (j–n) from 1994 to 2005 at the deepest valid level at each horizontal grid point, and the corresponding mean biases relative to WOA18 ($\Delta\theta$, f–i; ΔS , o–r). Columns correspond to WOA18 (reference), FESOM R, FESOM V, FESOM H, and FESOM VH, from left to right. The black contour indicates the 3000 m isobath, the red contour marks the $\theta = 0.0^\circ\text{C}$ isotherm, and the white contour marks the $\theta = -0.7^\circ\text{C}$ isotherm. White diamonds mark the position of the virtual profile depicted in Fig. A4. Rectangles in the WOA18 panels (a), (j) represent, from north to south, the Brazil Basin, Argentine Basin, and Weddell Sea.

Although these results highlight the dominant role of vertical resolution, they do not imply that grid resolution alone controls the simulated abyssal circulation. Other aspects of the model formulation, including atmospheric forcing, bathymetry, sea-ice representation, and subgrid-scale parameterizations, are also expected to contribute to the remaining differences among the simulations. In particular, the poorer performance of the horizontally refined configurations may partly reflect the interaction between increased horizontal resolution and the Gent–McWilliams (GM) parameterization, whose diffusivity scales with grid spacing. However, this interpretation remains speculative, as the parameterizations were intentionally kept unchanged in all experiments to isolate the effects of grid resolution. Assessing the interplay between horizontal resolution and subgrid-scale mixing schemes therefore lies beyond the scope of the present study.

4.2 TS diagram analysis

In the Argentine Basin, FESOM R shows a clear absence of waters colder than 0.0°C , with maximum densities reach-

ing only around 45.92 kg m^{-3} (Fig. 8c), and a saltier–warmer bias along these density levels relative to the reference (Fig. 8d). In the Brazil Basin, the absence of cold and dense water classes is even more pronounced, with minimum temperatures around 1.0°C and maximum densities near 45.84 kg m^{-3} (Fig. 8e and f), indicating a poor representation of the connection between the two basins, consistent with the common deterioration of abyssal thermohaline properties and the associated loss of the coldest and densest water classes from the Argentine Basin to the Brazil Basin identified in the previously evaluated simulations.

FESOM V shows subtle but notable changes relative to FESOM R in the Argentine Basin: temperatures now reach 0.0°C and waters with densities exceeding 45.92 kg m^{-3} are present, unlike in FESOM R where densities remain at or just above this value, though the saltier–warmer bias along density levels persists (Fig. 8g and h). In the Brazil Basin, a colder and denser class of waters now occupies the deepest part of the water column, with properties similar to those found in the reference (Fig. 8i). This indicates an improved

