



Physically-driven dissolved oxygen dynamics in the Bay of Biscay and the English Channel

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Abstract. The shelf of the Bay of Biscay and the English Channel form a contrasting hydrodynamic environment, with several areas recognised as exhibiting signs of hypoxia. However, research on low oxygen levels in the region has, until now, focused predominantly on the estuaries and small bays. Here we use a three-dimensional circulation model coupled with a simple oxygen model to examine the physical controls on dissolved oxygen concentration at the shelf scale. The model assumes an oxygen consumption rate in the water column that depends on the temperature and dissolved oxygen concentration. Despite its simplicity, the model reproduces a large part of the dissolved oxygen observed variability, thus highlighting the predominance of physical processes in driving dissolved oxygen at the regional scale. The areas exhibiting low oxygen concentrations are predominantly observed in coastal zones, especially within major Regions of Freshwater Influence. The variation in dissolution rates caused by rising temperature is found to be the fundamental factor driving the trend in bottom oxygen levels. Model results demonstrate that bottom temperature also acts as the primary driver of most interannual oxygen variability in Regions of Freshwater Influence, while stratification appears to play a minor role.

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1 Introduction

Dissolved oxygen is a critical factor in the functioning of marine ecosystems. A decline in oxygen levels can trigger mass mortality, species migration, shifts in community composition, reduced growth and biomass, as well as metabolic disruptions (Diaz, 2001; Diaz and Rosenberg, 2008; Roman et al., 2024). Hypoxia has conventionally been defined by a threshold of 2mg.L^{-1} , the point at which many marine species begin to suffocate (Diaz and Rosenberg, 1995). However, research has demonstrated that low oxygen levels above this threshold can still profoundly affect marine ecosystems (Gray et al., 2002; Vaquer-Sunyer and Duarte, 2008).

Since the mid-20th century, a decline in dissolved oxygen has been observed across the global ocean (Diaz and Rosenberg, 2008; Schmidtko et al., 2017; Breitburg et al., 2018; Keeling et al., 2010). The rising global temperatures reduce oxygen solubility in water while increasing microbial respiration. Additionally, warming is expected to diminish the reoxygenation



of bottom waters by enhancing stratification. It has been demonstrated that coastal environments are particularly vulnerable (Rabalais et al., 2009; Gilbert et al., 2010). The nutrient loading resulting from terrestrial inputs, notably of an anthropogenic nature, are higher than under pristine conditions and lead to generation of substantial quantities of organic matter. As this organic matter sinks below the pycnocline and undergoes remineralisation, it consumes oxygen, contributing to oxygen depletion and the increased frequency of hypoxic events—a process known as eutrophication. Furthermore, freshwater inflows from rivers near estuaries, where land-based nutrients are most concentrated, create salinity stratification. This prolongs the residence time of bottom water masses, making Regions of Freshwater Influence (ROFIs) particularly susceptible to hypoxia (Rabouille et al., 2008; Fennel and Testa, 2019; Große et al., 2019).

The processes influencing the dissolved oxygen concentration are significantly modulated by physical factors. Studies across diverse systems have shown that temperature, salinity, wind, and even topography substantially influence oxygen variability in bottom waters. Temperature and salinity affect both oxygen solubility in seawater and water column stratification, while the residence time of water masses determines the intensity and duration of hypoxia. Increased stratification, whether caused by surface warming or freshwater discharge, directly impacts bottom oxygen concentrations and exacerbates hypoxia. As demonstrated by Scully (2010) in the Chesapeake Bay and Feng et al. (2014) and Yu et al. (2015) in the Gulf of Mexico, wind can either intensify or mitigate hypoxia by influencing vertical mixing, river plume dispersion, or the advection of oxygen-rich waters. Additionally, topography plays a key role in the spatial variability of hypoxia, particularly in shallow coastal regions (DiMarco et al., 2010; Virtanen et al., 2019). A comprehensive understanding of the interplay between these factors is imperative for elucidating the mechanisms behind the formation and evolution of low-oxygen zones.

Hydrodynamic variations therefore play a significant role in oxygen concentration and the emergence of low-oxygen zones. It is anticipated that, within an environment characterised by contrasting dynamics, the trend in dissolved oxygen concentration will also vary, exhibiting significant spatial and temporal variability. The continental shelf of the Bay of Biscay and the English Channel thus provide a compelling case study, forming a coastal shallow region with contrasted dynamics. The Bay of Biscay opens in the north-east Atlantic ocean and is located between the north coast of Spain and French Brittany. The part of its continental shelf along the French coast, also called Armorican shelf, is a meso-tidal environment, characterised by an average depth of 100 m. The English Channel is a semi-enclosed shelf sea, with openings to the west towards the Celtic Sea and the Bay of Biscay and to the north-east towards the North Sea via the Dover Strait. This macro-tidal environment has an average depth of 50 m where the tides have a significant influence on the overall dynamics. Whereas most of the Bay of Biscay and western English Channel stratify seasonally, a large part of eastern Channel is permanently mixed by the barotropic tidal currents inducing bottom friction (Pingree, 1980). These regions are subject to significant influence from freshwater fluxes from land, distributed through three major rivers along the French coast: the Seine, the Loire and the Gironde rivers. These rivers form ROFIs which have significant temporal and spatial variability (Lazure and Jegou, 1998; Puillat et al., 2004; Martinez Almoyna et al., 2025).

Research on low oxygen levels in the region has focused predominantly on the estuaries. While the Gironde estuary experiences occasional summer hypoxia and several low-oxygen episodes, the Loire experiences regular summer hypoxia (Lanoux et al., 2013; Schmidt et al., 2019; Boukourt et al., 2025). Low oxygen values have also been observed and simulated in the Seine



estuary (Garnier et al., 2001; Billen et al., 2001). Although several modelling studies have addressed eutrophication linked to the Seine's river plume, the impact on oxygen levels has not been documented (Ménès-
 60 1998). Schmidt and Diallo (2024) studied the smaller Charente estuary, located between the Gironde and Loire estuaries, indicating the presence of a summer estuarine oxygen minimum zone. The bay of Vilaine, located to the west of the Loire estuary, is long known to be subject to hypoxia events and even anoxia (Chapelle et al., 1994). This bay has been observed to experience intense and recurrent eutrophication attributed to inputs from by both the Vilaine and the Loire river plumes (Ménès-
 65 2019; Ratmaya et al., 2019; Poppeschi et al., 2026). Furthermore, recent observations have revealed that parts of the shelf may experience low-oxygen levels outside estuaries and semi-enclosed bays (Dubosq et al., 2022).

The development and refinement of coupled 3D numerical models have greatly contributed to our understanding of the mechanisms influencing variations in dissolved oxygen concentrations, particularly the role of freshwater discharges in coastal environments (Peña et al., 2010). These are crucial for producing climate forecasts and anticipating future changes in marine ecosystems in the context of climate change. Ciavatta et al. (2016) completed a decadal model reanalysis to show that large
 70 parts of the north-west European shelf were vulnerable to oxygen deficiency. Wakelin et al. (2020) used a coupled physics-biogeochemical model NEMO-ERSEM to study the evolution to 2100 of oxygen concentration on the north-west European shelf under a high greenhouse gas emission scenario (RCP8.5). They predict decreases in near-bed oxygen concentrations across numerous regions of the shelf, including the English Channel, the Celtic Sea and the Armorican Shelf, mainly due to the impact of changes in temperature and salinity on solubility. Galli et al. (2024) confirmed this trend and demonstrated the
 75 high spatial heterogeneity of oxygen distribution, more than would be expected by the effects of temperature on the solubility alone.

However, the utilisation of coupled biogeochemical models remains computationally expensive and difficult to implement at high spatial resolution over extended periods, such as a decade. The previous studies (Wakelin et al., 2020; Galli et al., 2024) used a horizontal resolution of $1/15^\circ$ latitude by $1/9^\circ$ longitude (~ 7 km) on the north-western European shelf. While
 80 this resolution permits the simulation of regional evolution, it is insufficient for resolving the fine-scale coastal dynamics. In order to resolve these dynamics, a kilometre horizontal resolution is more appropriate. The high horizontal resolution and the necessity to simulate tides, which play a major role in such coastal regions, result in significant current velocities for small grid cells. In order to maintain the stability of the hydrodynamic model, it is necessary to employ a short time step, thereby significantly increasing the computational resources required to simulate long time periods. Another approach, less resource-
 85 intensive, consists of coupling a 3D hydrodynamic model with a simplified oxygen model. This method has been employed successfully in different locations, including the Chesapeake Bay (Scully, 2010), the Gulf of Mexico (Yu et al., 2015; Fennel et al., 2016) and the Baltic Sea (Jonasson et al., 2012; Lehmann et al., 2014), enabling the reproduction of most of the oxygen variability in these regions, sometimes as well as much more complex, nutrient-dependent biogeochemical models (Irby et al., 2016). This type of model facilitates the study of the impact of the physical dynamics on oxygen concentration, processes
 90 of fundamental importance that cannot be managed through watershed policies, in contrast to nutrients and other substances associated with human activities.



In the present study, a ten-year realistic simulation on the shelf of the Bay of Biscay and the English Channel has been realised using a three-dimensional circulation model with a simplified oxygen model. Through the analysis of this simulation, the objective is to study the impact of hydrodynamics on oxygen concentration in these contrasting environments and to identify the areas prone to experience low oxygen concentrations. The proportion of the variability in oxygen that is attributable to the hydrodynamics of this coastal environment is determined. The variability and evolution in dissolved oxygen concentrations in the bottom water column are then studied across the entire study area. A focus is finally made on the interannual variability of oxygen minima within sensitive Regions Of Freshwater Influence.

2 Methods

2.1 Model simulation

The numerical experiment in this study was conducted using the Coastal and Regional Ocean COmmunity model (CROCO; Auclair et al. (2024)). The simulation uses the GAMAR hydrodynamic configuration, developed by Martinez Almoyna et al. (2025), which has been set up for the Bay of Biscay and the English Channel. The configuration employs a one-kilometre horizontal resolution grid with 40 vertical terrain-following levels. The geographical domain extends from the Spanish coast in the south at 43°17'N latitude, to the north at 50°52'N, with a western boundary at 8°W longitude and an eastern limit at 1°40'E (Fig. 1).

