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Impact of ocean-forcing temporal resolution on biogeochemical dynamics and forecasting in the Mediterranean Sea

Laura Feudale[1], Giorgio Bolzon[1], Gianpiero Cossarini[1], Anna Teruzzi[1], Emanuela Clementi[2], Stefano Salon[1]

[1]National Institute of Oceanography and Applied Geophysics – OGS, Trieste, Italy
[2]CMCC Foundation - Euro-Mediterranean Center on Climate Change, Bologna, Italy

Correspondence to: Laura Feudale (lfeudale@ogs.it)

Abstract. The temporal forcing frequency of ocean dynamic fields used to drive transport–biogeochemical models in off-line coupling configurations can critically affect model performance, especially when mesoscale and high-frequency biogeochemical variability are resolved. This study demonstrates the benefits of using high-temporal-frequency ocean dynamics to force biogeochemical simulations within the Mediterranean Sea forecasting system of the EU Copernicus Marine Service. The OGSTM–BFM transport–biogeochemical model was forced with 6-hourly and 24-hourly averaged outputs from the Mediterranean Forecasting System (MedFS, based on NEMO–WW3-OceanVar) with particular attention to the role of vertical transport processes in regulating primary productivity. Validation against BGC-Argo and satellite observations revealed that the 6-hourly forcing improved the timing of phytoplankton blooms across several Mediterranean subbasins, as well as the spatial distribution of chlorophyll and nutrient concentrations—most notably in the western Mediterranean and Ionian Sea during winter. Enhanced sub-daily advection in winter and intensified mixing in summer were identified as the dominant processes driving these biogeochemical responses, leading to better representation of winter surface blooms and a broader deep chlorophyll maximum layer in summer. Although basin-scale primary productivity patterns remain broadly consistent, local productivity intensity varies in response to the altered vertical transport regime.

1 Introduction

Physics and biogeochemistry in the marine environment engage in highly complex and tangled interactions (McGillicuddy Jr., 2016), rooted in three fundamental mechanisms: (1) physical parameters like temperature and salinity govern chemical reaction rates and biological activities; (2) hydrodynamic processes—advection, diffusion and turbulence—redistribute dissolved and particulate matter throughout the water column (McGillicuddy Jr., 2007); and (3) interactions with incoming solar radiation generate feedbacks that influence both physical stratification and biogeochemical dynamics (Skákala et al., 2022). Among these processes, submesoscale dynamics, which operate on spatial scales of 1–10 km and on timescales comparable to phytoplankton growth, play a pivotal role in modulating marine productivity (Mahadevan, 2016; Lévy et al., 2012c).

Although biological feedback on physical fields does occur (e.g., organic matter-driven mixing; Hernandez et al., 2017; Lengaigne et al., 2007), models typically simplify this by using one-way coupling that includes the effects of physics on biogeochemistry and neglects the biological feedback on physics. The one-way coupling can be implemented by embedding a biogeochemical module within the physical model for online coupling (e.g., Bruggeman and Bolding, 2014; Cossarini et al., 2017, Gutknecht et al., 2021). Alternatively, offline one-way coupling runs physical and biogeochemical models separately, using physical outputs to drive biogeochemical processes (Lazzari et al., 2010; Salon et al., 2017 and 2019). This approach can be favoured in operational oceanography for its engineering flexibility and lower computational overhead, especially when multiple components (physics, ice, wave, biogeochemistry, optical and high trophic level components) and multivariate data assimilation are involved—but risks losing temporal fidelity in representing vertical mixing and mesoscale-to-biogeochemical interactions (Alvarez et al., 2022).

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Temporal interpolation schemes used in offline coupling—essential to reduce data storage and streamline operational workflows—tend to smooth extremes and suppress abrupt transitions, which helps prevent spurious inertial oscillations (Latif, 1987; Semtner and Chervin, 1988; Killworth, 1996). However, averaging over daily intervals also filters out sub-daily dynamics essential for nutrient entrainment and primary productivity. On the other hand, higher-frequency forcing captures realistic ocean–atmosphere exchanges but may introduce noise or unresolved circulation features.