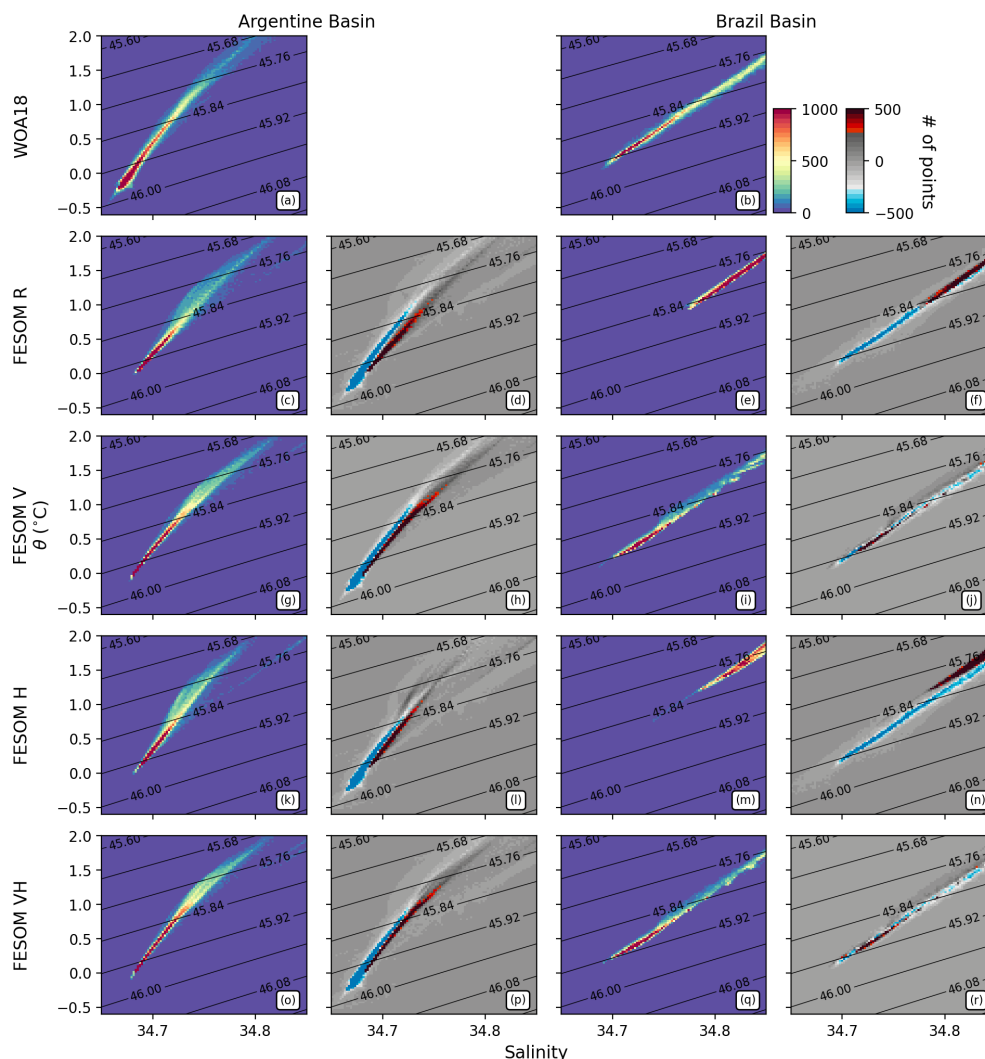


Figure 8. Time-averaged θ – S distribution of the Argentine Basin (first column) and of the Brazil Basin (third column). Averaged θ – S distribution of the difference between WOA18 and each simulation at the Argentine Basin (second column) and at the Brazil Basin (fourth column). The rows from top to bottom represent WOA18 (first row), FESOM R (second row), FESOM V (third row), FESOM H (fourth row), and FESOM VH (fifth row). Contour lines are σ_4 . The colorbar of the first and third columns indicates the number of grid points within each θ – S bin; the colorbar of the second and fourth columns indicates the difference in grid point counts between the simulation and WOA18, where positive (negative) values indicate bins where the simulation exceeds (falls below) the WOA18 reference count. The diagrams are zoomed at the abyssal layer ($-0.6\text{ }^{\circ}\text{C} < \theta < 2.0\text{ }^{\circ}\text{C}$; $34.65 < S < 34.85$).

connection between the two basins, with the θ – S curves lying much closer to the reference and nearly overlapping (Fig. 8j).

FESOM H shows a θ – S distribution in the Argentine Basin similar to that of FESOM R (Fig. 8k and l), but still being warmer and lighter. In the Brazil Basin, however, the deviation from the reference is larger than in FESOM R, with a greater loss of cold waters, a shift of the distribution toward lighter densities, and a higher concentration of warm points (Fig. 8m and n). This indicates that increasing horizontal resolution without modifying vertical resolution does not improve the representation of abyssal waters and can even degrade it.

FESOM VH closely resembles FESOM V in both the Argentine and Brazil Basins (Fig. 8o–r), with only minor differences in the θ – S distribution. Compared to FESOM H, FESOM VH recovers most of the improvement associated with enhanced vertical resolution, but the additional horizontal refinement does not substantially alter the θ – S relationship relative to FESOM V. These results confirm that vertical refinement provides consistent improvements in the representation of abyssal waters, whereas horizontal refinement alone has mixed or detrimental effects.

Overall, the θ – S analysis confirms that vertical resolution is the dominant factor controlling the representation of

abyssal water properties and inter-basin connectivity. Refining the vertical grid consistently improves the density structure and the connection between the Argentine and Brazil Basins, whereas horizontal refinement alone does not yield comparable benefits and can even degrade the results.

4.3 Temperature distribution across Vema Channel

In FESOM R (Fig. 4f), the Vema Channel is represented but remains poorly resolved, consistent with the goal of replicating the configurations of the previously assessed simulations. Only a few grid points fall inside the channel, and the deepest ones do not reach its full depth, with minimum temperatures staying above 0.0 °C. In FESOM V (Fig. 4g), the channel structure becomes more clearly defined and the deepest parts contain colder water than in FESOM R, including temperatures below 0.0 °C, although the amount of very cold water remains limited. FESOM H (Fig. 4h), in contrast, although offering a more detailed geometric description of the channel than the reference, does not improve the abyssal thermal structure: bottom waters remain warmer than in both FESOM R and FESOM V, and the coldest isotherms bend upward toward the western side of the channel, inconsistent with the expected structure. Note that FESOM V and FESOM H do not increase the maximum depth of the channel compared to FESOM R.