To study the oxygen evolution and its link to the dynamical forcings, we conducted a simulation called GAMAR-OXY using a simplified oxygen model. At the surface, we use the formula from Riley and Stefan (1988) to simulate the reoxygenation. The expression of pelagic respiration as a function of temperature and oxygen concentration was inspired by Hansen and Bendtsen (2013) :

$$P_r = f(T)R_1\left(\frac{O_2}{O_2 + k_1}\right) \quad (1)$$

where O_2 is the oxygen concentration, $k_1 = 0.16 \text{ mg.L}^{-1}$ is the low half-saturation constant, R_1 is a constant for respiration and the function f describes the temperature dependence:

$$f(T) = Q_{10}^{\frac{T - T_{ref}}{10}} \quad (2)$$

with $Q_{10} = 3$, T is the sea temperature and T_{ref} is a reference temperature.

As in Lehmann et al. (2014), R_1 is calculated based on a spatial value of net primary production. Here we use the 2014-2023 mean of net primary production from the Atlantic IBI Ocean BioGeoChemistry Hindcast (doi:10.48670/moi-00028) from the Copernicus Marine Center Service (CMEMS, <https://marine.copernicus.eu>). The net primary production expressed in carbon is interpolated at each grid cell (Fig. 1, right). We keep the ratio 1.1 between oxygen and carbon. Based on the measurements and recomposition of Marquis et al. (2007, 2011), we use a 50% rate of primary production remineralised in the water column for a reference temperature $T_{ref} = 11^\circ\text{C}$. The respiration rate is applied to the upper 200m of the water column. The simulated

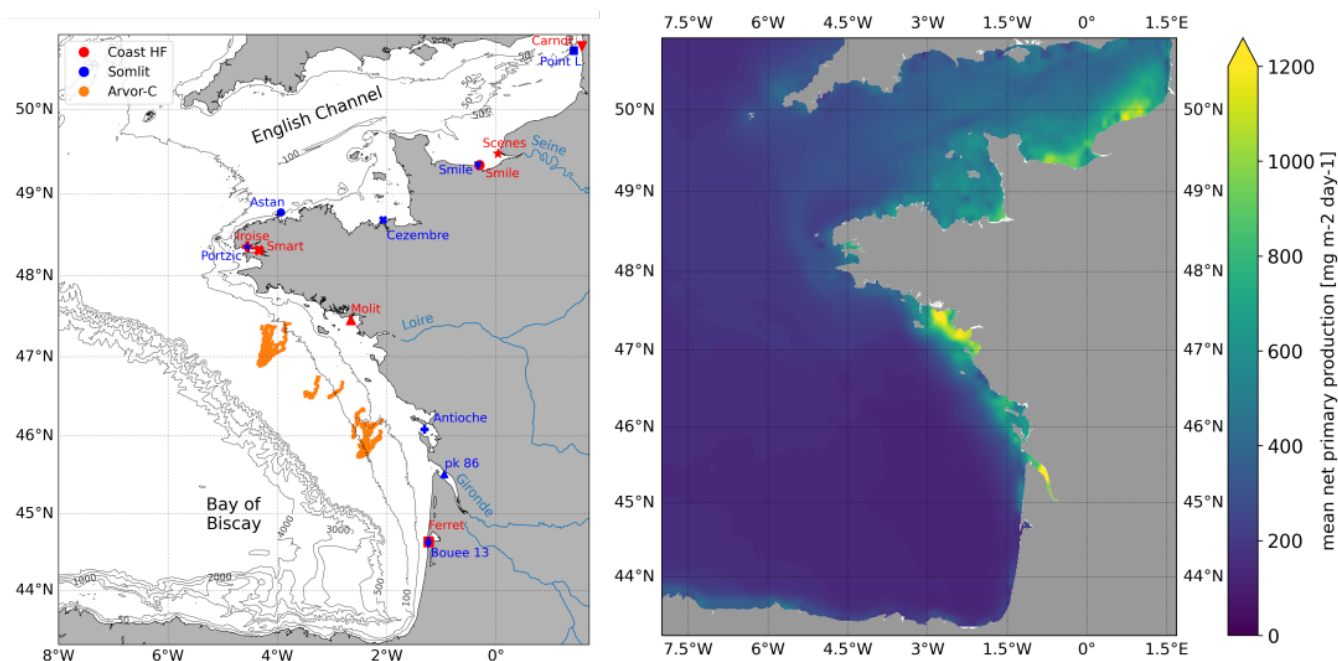


Figure 1. Left: Map of in-situ observation stations (COAST-HF and Somlit networks) and profiles (Arvor-C). Right: Interpolated map of mean net primary production integrated on the water column from the IBI reanalysis.

period runs from January 2014 to December 2023 with 30 seconds time step and instantaneous fields saved every hour.

- 125 The initial condition is extracted from the GAMAR simulation (Martinez Almoyna et al., 2025), with oxygen concentrations
 extracted from the Global Biogeochemistry Hindcast (GLOBH) (doi:10.48670/moi-00019) from the CMEMS. The hourly
 atmospheric forcings (air temperature, relative humidity, 10 m wind, and radiative fluxes) are from the ERA5 reanalysis (Hers-
 bach et al., 2020) and the open boundary conditions at the western and the northern boundaries are defined from prescribed
 fields extracted from the Global Ocean Physics Reanalysis GLORYS12V1 (doi:10.48670/moi-00019, Lellouche et al. (2021))
 130 for the dynamical forcings and from the GLOBH hindcast for the oxygen concentrations. , both products are available at the
 Copernicus Marine Center Service (CMEMS) (https://marine.copernicus.eu). The tidal sea surface elevation and currents with
 15 harmonic constituents are imposed along the boundaries using the FES2014 ocean tide atlas (Lyard et al., 2021). The daily
 river runoffs used for the 23 rivers within the configuration are the same as those used in the GAMAR simulation (Martinez Al-
 moyna et al., 2025) and are estimated based on observations at gauging stations. The oxygen concentration in river runoffs is
 135 set at the oxygen saturation concentration.



2.2 Observations for model assessment

2.2.1 Temperature and salinity data

To assess the model both spatially and temporally, comparisons have been performed using long fixed time series and spread vertical profiles.

140 Due to its small-scale dynamics, the coastal environment is subject to significant local variations at high frequencies. To assess the capabilities of the model to reproduce such variations, model simulation are compared with observed time series from the buoys of the COAST-HF network (Farcy et al., 2019; Cocquempot et al., 2019; Simon et al., 2023) in temperature and salinity. The COAST-HF (<http://www.coast-hf.fr>) network provides long-term in situ observation of physical and biogeochemical parameters measured from sensors on buoys. The temperature and salinity are measured at 20-minute intervals. We used the temperature observations from 7 COAST-HF stations for comparison with model simulation: Carnot (145 <https://doi.org/10.17882/39754>), Scenes (<https://doi.org/10.17882/99434>) and Smile (<https://doi.org/10.17882/53689>) stations in the eastern English Channel, Iroise (<https://doi.org/10.17882/74004>) and Smart (<https://doi.org/10.17882/86020>) in the Bay of Brest, Molit (<https://doi.org/10.17882/46529>) in the Bay of Vilaine, and Ferret (150 <https://doi.org/10.17882/100119>) in the Arcachon Bay entrance (Fig. 1). Due to gaps in observations, only 4 stations (Scenes, Smile, Iroise and Molit stations) have been considered for the salinity comparison.

The vertical structure of the water column simulated is validated based on *in situ* vertical profiles measured by Arvor-C profiler deployed on the shelf of the Bay of Biscay during ASPEX cruises (Marié, 2009). Starting in 2009, the Arvor-C profilers have been deployed regularly on the continental shelf in the Bay of Biscay (Fig. 1). ARVOR-C profiling floats are 155 similar to ARGO floats with modifications of the data collection cycle, measuring a vertical profile every day (Andre et al., 2010, 2016; Ker et al., 2016) and of the design to allow bottom landing between profiling cycles. These deployments provide a large dataset of *in situ* vertical profiles of temperature and salinity covering a large part of the studied period.

2.2.2 Oxygen observations

To investigate the ability of the oxygen model to reproduce variations in dissolved oxygen, a comparison was made between 160 the model output values and measurements taken as part of two monitoring networks: the Somlit and Coast-HF networks. Oxygen time series have been extracted from the Somlit database (Liénart et al., 2017, 2018; Cocquempot et al., 2019; Savoye et al., 2026). Somlit stations are measured fortnightly and sampled at high tide, with oxygen concentration being measured using the Winkler method. We used the oxygen data from eight stations : Point L and Smile stations in the western English Channel, Cezembre and Astan in western English Channel, Portzic station in the Bay of Brest, Antioche station in the Pertuis 165 Sea, pk 86 station in the Gironde estuary and Bouee 13 station in the Arcachon Bay entrance (Fig. 1). The measurement of oxygen concentration is conducted at the surface level at all stations, and additionally at the bottom at Point L, Astan and PK 86 stations.



To assess more high-frequency variability, we also include the oxygen measurements from the Coast-HF network. Coast-HF measurements are obtained by autonomous sensors at hourly frequency. The sensors have been deployed at 2 metres depth on the instrumented Smile, Iroise and Molit buoys, and additionally at the bottom (15 m depth) on the Molit buoy.

The measurements from these two networks cover a large part of the French Atlantic coast (Fig. 1), thereby ensuring adequate spatial representation of the coastal areas under study.

2.2.3 ROFIs characterisation

In order to investigate oxygen dynamics within ROFIs, the first step was to identify them in the numerical simulation. According to the definition established by Martinez Almoyna et al. (2025), a ROFI is defined as a contiguous surface with sea surface salinity below 33 psu that is in contact with the estuary mouth. Mean salinity fields were computed for the winter (December, January and February) and summer (July, August and September) periods. The ROFI identified from the summer mean field was classified as the "permanent ROFI", the region under freshwater influence during the whole considered months limited by the small extent during summer. The area covered by the winter ROFI, excluding the permanent ROFI zone, was designated the "seasonal ROFI". The adjacent shelf until 100 m depth was designated as the "shelf" zone for comparison (Fig. 2).