Previous studies examining the coupling between atmosphere forcing and ocean dynamics have shown that increasing the temporal resolution of atmospheric forcing (e.g., from daily to sub-daily intervals) enhances the representation of short-term ocean variability. Daily forcing tends to smooth out diurnal signals and sub-daily atmospheric events, while 6-hourly forcing captures transient phenomena such as diurnal wind cycles and rapid surface flux changes. For example, Large and Yeager (2004) demonstrated that 6-hourly forcing improves the simulation of mixed-layer depth, sea surface temperature variability and energy exchanges at the ocean surface, particularly in regions affected by strong atmospheric variability. Balmaseda et al. (2008) further confirm that higher-frequency inputs yield better reanalysis performance by more accurately representing rapid atmospheric transitions.

On the biogeochemical (BGC) side, improving physical variability representation enhances vertical mixing and nutrient availability, which directly influence positively the primary production (Lévy et al., 2012a, 2012b; Oschlies, 2002): experiments have demonstrated that entrainment induced by high-frequency wind variability can boost nutrient supply to the euphotic zone, increasing phytoplankton biomass and primary production by orders of magnitude (Whitt et al., 2017; Thian et al., 2022). Moreover, Ramirez-Romero et al. (2020) and Fransner et al. (2020) highlight that chlorophyll cycles and deep chlorophyll maxima are highly sensitive to physical stratification and mixing timescales, with broader implications for CO_2 fluxes and carbon export dynamics in Earth system models (e.g., Bourgeois et al., 2022; Goris et al., 2023). Nonetheless, this improvement in dynamical realism comes with trade-offs: processing and storage demands increase, and higher-frequency coupling may amplify the effects of unresolved small-scale variability or approximations in interpolation and parameterizations.

Primary production is regulated by the interaction between physical circulation and biogeochemical processes, which together control the supply of nutrients to the euphotic zone. In oligotrophic regions as the Mediterranean Sea, biological productivity is largely limited by nutrient availability rather than by light, making vertical exchanges between nutrient-rich subsurface waters and surface layers a key control on ecosystem functioning (Falkowski et al., 1998; Williams & Follows, 2003). Among macronutrients, nitrate plays a dominant role in sustaining new and regenerated production, particularly in stratified oceanic environments: vertical nitrate fluxes across the nutricline have long been recognized as a primary mechanism sustaining phytoplankton growth in nutrient-poor surface waters (Lewis et al., 1986). These fluxes arise from a combination of turbulent diffusive mixing and vertical advection, associated with processes such as wind-driven mixing, internal wave breaking, mesoscale eddies, and submesoscale dynamics. Numerical and theoretical studies have shown that these processes can significantly enhance nutrient supply and primary production, even in the absence of large-scale upwelling (Oschlies & Garçon, 1998; Klein and Lapeyre, 2009).

Recent works have emphasized that high-frequency physical variability plays a distinctive role in regulating vertical nutrient transport (Lévy et al., 2012b; Mahadevan, 2016): sub-daily atmospheric forcing, internal waves, and intermittent mixing events can generate episodic but biologically effective nutrient injections at depth, particularly near the nutricline and the deep chlorophyll maximum (DCM). However, many basin-scale biogeochemical models are still forced with daily or coarser physical fields, potentially underestimating the magnitude and vertical structure of nutrient fluxes and their impact on biological production. The unresolved temporal scales in the physical forcing add another layer of uncertainty to those linked to biogeochemical formulations. Indeed, biogeochemical models suffer from considerable uncertainties, as they rely on empirical relationships and poorly constrained parameterizations rather than first principles (Bertino et al., 2022; Kriest et al., 2010; Löptien and Dietze, 2015; Fennel et al., 2022; Cossarini et al., 2025). Missing processes (Dietze and Löptien,

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2013), inadequate parametrizations (Anderson, 2005; Dietze and Löptien, 2013), or suboptimal parameter choices (Sauerland et al., 2018) can all affect biogeochemical predictions. Nevertheless, it has been shown that biogeochemical processes, such as primary production, can be highly sensitive to the better-resolved mesoscale and sub-mesoscale dynamics that emerge under higher-resolution and higher-frequency forcing (Lévy et al., 2001; Barboni et al., 2024).

The Mediterranean Sea provides an ideal framework to investigate these physical-biogeochemical interconnection, as it is characterized by strong west–east gradients in nutrient availability and stratification, pronounced seasonal variability and a persistent DCM that reflects the tight coupling between light, nutrients, and vertical physical processes (Estrada, 1996; Crispi et al., 2001). In addition, primary production is particularly sensitive to vertical nutrient supply mechanisms rather than to surface nutrient concentrations alone (Bosc et al., 2004; Lazzari et al., 2012), making the Mediterranean Sea a natural laboratory for assessing the role of high-frequency physical forcing.