FESOM VH (Fig. 4i), which combines the enhanced vertical resolution of FESOM V and the finer horizontal grid of FESOM H, restores and extends the improvements obtained with higher vertical resolution. The coldest isotherms are again present within the channel, and the bottom water layer bends toward the eastern wall. This eastward displacement of the cold core is consistent with in situ observations of the AABW flow through the Vema Channel (Morozov et al., 2018), which describe a bottom-intensified current steered along the eastern flank. The mechanism behind this deflection has been attributed to the Ekman flux induced by bottom friction, which drives a lateral shift of the densest water mass toward the eastern boundary. This feature is also reproduced in regional numerical simulations of AABW flow (Frey et al., 2019), where the cold core similarly adheres to the eastern wall while maintaining a narrow bottom-intensified jet. The presence of this structure in FESOM VH therefore indicates that the combined refinements enable the model to reproduce both the cold core and its realistic eastward deflection, though waters colder than 0.0 °C remain absent. Note that in FESOM VH the maximum depth of the channel is increased compared to the other three FESOM experiments, which further contributes to a better representation of the channel bathymetry.

The vertical refinement in FESOM V and FESOM VH brings the abyssal waters closer to the observational reference, resulting in a colder abyssal ocean and explaining the smaller temperature bias in the Argentine Basin (Fig. 7g, i) relative to FESOM R and FESOM H (Fig. 7f, h). This cool-

ing is not restricted to the deepest model level. Instead, it extends upward through the lower water column, allowing colder waters to reach the depth of the Vema Channel sill (compare Figs. 4 and A4). This likely explains the reduced temperature bias in the Brazil Basin (Fig. 7g, i), as colder waters are able to propagate northward through the channel. Note that, although FESOM V is slightly colder than FESOM VH in the deepest layers, FESOM VH provides a more realistic representation of the Vema Channel. This likely facilitates the northward propagation of cold abyssal waters, explaining why FESOM VH exhibits a similarly reduced bias in the Brazil Basin despite its slightly warmer abyssal temperatures.

These results show that vertical resolution is the key factor enabling the representation of cold abyssal waters within the Vema Channel, whereas horizontal refinement alone distorts the thermal structure without recovering the coldest water masses. The combined refinement of both grids, however, goes beyond simply improving the temperature field: it also allows the model to reproduce the eastward deflection of the AABW core, a dynamical feature that cannot be captured without sufficient resolution in both dimensions. As in the previous subsections, no adjustments were made to the mixing parameterizations, and the degradation observed in FESOM H may partly reflect this limitation.

4.4 Comparison with in situ data

During the CLIVAR period (Fig. 5a and d), FESOM R shows the highest correlation (≈ 0.75) among the four experiments, but its mean temperature substantially overestimates the reference. FESOM V, despite a near-zero correlation (≈ 0.02), reproduces the observed variability more faithfully (small RMSE) and exhibits the smallest warm bias, with a mean temperature close to the reference. FESOM H displays a weak correlation (≈ 0.08) and the largest warm bias among the four configurations. FESOM VH, like FESOM V, has a small RMSE, it also improves upon FESOM H in the mean temperature, but still exhibits small correlations (≈ 0.20). Overall, vertically refined configurations (FESOM V and VH) better capture the variability and mean state of the temperature within the channel, while the horizontal refinement seems to deviate the temperature mean to warmer values.

During the E2 period (Fig. 5b and e), FESOM V achieves the highest correlation (≈ 0.64) among the four experiments, with small variability, a near-zero RMSE, and the smallest warm bias, making it the configuration most similar to the reference. FESOM VH also shows small variability and RMSE, but with a worse correlation (≈ -0.23) than FESOM V. FESOM R shows no correlation (≈ 0.00) and a larger variability, while FESOM H remains the warmest and most variable configuration, its correlation is (≈ 0.22). As in the CLIVAR period, vertically refined configurations outperform those with horizontal refinement alone when representing the mean state and variability of the temperature in the channel.