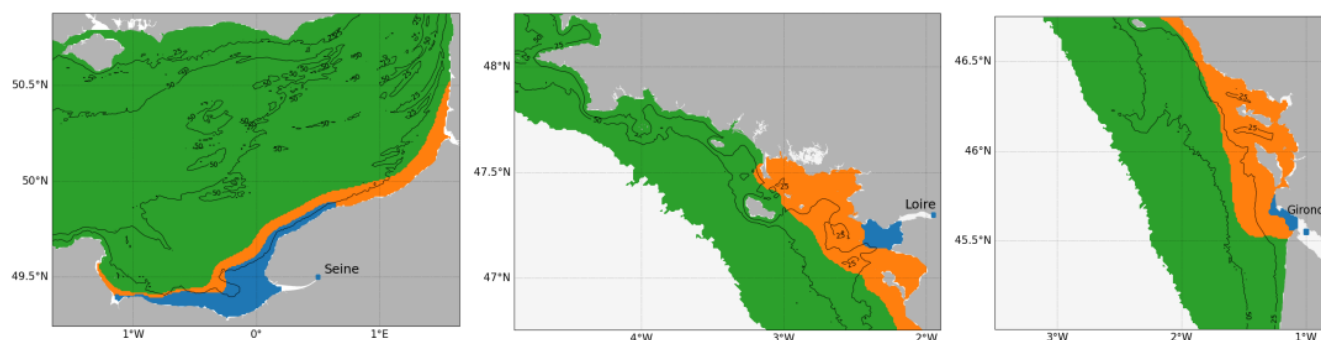


Figure 2. Maps of permanent (blue) and seasonal (orange) ROFIs and the adjacent shelf (green) for, respectively from left to right, the Seine, the Loire and the Gironde ROFIs

For each ROFI and shelf zone, oxygen concentration data were averaged over the summer months. The number of days during which near-bottom oxygen concentrations fell below 6 mg.L^{-1} was quantified. This threshold corresponds to the biological stress threshold used in different studies (Best et al., 2007; Poppeschi et al., 2026), below which fish growth is affected by oxygen deficiency. Additional calculations were performed to analyse the parameters governing oxygen concentrations: the mean near-bottom temperature and stratification (defined as the difference between the bottom and surface water densities).



3 Results

3.1 Temporal evolution of temperature and salinity

A comparison is made between the 10-year simulation GAMAR_OXY and *in situ* temperature and salinity observations. An overview of these features is presented through the application of principal statistical techniques, including correlation, standard deviation, bias, and unbiased Root Mean Square Difference (uRMSD), as illustrated in Taylor and target diagrams (Fig. 3).

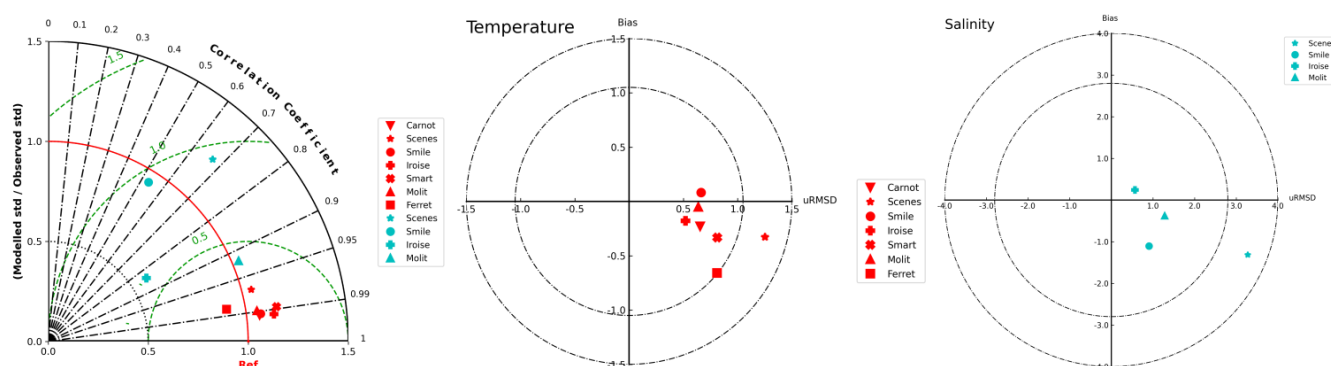


Figure 3. Taylor (left) and target (middle and right) diagrams with statistics for the COAST-HF stations considered for comparisons in temperature (red) and salinity (blue). All *in situ* data available for the considered decades are considered in statistics computation.

Seven stations are considered for the temperature evaluation. The correlation between observed and modelled temperature remains higher than 0.9 with a ratio of modelled and observed standard deviation close to 1 (Fig. 3, left). On average, the model displays a cold bias compared with the observations, as it was the case for Martinez Almoyna et al. (2025). However at the COAST-HF stations, the biases do not exceed 0.5 °C with a uRMSD below 1.5 °C, except for Ferret station which present a bias of 0.7°C. The correlation coefficient for all stations ranges from 0.95 to 0.99, and the ratio between simulated temperature and observed temperatures is close to 1.

For the salinity, four stations are considered for the analysis. The measured correlations range from 0.5 to 0.95. With regard to biases, these remain confined below 1.5 psu. However, the uRMSD can exceed 3 psu, as evidenced by the Scenes station located in proximity to the Seine river mouth. The correlation coefficients range from 0.53 (Smile station) to 0.92 (Molit station). The ratio between the simulated and observed salinity values is found to be close to 1 for the Smile and Molit stations, marginally higher for the Scenes station, and close to 0.5 for the Iroise station. This finding indicates that the simulated salinity values at the Iroise station location exhibit a less pronounced distribution compared to the observed data.

To assess the vertical structure of the simulated water column, simulated temperature and salinity data are compared with *in situ* vertical profiles measured by Arvor-C profilers. Figure 4 illustrates distributions of biases between observed and modelled vertical profiles. Within the top 20 metres of the water column, the model exhibits a cold bias, with temperature differences ranging from -2 to 0.5 °C. Those between 20 and 50 metres are, for the most part, within the same range as at the surface, but



a quarter of them show a significant positive bias of up to 2.5 °C. These significant deviations can be attributed to the position of the thermocline in the simulation, which is consistently deeper than in the observations. In the bottom water column, the simulation displays a warm bias, with deviations ranging from 0 to 1.5 °C. Across the three groups of years studied, no change in the biases over time is observed, with a model remaining cooler at the surface and warmer at the bottom, with most of the bias between -1.5°C and 1.5°C.

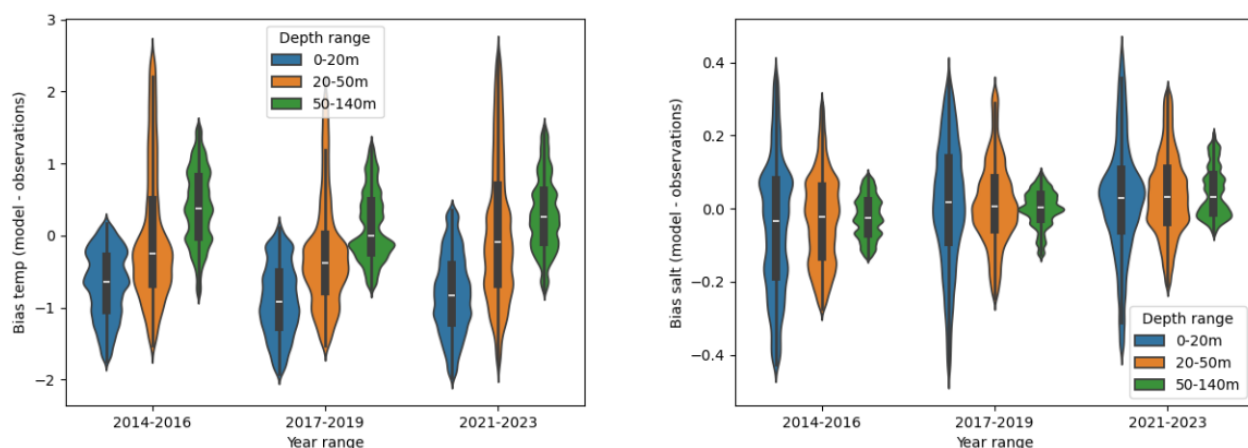


Figure 4. Violin diagram representing the observed biases between the modelled and observed Arvor-C vertical profiles for temperature (left) and salinity (right). The data are separated in three time range: 2014-2016, 2017-2019 and 2021-2023 (no deployments during 2020), with consideration given to three depth ranges: 0-20m (blue), 20-50m (orange), 50-140m (green). The grey rectangle represents the distribution of biases between the first and third quartiles. The white segment represents the median value. Only the computed biases between 5th and 95th percentiles are displayed.

The majority of salinity biases fall between -0.4 and 0.4 psu, with the median bias approaching zero for all depths (Fig. 4, right). The widest distribution of bias is at the surface, whilst the biases between 50 and 100 m range from -0.2 to 0.2 psu.

215 3.2 Temporal variability of dissolved oxygen concentrations

For each measurement of dissolved oxygen concentration, a comparison is made with the closest point in the simulation, both spatially and temporally. Taylor and target diagrams illustrate the comparisons, synthesising correlation, standard deviation, bias, and unbiased Root Mean Square Difference (uRMSD) on figure 5.