A crucial aspect in assessing the impact of forcing on model outputs is the availability of validation metrics and datasets capable of capturing relevant processes and their variability across appropriate spatial and temporal scales. While the validation of ocean dynamics models often relies on surface and profile metrics based on comparison with remote sensing and in situ observations (e.g., sea surface temperature, sea level, salinity and temperature profiles), the evaluation of their ability to represent vertical transport processes—key modulators of biogeochemical variability—remains often underexplored. On the other hand, developing biogeochemical metrics to quantify the impact of temporal approximations in physical forcing on biogeochemical processes is essential. Process-based metrics based on BGC-Argo profiles (Cossarini et al., 2019; Salon et al., 2019; Mignot et al., 2023) have demonstrated that assessing the intensity, the timing and position of key processes (e.g., deep chlorophyll maximum formation) provides valuable insight into the physical mechanisms driving marine biogeochemistry.

In this study, we aim to assess how the forcing frequency of the ocean physical dynamics, specifically transitioning from daily to sub-daily, affects biogeochemical outputs within the Mediterranean Sea operational modelling framework delivered through the European Copernicus Marine Service (CMEMS). The Mediterranean, renowned for its remarkable heterogeneity and often described as a “miniature ocean” (Bethoux et al., 1999; Schroeder and Chiggiato, 2023), provides a compelling testbed for investigating the linkages between physical processes and biogeochemical responses.

The paper is organized as follows: Section 2 describes the model configuration, data, and methods; Section 3 analyses the physical forcing characteristics at different temporal resolutions; Section 4 explores the resulting biogeochemical differences via vertical profiles and basin-wide diagnostics, including validation; Section 5 concludes with implications for operational forecasting and future coupling strategies. Section 6 provides the Appendix A containing supporting material.

2. Data and Methods

2.1 Modelling framework

The CMEMS’s Mediterranean Monitoring and Forecasting Centre (Med-MFC) modelling systems (Coppini et al., 2023) comprise three components: the coupled NEMO-WW3 ocean model (Med-PHY), the WAM wind wave model (Med-WAV), and the OGSTM-BFM transport-biogeochemical model (Med-BGC). Med-PHY employs NEMO v4.2 with a 1/24° horizontal resolution (~4 km) and 141 vertical levels, coupled online to WW3 v6.07 via OASIS and corrected through OceanVar 3D-Var assimilation of temperature, salinity vertical profiles and sea level anomaly (SLA) observations (Dobricic and Pinardi, 2008; Storto et al., 2016; Coppini et al., 2023, Oddo et al., 2025). Med-BGC (MedBFM4) integrates, at the same spatial resolution of Med-PHY, OGSTM_BIOPTIMOD v4.6 and BFM v5.3 including a bio-optical module for in-air and in-water (downward, upward and diffuse) multispectral light propagation (Lazzari et al., 2021a, b) as shown in Fig. 1. In the operational version, MedBFM4 is equipped with the 3DVarBio v4.1 variational scheme assimilating surface chlorophyll and chlorophyll, nitrate, and oxygen profiles from BGC-Argo floats (Teruzzi et al., 2014, 2021; Salon et al., 2017). Daily

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temperature, salinity, velocity, eddy diffusivity and variable vertical grid coordinates (Z*-levels) fields are linearly interpolated, consistent with the Z-level dynamics of NEMO (Salon et al., 2017; Coppini et al., 2023). Transport is handled via source splitting: i) advection and horizontal diffusion via an explicit Euler scheme, ii) vertical diffusion via implicit methods, with variable time-stepping tailored for numerical stability (between 5 and 10 min per step at current 1/24° horizontal resolution).

The BFM component (Fig. 1) simulates carbon, nitrogen, phosphorus, silicate, and oxygen cycles, with 54 prognostic variables, including four phytoplankton functional groups (i.e. diatoms, flagellates, picophytoplankton and dinoflagellates), four zooplankton groups (i.e. carnivorous and omnivorous mesozooplankton, heterotrophic nanoflagellates and microzooplankton), and heterotrophic bacteria. Dissolved inorganic nitrogen is tracked as nitrate and ammonium; non-living organic pools and carbonate system processes are also represented (Vichi et al., 2007; Cossarini et al., 2015).