During the SAMBA period (Fig. 5c and f), FESOM V and VH remain consistently closer to the reference than FESOM R and H, both in mean temperature and variability. FESOM H shows the largest warm bias and variability, while FESOM V and VH exhibit smaller biases and RMSE values. None of the four simulations achieve high correlation values: FESOM R (≈ 0.24), FESOM V (≈ 0.15), FESOM H (≈ -0.010), and FESOM VH (≈ 0.12).

Across all three mooring periods, vertical resolution consistently emerges as the key factor controlling model performance. FESOM V and VH systematically reduce warm biases and better reproduce the observed variability, while FESOM H generally performs worse than FESOM R in terms of mean temperature and variability. However, the correlation analysis across the three mooring sites does not allow a single FESOM configuration to be identified as systematically superior. FESOM R shows the highest correlation at the CLIVAR mooring ($r = 0.75$), while FESOM V performs best at the E2 mooring ($r = 0.64$), and all configurations show weak correlations at the SAMBA mooring. This suggests that vertical resolution primarily controls the mean state and variance of the simulated temperature, but does not guarantee phase agreement with the observed temporal variability at individual mooring locations.

The simulations were also compared with CTD data from the SAMBA-West array at Sites BB, C, and D (Table 3, Fig. 6). At Site BB, all FESOM configurations produce temperatures warmer than the reference, with FESOM V providing the closest match and FESOM R the largest deviation. The observed CTD trend at this site is not statistically significant, which excludes a meaningful comparison of warming trends with the simulations.

At Sites C and D, FESOM V again provides the closest representation of the reference mean temperature, while FESOM H shows the largest deviations. FESOM VH performs comparably to FESOM V in terms of mean temperature, while FESOM R shows intermediate values. Regarding trends, all configurations overestimate the observed warming, with FESOM H showing the largest overestimation and FESOM R the smallest. These results confirm that enhanced vertical resolution is the primary factor driving improvement in the representation of abyssal temperatures along the SAMBA-West line, while horizontal refinement alone has little systematic benefit.

Taken together, the comparison with in situ data reinforces the conclusions drawn from the previous subsections: vertical resolution is the dominant factor controlling the representation of abyssal water properties in the Vema Channel and along the SAMBA-West array, while horizontal refinement alone does not yield systematic improvements and can even degrade model performance.

5 Summary and conclusions

This study investigates whether or not the recurring limitations identified across widely used global ocean simulations in the representation of abyssal water properties and inter-basin connectivity can largely be explained by grid resolution. To address this question, outputs from the ocean reanalyses ECCO, SODA, and GLORYS together with the forward ocean model OFES were first evaluated to identify common biases in abyssal water properties and inter-basin connectivity, motivating four targeted experiments with FESOM 2, in which horizontal and vertical grid resolution are modified independently and in combination to isolate their relative influence. The analysis focuses on the connectivity between the Argentine and Brazil Basins through the Vema Channel, while also considering the upstream link with the Antarctic continental slope and the abyssal Weddell Sea.

Despite substantial differences in model formulation, the intercomparison revealed recurring limitations in the representation of abyssal water properties and inter-basin connectivity between the Weddell Sea, Argentine Basin, and Brazil Basin. Across the evaluated models, the degradation of abyssal water properties along this pathway was consistently associated with reduced inter-basin connectivity and density errors were found to be largely controlled by temperature biases. Also, none of the evaluated simulations clearly captures the downslope cascading of dense shelf waters from the Antarctic continental shelf. Together, these recurring deficiencies suggested that an aspect shared across otherwise independent ocean models, rather than model-specific characteristics, could play a dominant role in limiting the representation of the abyssal ocean.

To constrain the reason for the recurring deficiencies, four FESOM experiments were conducted with targeted modification of horizontal and vertical resolution. The vertical-refinement experiment (FESOM V) provided the most substantial basin-scale improvement in the representation of abyssal waters. Increasing vertical resolution markedly reduced the warm bias common to all experiments while preserving the coldest and densest abyssal water classes during their northward propagation, thereby improving the continuity of abyssal properties between the Weddell Sea, Argentine Basin, and Brazil Basin. Although the Vema Channel sill is represented as shallower than in reality, the colder abyssal thermal structure allows cold waters to reach sill depth and propagate into the Brazil Basin, substantially reducing the downstream degradation of abyssal properties.