The biases range from -1 to 0.25 $mg.L^{-1}$ of oxygen concentration. For the majority of comparisons, the bias is negative, indicating that, on average, the simulated oxygen concentration is higher than the observed concentrations. However, the biases for the measurement points at the bottom – with the exception of point pk86 – show an average bias close to 0. For most measurements, the uRMSD is lower than 1, with the exception of the Somlit pk 86 station and the Somlit and Molit (surface) COAST-HF stations. The higher bias and uRMSD values obtained for the COAST-HF stations are likely due to the model's

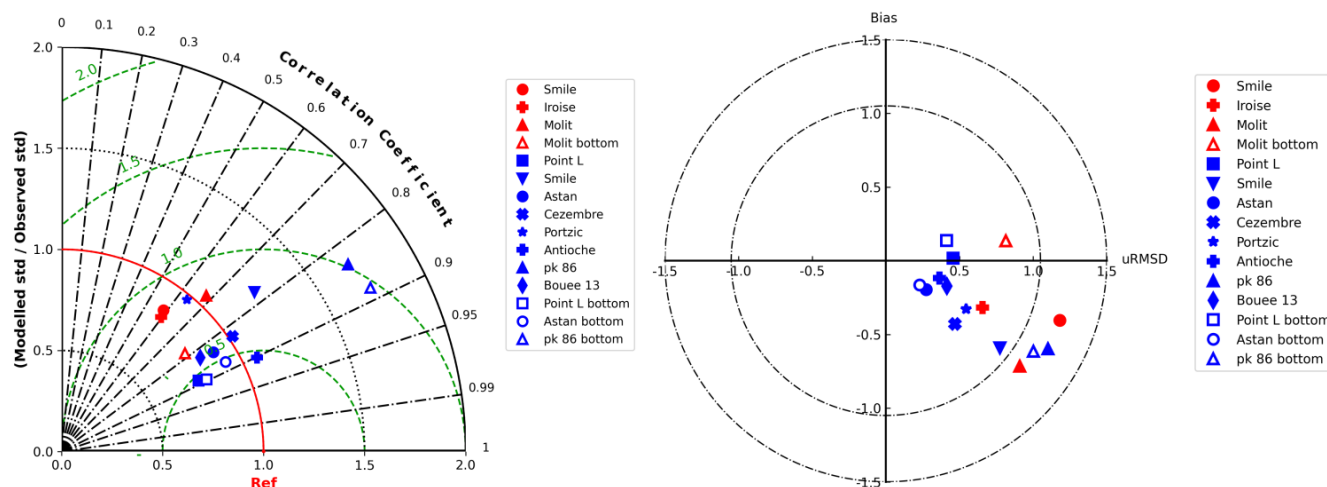


Figure 5. Taylor (left) and target (right) diagrams with statistics for the three COAST-HF stations (red) and the eight Somlit stations (blue) considered for comparisons in oxygen. The surface measurement points are denoted by solid markers, whilst those located at the bottom are indicated by contour markers. All in situ data available for the considered decades are considered in statistics computation.

difficulty to reproduce the observed high-frequency variations. With regard to the pk86 station, it also exhibits a modelled-to-observed standard deviation ratio greater than 1.5 (Fig. 5 left). The comparison with this station, located in the Gironde estuary (see Fig. 1), shows that the model fails to accurately reproduce oxygen variations within this highly turbid estuary. The other measurements present modelled-to-observed standard deviation ratio close to 1. The correlation coefficients of all measurements range from 0.6 to 0.9. The three Coast-HF surface measurement stations have a correlation coefficient of less than 0.7. All the measurements taken at bottom show a correlation coefficient ranging from 0.78 to 0.9 and the majority of Somlit stations exhibit a coefficient value greater than 0.8. Apart from the Gironde estuary, there do not appear to be any major geographical variations in the distribution of errors.

In order to further explore the model's ability to simulate dissolved oxygen over the simulated period, a more complete analysis is conducted by comparing the model with data measured at the bottom (15 metres depth) by the COAST-HF Molit station (Fig. 6).

At this monitoring station, the R^2 between the simulated and measured values is 0.61. The model appears to reproduce the seasonal cycle. Over the ten-year simulation period, the average bias remains below 1 mg.L^{-1} (Fig. 6, bottom left). However, the bias climatology shows that the model presents an excess of oxygen from mid-May to July, ranging from 0.5 to 1 mg.L^{-1} . Conversely, between August and November, the simulated oxygen concentration is, on average, lower than the observed value, with bias values ranging from -0.25 to -0.5 mg.L^{-1} . The simulation reproduces interannual variability, particularly the duration of seasonal periods of lower oxygenation and there is no significant trend in the bias over the simulated period. However, the model fails to reproduce extreme values. Episodes of high oxygenation in winter and episodes of low

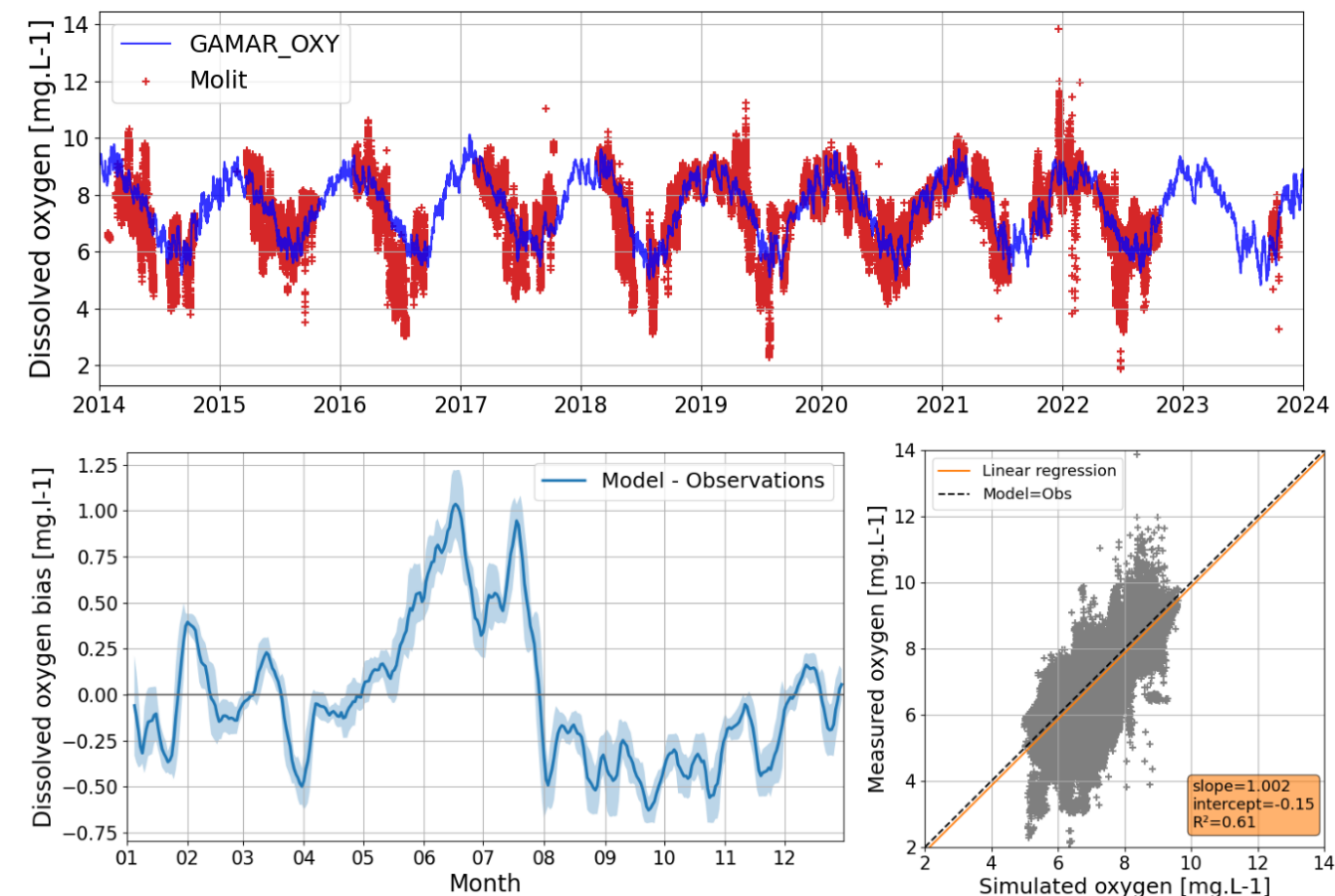


Figure 6. Bottom dissolved oxygen concentrations at Molit station. Top : Time series of simulated (blue line) and measured (red scatter plot) dissolved oxygen concentrations. Bottom left : Bias climatology between simulated and measured dissolved oxygen concentrations. Bottom right : Scatter plot of measured (y-axis) versus simulated (x-axis) oxygen values. Solid orange line is the linear regression, the dashed line is the line with slope 1 and intercept 0.

oxygenation in summer are not reproduced by the model. This is confirmed by the scatter plot in Figure 6. Whilst the measured oxygen values range from 2 to 12 $mg.L^{-1}$, the simulated oxygen values remain confined between 5 $mg.L^{-1}$ and 9.5 $mg.L^{-1}$.

245 3.3 Spatial variability of bottom oxygen concentration minima and temporal evolution

In order to illustrate the spatial distribution of oxygen concentration minima, the minimum values at each point were calculated for the entire simulation in the deepest level and plotted in Figure 7.

The minimum oxygen concentrations across the shelf range from 3 to 8 $mg.L^{-1}$. The lowest values are found along the coast, where four regions stand out for their particularly low minimum values, ranging from 3 to 5 $mg.L^{-1}$. The two areas

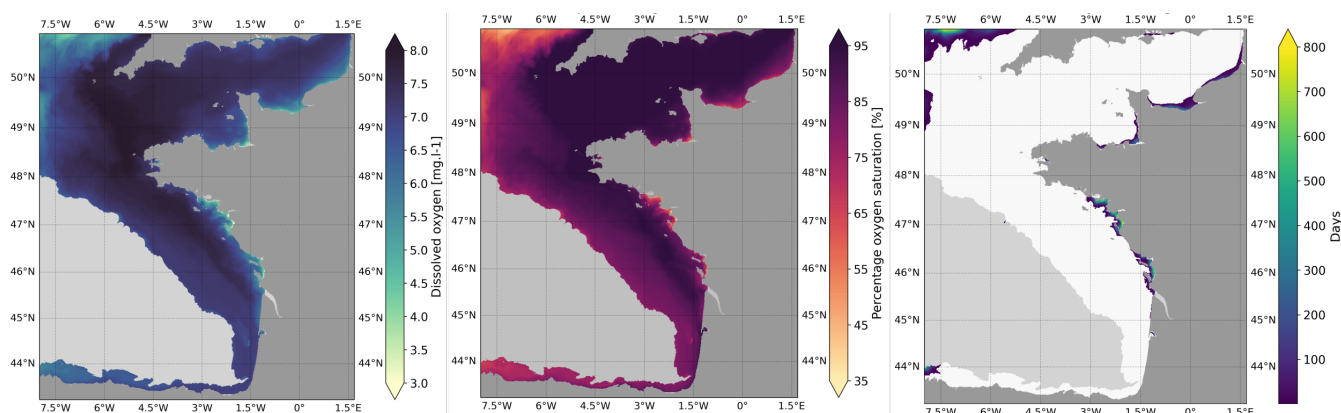


Figure 7. Left: Map of minimum near-bottom oxygen concentration over the 10-year simulation period. Middle: Map of minimum oxygen percentage saturation near the bottom over the 10-year simulation period. Right: Number of days below the 6 mg.L^{-1} oxygen concentration threshold at each grid cell over 10 years.

where oxygen concentration levels locally reach 3 mg.L^{-1} are situated on the coast of the Bay of Biscay. The regions in question are as follows: Loire ROFI comprises the area near the estuary, as well as the two bays to the south and north of it (Bourgneuf Bay and Vilaine Bay); Gironde ROFI comprises the area located at the north of the estuary, which exhibits the lowest oxygen concentrations in the Pertuis sea. These coastal regions also experiment the highest number of days with an average daily oxygen concentration below 6 mg.L^{-1} , with a range of between 500 and 800 days falling below the threshold over the 10-year simulation period (Fig. 7 b).