While the operational Med-BGC system routinely employs the 3DVarBio assimilation, the system configuration adopted in this study is run in hindcast mode to isolate the biogeochemical response to physical variability without assimilation damping. Atmospheric forcing fields—including aerosol, cloud, wind, and solar radiation - are from ERA5 with hourly solar radiation computed based on seasonal evolution of the day-length at the proper latitude. Riverine freshwater, carbon, nutrient inputs from 39 major rivers (i.e., discharge larger than 50 m^3/s), and atmospheric nitrogen and phosphorus deposition are also included (Coppini et al., 2023).

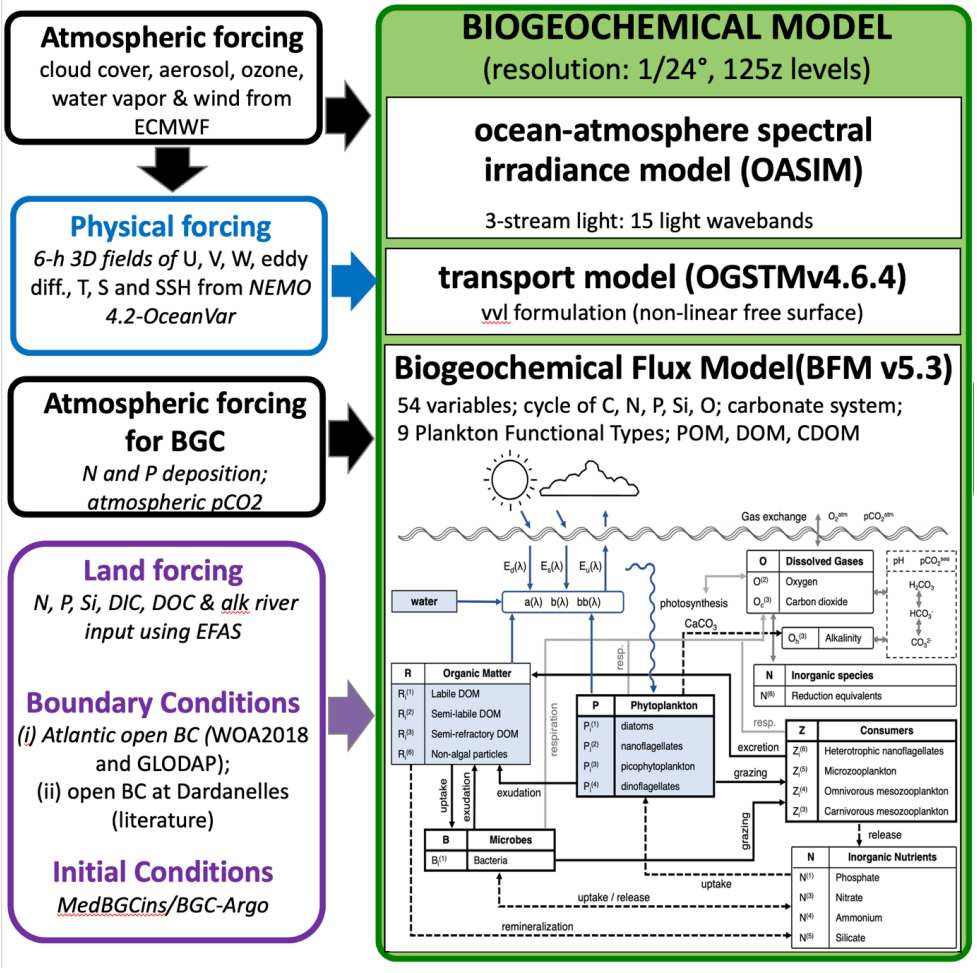

Figure 1: Scheme of the components of the Med-BGC model and its input, forcings, initial conditions and boundary conditions.

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2.2 Experiments Setup

Two experiments were conducted using ocean physical forcing at different temporal resolutions: the 24-hour (daily) average (24H), and a higher-resolution 6-hour average (6H).

The physical forcings, which are from the same simulation run with the coupled NEMO-WW3 configuration including assimilation of tracers from in-situ observations and sea level anomaly from remote sensing, are composed by 3D fields of potential temperature, salinity, currents (horizontal and vertical velocity components), vertical eddy viscosity and diffusivity, and sea surface height. Storage requirements of the 1-year datasets are 167 GB and 584 GB for 24H and 6H, respectively.