In contrast, the horizontal-refinement experiment (FESOM H) does not lead to systematic improvements, resulting in warmer abyssal layers. One possible explanation is that changes in horizontal resolution alter the balance between resolved and parameterized mesoscale eddy activity, as scaling diffusivity linearly with horizontal resolution may not sufficiently suppress the eddy parameterization in regions where the grid is fine enough to partially resolve eddies.

These results suggest that recalibrating mixing parameterizations when modifying horizontal resolution may be necessary, particularly in eddy-permitting regimes.

When both vertical and horizontal refinements are applied together (FESOM VH), the model more realistically represents the geometry of the Vema Channel and the eastward displacement of the AABW core. Although the abyssal waters remain slightly warmer than in FESOM V at the basin scale, the improved representation of the channel allows cold waters to propagate through the sill more effectively, partially compensating for the warmer abyssal thermal structure. These results highlight the complementary roles of vertical resolution, which controls the large-scale abyssal thermal structure, and horizontal resolution, which improves the representation of narrow topographic pathways.

Taken together, these findings indicate that many of the recurring limitations identified across widely used global ocean models are associated with an inadequate representation of abyssal water masses and their propagation across major bathymetric barriers. The controlled experiments further demonstrate that preserving the thermal structure of abyssal waters through enhanced vertical resolution substantially improves their downstream propagation and inter-basin continuity. These results highlight vertical grid resolution as a first-order control on the large-scale representation of abyssal circulation and suggest that its careful design should be a central consideration in the development of future global ocean models.

Appendix A

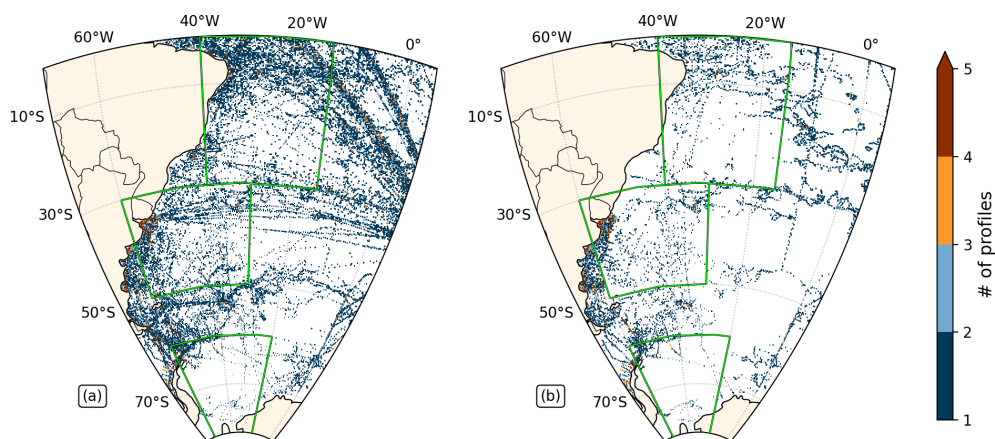


Figure A1. Spatial distribution of hydrographic profile counts used to construct the World Ocean Atlas 2018 (WOA18) temperature (a) and salinity (b) climatology within the study region. Rectangles represent, from north to south, the Brazil and Argentine basins and the Weddell Sea.

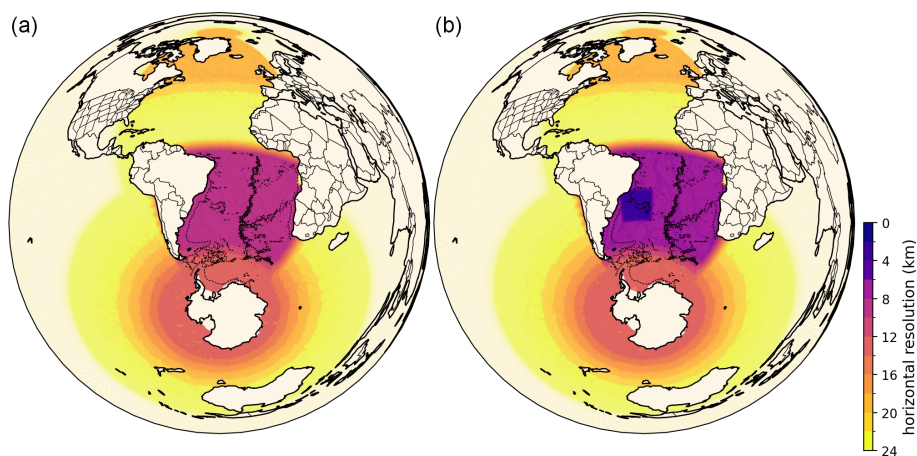


Figure A2. (a) Square root of grid-cell area (FESOM R and FESOM V) of the entire globe. (b) Same as (a), but of FESOM H and FESOM VH. Dashed black contour marks the isobath of 3000 m and solid black contour the continents.