The remaining two areas exhibiting low oxygen concentrations are located in the English Channel, with values ranging from 3.5 to 5 mg.L^{-1} . The regions concerned are as follows: Seine ROFI comprises the area extending from the Bay of Seine and along the coast at the north-east of the estuary; the Bay of Mont Saint-Michel is situated in the western part of the English Channel. These two areas also experiment between 100 and 200 days with an average daily oxygen concentration below 6 mg.L^{-1} . These coastal areas also experience minimum oxygen levels, as a percentage of the saturation value, ranging from 35% to 75%.

Furthermore, areas in proximity to the boundary of the simulated domain exhibit lower minimum oxygen concentrations in comparison to the remaining shelf. Across extensive regions adjacent to the western and northern boundaries of the study area, the minimum oxygen concentration ranges from 4 to 5.5 mg.L^{-1} . However, this is not the case for the boundary to the north of the English Channel. To a lesser extent, the simulated minimum oxygen concentration is also lower near the continental slope, with values of around 6.5 mg.L^{-1} . Conversely, the remaining continental shelf exhibits minimum oxygen concentrations ranging from 7 to 8 mg.L^{-1} , with the oxygen percentage relative to the saturation level consistently surpassing 90%.

The oxygen concentration in the regions adjacent to the north-west border and along the edge of the shelf seems to be substantially impacted by the boundary forcing. This issue will be discussed in more detail in Section 4. In the following sec-



tions, the analysis will focus on the Bay of Biscay, from the coast to the centre of the continental shelf, and the English Channel.

In order to investigate long-term changes across the shelf, linear trends in near-bottom oxygen concentration are calculated for each grid cell in the model. Subsequently, these trends are compared with those of the bottom temperature. Finally, the trend in dissolved oxygen related to the dissolution rate — and thus to variations in temperature and salinity — is calculated and subtracted from the oxygen trend (Fig. 8).

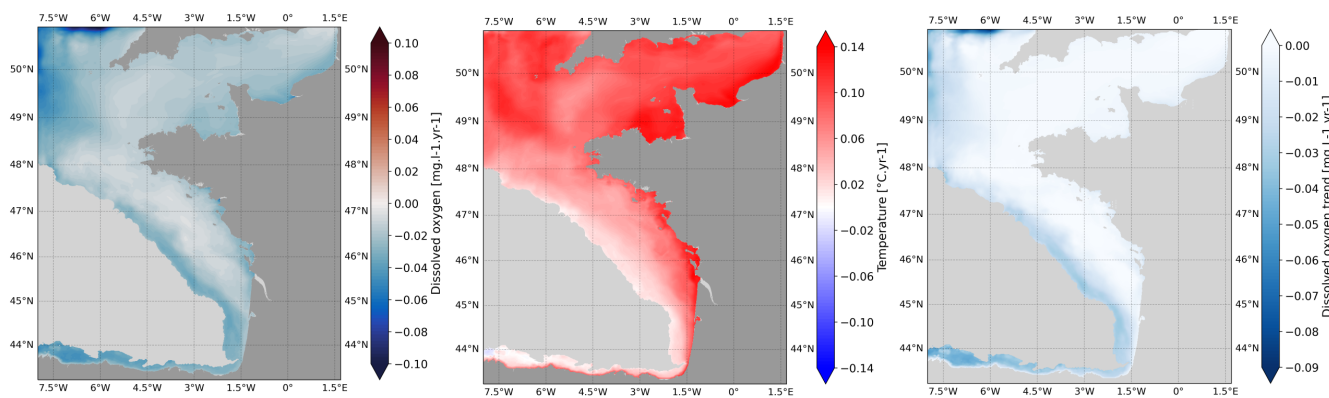


Figure 8. Map showing the linear trends in near-bottom oxygen concentrations (left panel) and temperature (central panel) over the 10-year simulation period. Differences between the oxygen concentration trend and the trend equivalent to that attributable solely to the dissolution rate (right panel).

The initial observation is that the oxygen concentration exhibits a decline across the entire shelf. In the English Channel, a clear decreasing trend is also observed, particularly along the French coast, with values ranging between -0.02 and $-0.04 \text{ mg.L}^{-1}.\text{yr}^{-1}$. A similar decline is present along the coast of the Bay of Biscay, with trends between -0.02 and $-0.03 \text{ mg.L}^{-1}.\text{yr}^{-1}$. Conversely, the central part of the shelf exhibits only a minor decrease, with trends below $-0.01 \text{ mg.L}^{-1}.\text{yr}^{-1}$.

Concerning the temperature, an upward trend in near-bottom temperature is evident across the shelf. This trend is particularly pronounced in the English Channel, especially along the coast, where it can reach up to $+0.14^\circ\text{C}$ per year. A comparable increase is evident along the coasts of the Bay of Biscay. In the Celtic Sea, the trend varies spatially between $+0.05$ and $+0.12^\circ\text{C}$ per year. However, in the central part of the shelf of the Bay of Biscay and near its edge, the trend is less marked, with values below $+0.03^\circ\text{C}$ per year. No trends in the bottom salinity were observed, with the exception of a slight increase near the estuaries (not shown here).

The remaining trend after subtraction the dissolution rate evolution is negligible outside the boundary and the edge of the continental slope. In the English Channel and the Bay of Biscay away from the continental slope, the difference is at most -0.01 mg.L^{-1} per year in the Gironde and Loire ROFIs.



290 3.4 Interannual variability inside ROFIs

The analysis of dissolved oxygen concentration time series across the Regions of Freshwater Influence (ROFIs) and the adjacent continental shelf reveals distinct seasonal and interannual patterns (Fig. 9).

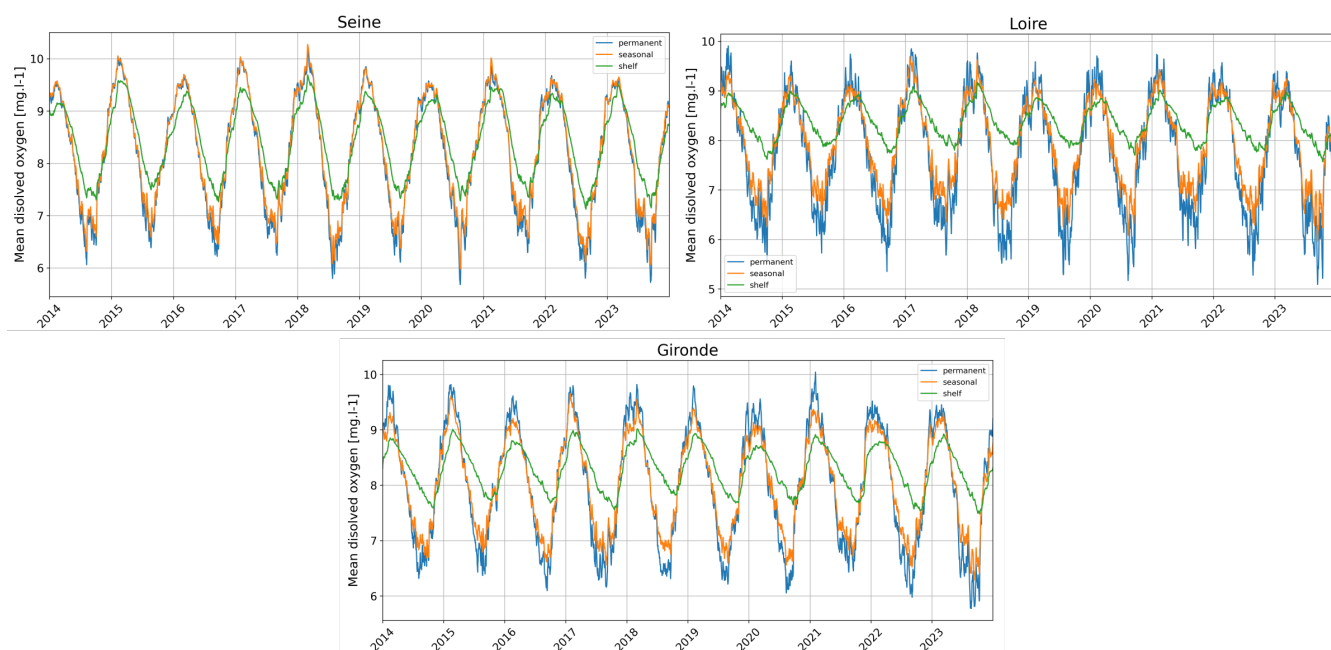


Figure 9. Time series of near-bottom dissolved oxygen concentration spatial mean in the three different ROFI and shelf areas for respectively the Seine, the Loire and the Gironde ROFIs. Each color corresponds to a region defined in figure 2 - blue for permanent ROFI region, orange for seasonal ROFI region, and green for shelf region outside ROFI.