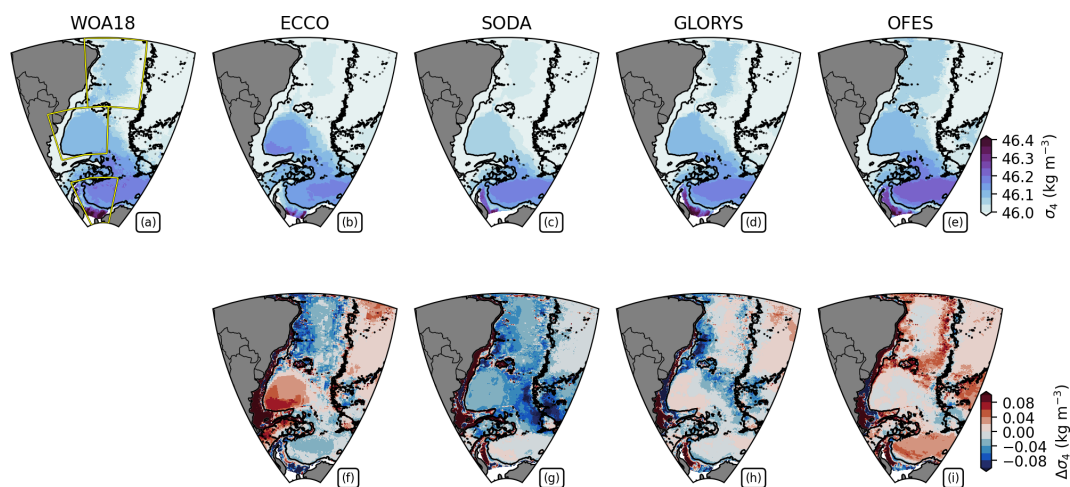


Figure A3. Mean potential density referenced to 4000 m (σ_4 ; **a–e**) from 1994 to 2005 at the deepest valid level at each horizontal grid point, and the corresponding mean biases relative to WOA18 ($\Delta\sigma_4$, **f–i**). Columns correspond to WOA18 (reference), ECCO, SODA, GLORYS, and OFES, from left to right. The black contour indicates the 3000 m isobath. Rectangles in the WOA18 panel (**a**) represent, from north to south, the Brazil Basin, Argentine Basin, and Weddell Sea.