The seasonal cycles are more pronounced in the ROFIs zone (seasonal and permanent) than in the adjacent shelf, with higher oxygen concentrations in winter and significantly lower values in summer. This seasonal contrast is less marked in the Seine ROFI, where summer differences between the shelf and ROFIs generally remain below 1 mg.L^{-1} , and the seasonal cycles of the permanent and seasonal ROFIs follow a similar evolution as over the shelf. In contrast, the Loire and Gironde ROFIs exhibit substantially lower summer oxygen concentrations in their ROFI zones compared to the shelf, with differences exceeding 1.5 mg.L^{-1} . For the three ROFIs, both seasonal and permanent ROFIs display similar variations, though oxygen concentrations are slightly lower in the permanent ROFI.

300 Focusing on the permanent ROFI zones, dissolved oxygen concentrations exhibits notable interannual variability, particularly in the minimum summer values. In contrast to the Seine and Gironde ROFIs, the permanent Loire ROFI exhibits annual periods during which the average dissolved oxygen concentration is below 6 mg.L^{-1} . In the Gironde, these episodes occurred only in 2022 and 2023, while in the Seine, they occurred in 2018, 2020, 2022, and 2023. For the Gironde ROFI, summer 2023 was particularly notable for its significant oxygen depletion compared to other summers. Conversely, the years with the highest



305 summer oxygen concentrations across all three ROFIs were 2015 and 2018, with 2017 also being a notable year for the Loire ROFI.

Bottom oxygen concentration dynamics with environmental conditions (bottom temperature and stratification) analysis for the Loire ROFI (Fig. 10) reveals that years with low mean oxygen concentration values and large number of days below 6 $mg.L^{-1}$ primarily correspond to warmer years. Summers with mean temperatures exceeding $19^{\circ}C$ are consistently associated
 310 with concentrations below $6.3 mg.L^{-1}$. Stratification also appears to play a supplementary role. For instance, summer 2018 was less warm than 2019, yet more stratified, and exhibited lower oxygen levels. Nevertheless, stratification alone seems to have little effect on oxygen variability, as evidenced by 2014 and 2021, when the stratification was stronger than in other years and the oxygen levels were not particularly low. The temperature effect is similar in the other two ROFIs, though stratification is less pronounced and its effects are less noticeable (see Appendix A, Figs. A1 and A2).

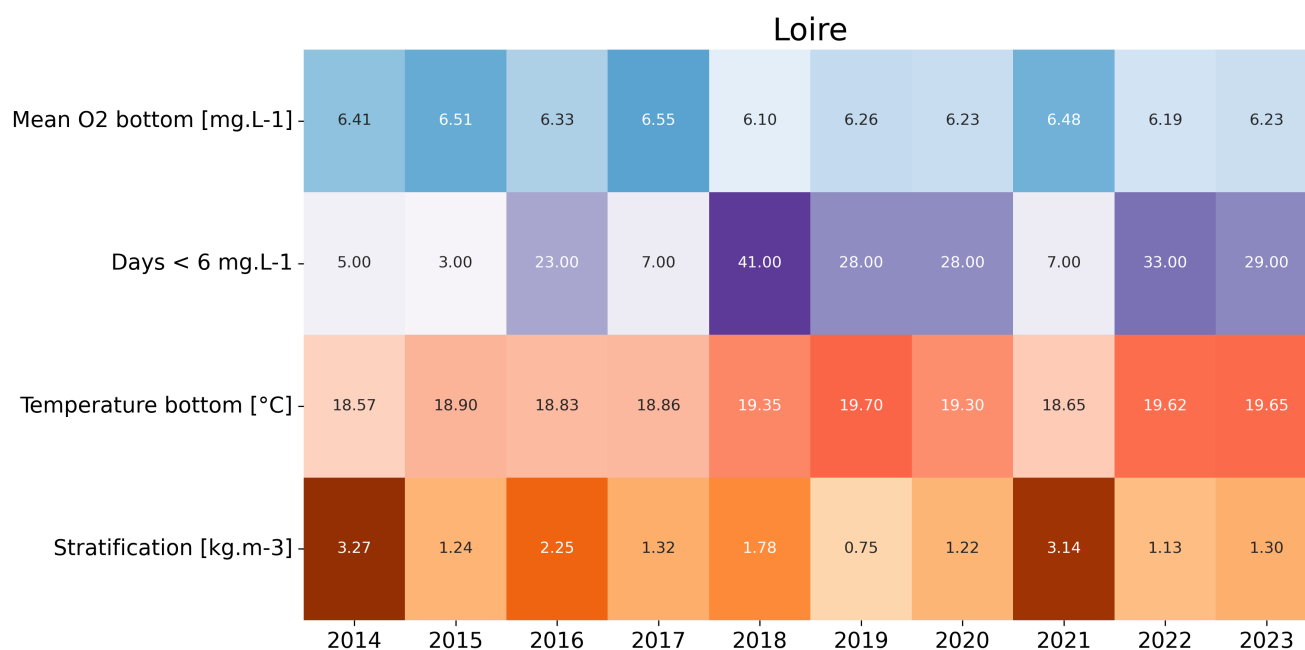


Figure 10. Heatmap representing the mean near-bottom oxygen concentration, the number of days with an oxygen concentration below 6 $mg.L^{-1}$, the mean near-bottom temperature, and the mean stratification for the 10 summers of the simulated period in the permanent Loire ROFI.

315 A multiple linear regression analysis of summer monthly near-bottom oxygen concentration, bottom temperature, and stratification confirmed that temperature is the dominant factor influencing oxygen variability. Its contribution alone accounts for 59% of the variance in the Loire and Gironde ROFIs and up to 78% in the Seine ROFI. Stratification alone has no significant contribution, except in the Gironde ROFI, where it explains 5% of the oxygen variance. However, the combined effect of



temperature and stratification contributes to 5% (Gironde), 7% (Seine), and 10% (Loire) of the bottom oxygen concentration variability.

4 Discussion

The employment of a simplified oxygen model as opposed to a coupled biogeochemical model facilitates the investigation of the evolution of oxygen concentration across a region of contrasted characteristics at a high spatial resolution. This model has been shown to require a lower computational cost (estimated to be four times less resource-intensive) and thus allows the simulation of the oxygen evolution over a decade. The model simulates the oxygen variations resulting from its physical dynamics, namely changes in the dissolution rate, stratification, mixing and advection. In order to study the impact of these processes, it is necessary to have a dynamic model that is as realistic as possible.

The GAMAR hydrodynamic configuration, which has already been validated by Martinez Almoyna et al. (2025), has undergone several modifications for improvements, including the inclusion of additional tidal components. A comparison has been made between the temperature and salinity of the new simulation and in-situ data.

Overall, the discrepancies between the simulation and the observations remain small. The comparison with the Coast-HF measurements shows that the model still accurately reproduces the observed temperature and salinity values and variability, compared to the GAMAR simulation. However, as previously discussed in Martinez Almoyna et al. (2025), there are few limitations to the model's capacity to replicate the variability observed at specific locations. Even with the modifications, the analysis of the vertical structure indicates that the model still does not accurately replicate the stratification observed on the shelf. Indeed, the observed surface cold bias and bottom warm bias and the simulated thermocline, which is deeper than the observed one, suggest that the model mixes the water column more than does the actual system, particularly at the shelf break. These comparisons provide confidence that the physical processes have been accurately modelled at the scale of the shelf. It is therefore possible to investigate the part of oxygen variability influenced by these processes.

The results of the oxygen comparison show that, on average, the simplified oxygen model successfully explains between 60% and 80% of the variance observed at seasonal timescale. This finding supports the hypothesis that physical processes account for a significant proportion of the variability in oxygen levels in the coastal environment. Analogous conclusions have been reached by other studies that have employed a simplified oxygen model. Comparisons between the simplified OXYCON model and observations in the North Sea–Baltic transition zone have led to the conclusion that physical processes play an important role in controlling the spatiotemporal variation of dissolved oxygen (Jonasson et al., 2012; Hansen and Bendtsen, 2013). This conclusion has also been made regarding the hypoxia on the Louisiana shelf in the northern Gulf of Mexico. However, model sensitivity experiments show that hypoxia generation is driven by oxygen utilization in the sediment (Yu et al., 2015). In our study, the processes occurring within the sedimentary compartment are not modeled, nor is their contribution to oxygen consumption simulated. In view of the results obtained across the shelf, it can be deduced that respiration within the sediment



accounts for a limited proportion of total consumption at the scale of the study area. At the local scale, the Gironde estuary demonstrates a larger bias and uRMSD, as well as a higher ratio between modelled and observed standard deviation. This indicates that the model fails to accurately reproduce oxygen variations within this turbid estuary, where oxygen consumption
 355 due to sediment is likely to be more significant. In order to confirm this result, a parametrisation of benthic respiration would be a way to improve the model.

The simplified model employed is subject to a number of limitations due to its definition. It is evident that the model can not reproduce the biogeochemical variations in oxygen concentrations that are associated with photosynthesis and phytoplankton growth. This includes diurnal variations caused by fluctuations in photosynthesis throughout the day, as well as episodes of
 360 rapid phytoplankton blooms leading to supersaturation at the surface and, subsequently, significant oxygen consumption in the water column. This is illustrated by the lower correlation coefficient of the Coast-HF surface stations, which are sampled hourly, whereas the Somlit stations are sampled only every two weeks. Similar observations have been made regarding the inability of simplified oxygen models to capture short-term feedback mechanisms between organic carbon sources and respiration rates or to represent the observed supersaturated oxygen concentrations at the surface, due to the lack of biological oxygen production
 365 (Hansen and Bendtsen, 2013; Yu et al., 2015).

Furthermore, the amount of organic matter used to parametrise the model is averaged over the year (Fig. 1, right). Seasonal variations in primary production are neither simulated nor forced. Although the model reproduces a part of the seasonal cycle by simulating the impact of temperature on bacterial activity, it nevertheless exhibits a positive bias in early summer and a negative bias in late summer and autumn. In the model, the absence of an increase in the amount of organic matter at the
 370 beginning of summer leads to lower oxygen consumption. Conversely, the amount of organic matter does not decrease at the end of summer, resulting in higher respiration rates in the model during autumn. One possible way to improve the model would be to force the oxygen model using monthly climatological data on primary production rather than an annual average.