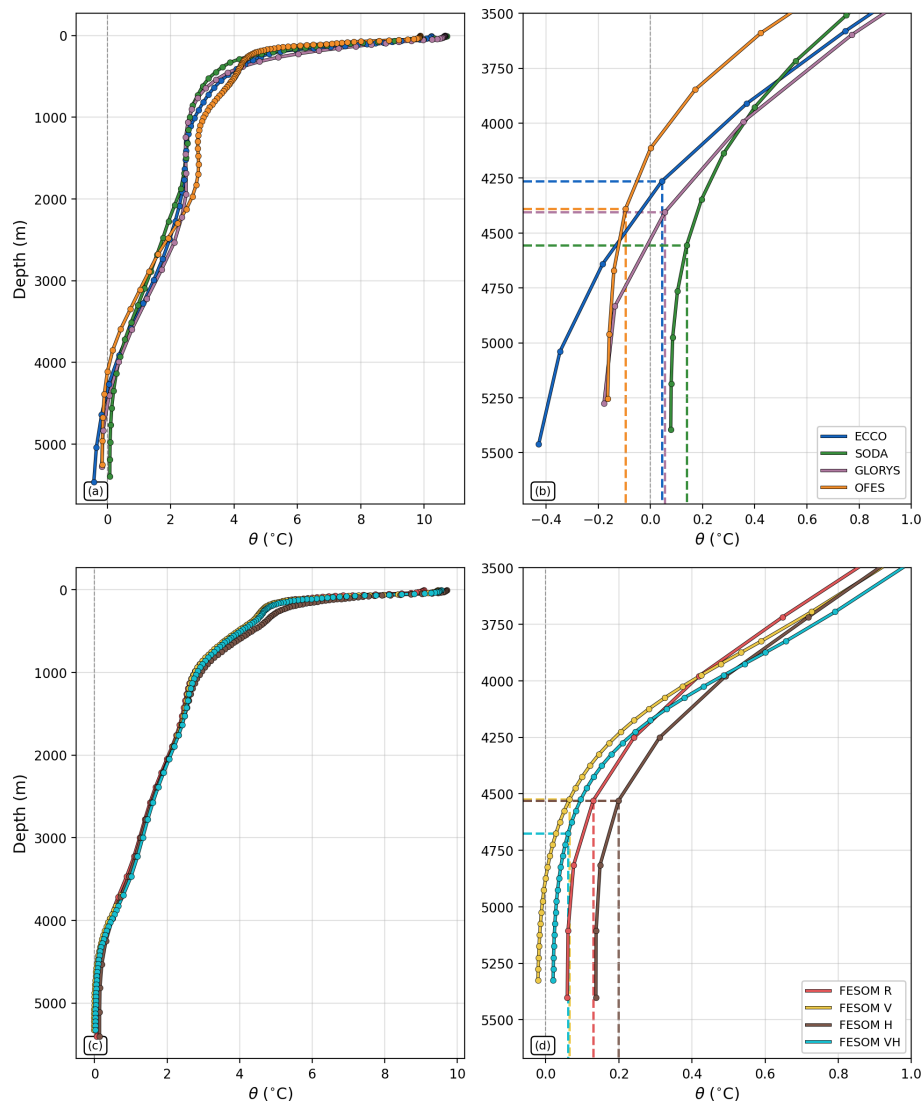


Figure A4. Vertical profiles of potential temperature (θ) at (46° S, 43° W), averaged over 1994–2005. **(a)** Full-depth profile of ECCO (blue), SODA (green), GLORYS (purple), and OFES (orange). **(b)** Abyssal zoom below 3500 m of **(a)**. **(c)** Full-depth profile of FESOM R (red), FESOM V (yellow), FESOM H (brown), and FESOM VH (pink). **(d)** Abyssal zoom below 3500 m of **(c)**. In all panels, filled circles indicate the discrete vertical levels of each simulation. Dashed L-shaped lines in **(b)** and **(d)** indicate, for each simulation, the shallowest depth level at or above the Vema Channel sill depth.

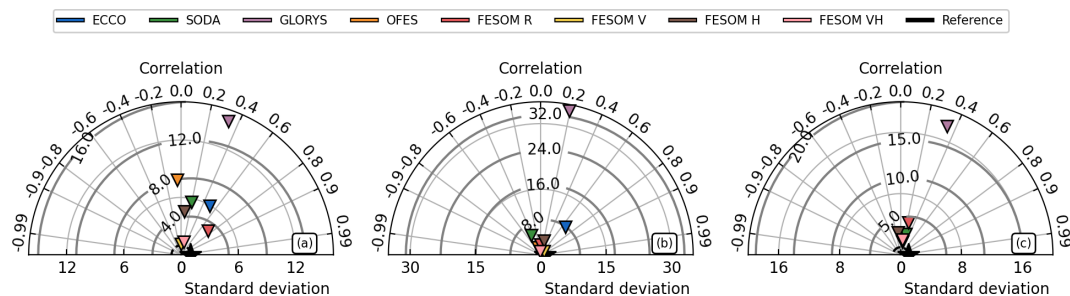


Figure A5. Taylor diagrams comparing temperature records from the CLIVAR (a), E2 (b), and SAMBA (c) moorings with model simulations within the Vema Channel. The standard deviation is normalized by the reference (mooring observation, black star), and gray arcs indicate the normalized RMSE. Colors indicate: Reference (black), ECCO (blue), SODA (green), GLORYS (purple), OFES (orange), FESOM R (red), FESOM V (yellow), FESOM H (brown), and FESOM VH (pink).

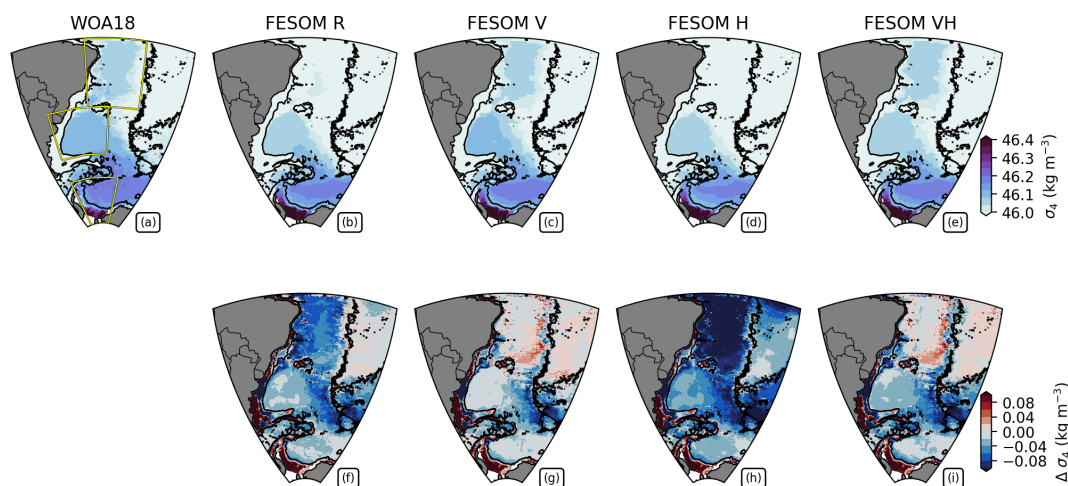


Figure A6. Mean potential density referenced to 4000 m (σ_4 ; a–e) from 1994 to 2005 at the deepest valid level at each horizontal grid point, and the corresponding mean biases relative to WOA18 ($\Delta\sigma_4$, f–i). Columns correspond to WOA18 (reference), FESOM R, FESOM V, FESOM H, and FESOM VH, from left to right. The black contour indicates the 3000 m isobath. Rectangles in the WOA18 panel (a) represent, from north to south, the Brazil Basin, Argentine Basin, and Weddell Sea.

Data availability. The WOA18 climatology is freely available at <https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/> (last access: February 2025). ECCO Version 4 Release 4 outputs are available at https://podaac.jpl.nasa.gov/dataset/ECCO_L4_TEMP_SALINITY_LLC0090GRID_MONTHLY_V4R4 (ECCO Consortium et al., 2025). SODA version 3.4.2m outputs were downloaded from <https://dsrs.atmos.umd.edu/DATA/soda3.4.2/> (last access: February 2025). GLORYS reanalysis outputs are available through the Copernicus Marine Service at https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/files?subdataset=cmems_mod_glo_phy_my_0.083deg_P1M-m_202311 (last access: February 2025). OFES2 potential temperature and salinity outputs are distributed through <https://www.jamstec.go.jp/esc/fes/dods/OFES2/Monthly/tempe> (last access: February 2025) and <https://www.jamstec.go.jp/esc/fes/dods/OFES2/Monthly/salinity> (last access: February 2025), respectively. The hydrographic data from the SAMBA-West array and from the MSM60 cruise are described in Santos et al. (2026a). The mooring data are described in Zenk (2008), Zenk and Visbeck (2013), and Campos et al. (2021). The FESOM2 simulation outputs are archived in Zenodo and organized into thematic datasets. Outputs associated with the Vema section (<https://doi.org/10.5281/zenodo.19595306>, Santos et al., 2026b), TS diagrams (<https://doi.org/10.5281/zenodo.19597204>, Santos et al., 2026c), PIES (<https://doi.org/10.5281/zenodo.19597367>, Santos et al., 2026d), and mooring analyses (<https://doi.org/10.5281/zenodo.19597574>, Santos et al., 2026e) are each provided under dedicated DOIs. Abyssal property fields are further subdivided by experiment: FESOM R (<https://doi.org/10.5281/zenodo.19598232>, Santos et al., 2026f), FESOM V (<https://doi.org/10.5281/zenodo.19597878>, Santos et al., 2026g), FESOM H (<https://doi.org/10.5281/zenodo.19597860>, Santos et al., 2026h), and FESOM VH (<https://doi.org/10.5281/zenodo.19597737>, Santos et al., 2026i), with each experiment archived under its own DOI.

Video supplement. Video supplements showing the temporal evolution of potential density referenced to 4000 m depth (σ_4) at the deepest valid level for each simulation are archived in Zenodo under the DOI: <https://doi.org/10.5281/zenodo.19699061> (Santos et al., 2026j).

Supplement. The supplement related to this article is available online at <https://doi.org/10.5194/os-22-3079-2026-supplement>.

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Administration (lead); Supervision (lead); Writing – Review & Editing (supporting).

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