The model correctly reproduces the seasonal cycle and interannual variations in near-bottom oxygen concentrations. However, it fails to reproduce extreme values and episodes of high and low oxygen concentrations due to the variance part that
 375 is not reproduced. Nevertheless, it provides an initial indication, at the scale of a shelf, of areas with low oxygen levels. It is evident that, despite the model's inability to replicate the severity of observed low oxygen levels in reality, it is anticipated that the simulated regions exhibiting the lowest oxygen concentrations are likely to undergo even more pronounced declines in reality.

380 As it can be observed on the oxygen minimum maps (Fig. 7), two regions with low oxygen levels stand out: the domain boundary, particularly in the north-west of the shelf, and the coastal areas.

The low oxygen signal at the boundary, characterised by a low percentage relative to saturation and a trend towards decreasing oxygen concentrations that is not primarily linked to rising temperatures, indicates that it originates from GLOBH open boundary forcing. This forcing exhibits significantly lower oxygen concentrations than those simulated by the simplified
 385 model over the shelf. A comparison of the GLOBH data with the climatological data from the World Ocean Atlas (Garcia et al., 2024) reveals a negative oxygen bias between depths of 100 and 1000 m in GLOBH simulation (Fig. A3, Appendix A). The



bias averages between -2 and -2.5 mg.L^{-1} of oxygen concentration near bottom in the north-west of the shelf. Furthermore, in GLOBH, the oxygen concentration in this layer demonstrates a significant trend, reaching up to -0.2 mg.L^{-1} per year in the north-western part of the shelf. Previous studies have already demonstrated that GLOBH lacks the resolution required to fully capture the physical-biogeochemical interactions that regulate oxygen concentrations in the ocean (Calil, 2023). Additionally, the biogeochemical model in GLOBH is coupled with a non-assimilative physical model that does not account for tidal processes, which play a critical role in vertical mixing, particularly on the Celtic Sea shelf.

This comparison elucidates the reduced oxygen levels and declining trends observed on the shelf in the simulation along the north-western boundary and in proximity to the continental slope, the abyssal plain current transporting the low concentrations from the boundary to the edge of the Bay of Biscay shelf (Koutsikopoulos and Cann, 1996). The shelf region adjacent to the northern border of the English Channel remains unaltered due to the predominance of northward circulation in the Dover strait, which transports water towards the North Sea (Prandle et al., 1996).

In coastal regions, the three main ROFIs (the Seine, the Loire and the Gironde) and the western part of the Cotentin Peninsula in the English Channel experience particularly low oxygen levels. These areas primarily correspond to zones of high primary production, attributable to the nutrient inputs from rivers, which in turn leads to increased bacterial respiration. (Figure 1 right). Furthermore, they are shallow areas where the bottom layer is close to the surface. In this more confined volume, the temperature at the bottom may rise during summer, of 4°C in the English Channel and up to 10°C in the coastal areas of the Bay of Biscay compared with the centre of the continental shelf, thereby reducing the rate of oxygen dissolution whilst increasing the rate of respiration.

In the simplified model, the near-bottom oxygen trend may be influenced by several processes, including variations in the dissolution rate, increased respiration due to rising temperatures, or increased stratification. The comparison of the model's trend with the trend resulting from the dissolution rate indicates that the dissolution rate is the primary factor contributing to the decline in oxygen on the shelf. It is acknowledged that changes in the ecosystem and variations in primary production, which have not been simulated in this model, could also exert an influence on changes in oxygen levels. However, the projections carried out by Wakelin et al. (2020) demonstrate that, up to 2040, changes in the dissolution rate are the predominant factor across the north-western European shelf. This simplified model has shown that the English Channel presents relatively homogeneously oxygen decline, whereas the Bay of Biscay exhibits greater spatial heterogeneity, with a less pronounced trend in the center of the shelf and more so near the coast. The English Channel is a region characterised by a distinctive tidal mixing regime, which engenders a homogeneous vertical structure. Within the context of global warming, the bottom water temperature is rising at a faster rate than in the Bay of Biscay, which experiences a stratification during the summer months, particularly in the shallow coastal areas where water volume is more limited. This consequently leads to a relatively greater decrease in the dissolution rate in the English Channel. This discrepancy in oxygen trend, attributable to variations in temperature and salinity, is also visible in the long-term projections conducted by Wakelin et al. (2020).

Nevertheless, the trends observed over this 10-year period are very pronounced, especially when compared to the trend predicted by Wakelin et al. (2020) for these regions, which is around -0.5 mg.L^{-1} for a hundred years. Trends in near-bottom



temperature are particularly strong, exceeding 0.1°C per year in coastal regions. Upon examination of the anomalies in summer mean oxygen levels and near-bottom temperature (Fig. 11), it becomes evident that this trend obscures substantial interannual variability. They are likely to be accentuated by the summers of 2022 and 2023. The analysis of two consecutive summers reveals a marked positive anomaly in temperature and an associated negative anomaly in oxygen concentrations. The summers of 2022 and 2023 were characterised by the occurrence of significant marine heatwaves in the Bay of Biscay and the English Channel (Simon et al., 2023; Berthou et al., 2024), which exacerbated the high temperatures and oxygen decline.

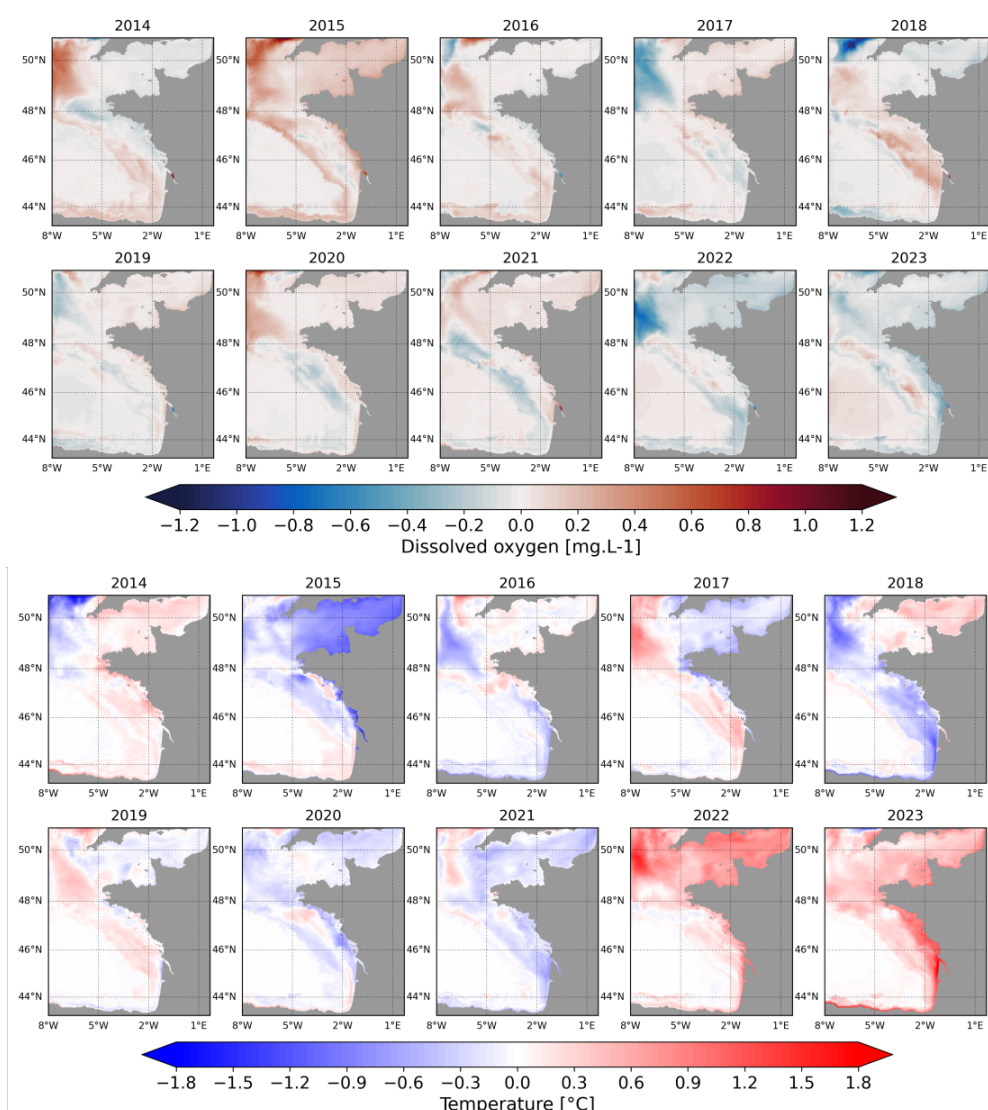


Figure 11. Summer anomalies of near-bottom oxygen concentration (top panel) and temperature (bottom panel)



This interannual variation is reflected in the ROFIs, being evident in years with low oxygen concentrations. The analysis of variance indicates that bottom temperature accounts for the largest proportion of the oxygen concentration variance. Stratification only contributes to the variance in conjunction with temperature. It can be concluded that, whilst stratification may indeed serve to amplify the effect of elevated bottom-water temperatures on the decline in oxygen concentration, it cannot, in isolation, be held accountable for the occurrence of oxygen minima on an interannual timescale.

5 Conclusions

In order to investigate the impact of hydrodynamics on dissolved oxygen concentration in the contrasting environments of the Bay of Biscay and the English Channel, a high-resolution hydrodynamic simulation was developed coupled with a simplified oxygen model. A comparison with observations demonstrated that the simplified model accounts for a significant portion of the observed variance, thus highlighting the dominance of physical processes in driving the variability of dissolved oxygen at the regional scale. The areas exhibiting low oxygen concentrations have been predominantly observed in coastal zones, especially within major ROFIs, where riverine inputs drive high primary production, impacting the parametrisation of the respiration rate. The variation in dissolution rates caused by rising temperature is the fundamental factor driving the trend in bottom oxygen levels. A more pronounced and homogeneous decline in oxygen is observed in the English Channel, whereas in the Bay of Biscay, oxygen decline trends are mainly confined to coastal areas. However, these trends mask substantial interannual variability, particularly associated with summers marked by significant marine heatwaves, particularly during more recent years. Bottom temperature also emerges as the primary driver of most interannual oxygen variability in ROFIs, while stratification appears to play a minor role in interannual variability, acting only in conjunction with temperature effects.

Future research would involve comparing these findings with a comprehensive physical-biogeochemical model, both with and without a sedimentary compartment, to further elucidate the role of each component. Moreover, the simplified model presents a distinct advantage in that it requires lower computational resources compared to full biogeochemical models, while still accounting for a substantial proportion of the observed variance. This computational efficiency renders it particularly suitable for integration into long-term regional climate simulations, thereby enabling high-resolution projections of oxygen level changes. Given the projected increase in the frequency and intensity of marine heatwaves under climate change (Frölicher et al., 2018), it is anticipated that these events will significantly impact dissolved oxygen levels in the coming decades.

Data availability. Data will be made available on request.



455 Appendix A: Supplementary figures

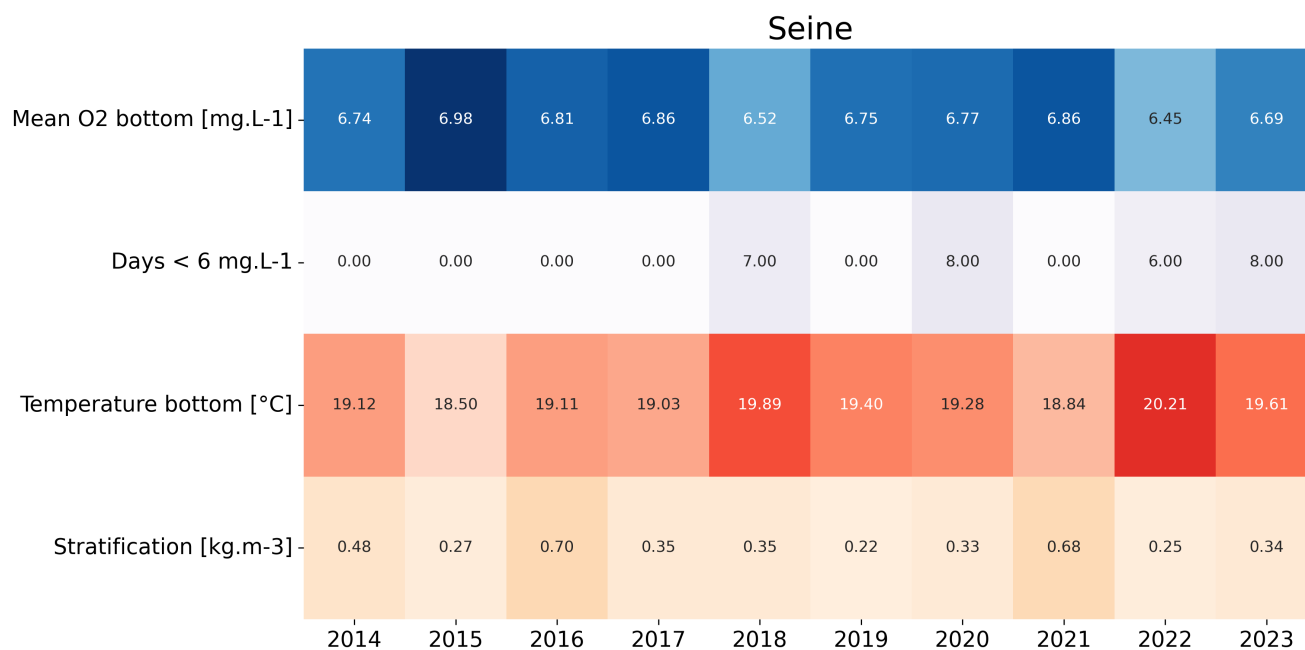


Figure A1. Heatmap representing the mean near-bottom oxygen concentration, the number of days with an oxygen concentration below 6 $mg.L^{-1}$, the mean near-bottom temperature, and the mean stratification for the 10 summers of the simulated period in the permanent Seine ROFI

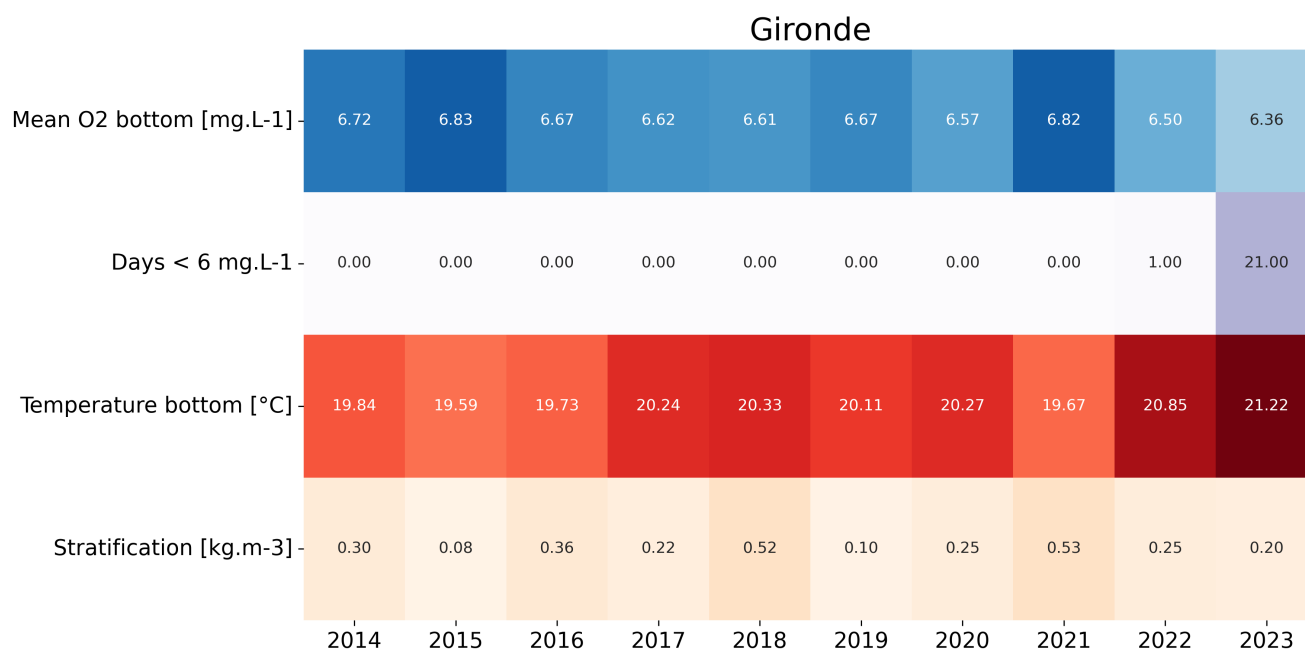


Figure A2. Heatmap representing the mean near-bottom oxygen concentration, the number of days with an oxygen concentration below 6 mg.L^{-1} , the mean near-bottom temperature, and the mean stratification for the 10 summers of the simulated period in the permanent Gironde ROFI

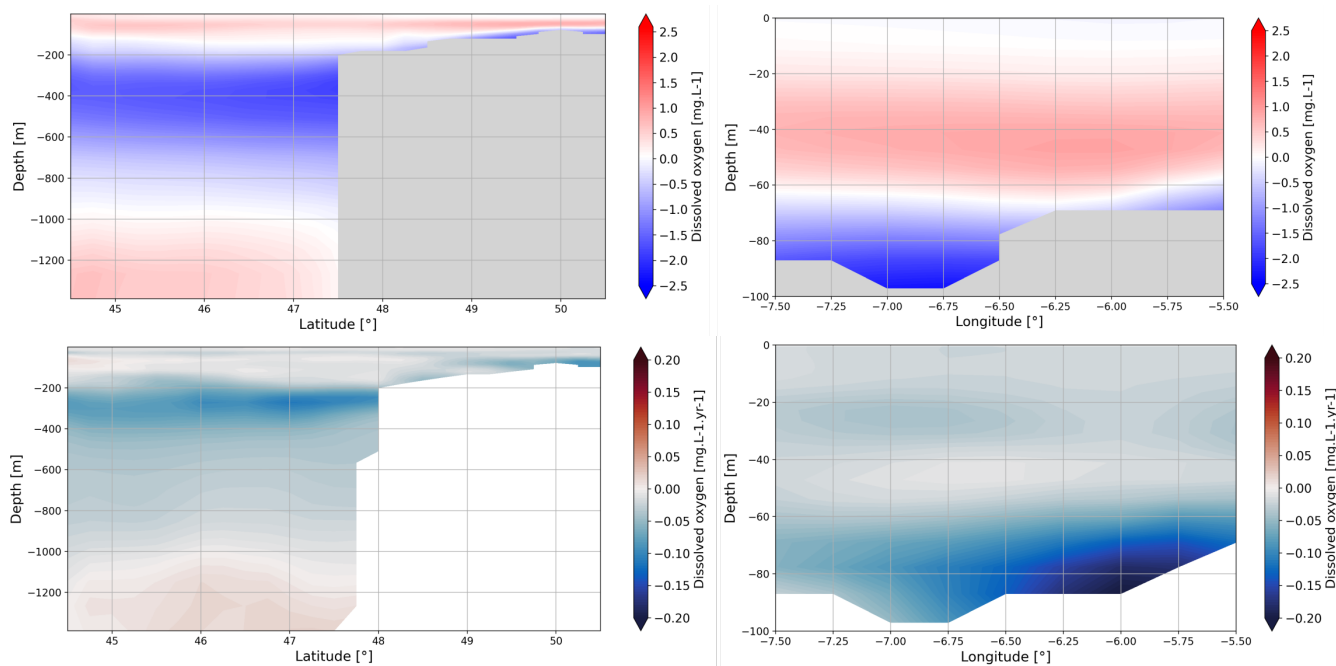


Figure A3. Top : difference between GLOBH and World Ocean Atlas oxygen mean concentration at the western (left panel) and northern (right panel) boundary of the domain. Bottom : Oxygen concentration trend of GLOBH simulation at the western (left panel) and northern (right panel) boundary of the domain.



Author contributions. MMA, MS, and GC were responsible for the investigation, conceptualisation and methodology; MMA performed the simulations and analysed the data; GC acquired funding; MS, and GC supervised the project; MMA prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have
460 appeared to influence the work reported in this paper.

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