Both simulations span the year 2019 starting from a 5-year spin-up hindcast simulation using the 24-hour forcing in a perpetual mode.

Model outputs from OGSTM-BFM were analysed at a daily frequency, consistently with the standard temporal resolution of biogeochemical products provided by Med-MFC in CMEMS (Coppini et al., 2023; Feudale et al., 2024).

2.3 Diagnostic metrics

To investigate the influence of the temporal resolution of physical forcing on biogeochemical processes, we propose a set of diagnostic metrics (Table 1) derived from key physical and biogeochemical model outputs. The list of physical metrics includes:

- Total Kinetic Energy (KE_{TOTAL}) that measures the system's kinetic energy associated with transport processes of tracers, and is analogous to the effective total kinetic energy, excluding the density component (as in Kukulka and Brunner, 2015 and Chamecki et al., 2019);
- Vertical-to-Horizontal Kinetic Energy Ratio (KE_{RATIO}) that captures the intensity of vertical transport processes, such as convection and upwelling, which affect the distribution of subsurface nutrients. These processes are critical in sustaining vertical nutrient fluxes and potentially enhancing primary production;
- Subsurface Vertical Eddy Diffusivity (VED150) that measures vertical turbulent mixing fluxes of tracers (Gargett, 1984) in the upper ocean (0–150 m). It is related to the transport associated with turbulent mixing and thus the potential for upward nutrient injection into the euphotic zone or the downward dilution of surface-produced organic matter.

The set of biogeochemical metrics comprises the following:

- Deep Chlorophyll Maximum (DCM) that is the depth at which phytoplankton chlorophyll concentration is maximum, typically corresponding to enhanced primary productivity during summer stratification (April-October).
- Winter Bloom Layer (WBL) that provides the depth of the surface mixed layer involved in the winter–spring phytoplankton bloom (January-March), reflecting the vertical extent of the productive layer during this period.
- Nutricline Depth (NUTR) that is the depth at which an intense gradient in nutrient concentration is observed, marking the transition between the nutrient-depleted surface layer and the nutrient-enriched subsurface pool.
- Subsurface Oxygen Maximum (SOM) that measures the vertical maximum in the dissolved oxygen concentration of the upper ocean.
- Euphotic Layer Depth (ZEU) that is the vertical extent of the water column that receives sufficient irradiance to support net photosynthetic activity.

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Table 1: Metrics on physical and biogeochemical model output. In the table, U, V, and W are the zonal, meridional and vertical velocity respectively; z is the depth, Kd is the vertical eddy diffusivity.

Metrics	units	formula	Calculation
KE_{TOTAL}	$[m^4/s^2]$	$\sum_{200}^{0} \frac{1}{2} * \left[\int U^2 \, dA_{yz} + \int V^2 \, dA_{xz} + \int W^2 \, dA_{xy} \right]$	Vertical integral of the total kinetic energy per unit mass in the 0-200 m layer. The integral is weighted on the model grid cell dimensions.
KE_{RATIO}	[-]	$\sum_{200}^{0} \{½ \, W^2 / [½ \, (U^2+V^2)] \, dz\}$	0-200m layer vertical integral of the ratio between the vertical and the horizontal components of the kinetic energy. The integral is weighted on the model grid cell dimensions.
VED150	$[m^2/s]$	$\frac{\int_{150}^{0} Kd\,(x,y,z)\,dz}{\int_{150}^{0} dz}$	Vertical Eddy Diffusivity averaged, respectively, in the "surface" layer (defined between 0 and 150 m depth)
DCM	m	Z for max(CHL_z)	depth of the chlorophyll maximum below 40 m during summer
WBL	m	Z for $CHL_z = 0.01 * CHL_{z=0}$	depth at which chlorophyll concentration is 10% of surface concentration during winter
SOM	m	Z for max(O2o)	Depth of the shallow subsurface [0-200 m] oxygen maximum
Zeu	m		depth where the Photosynthetically Available Radiation (PAR) levels drop to 1% of their surface value
NITR2	m		depth of the isoline of 2 mmol m^{-3} nitrate concentration

185 The metrics are visualized as vertically integrated to reduce the original three-dimensional data to two-dimensional fields. They are calculated at the same temporal resolution as the physical forcing and are analyzed statistically across specific seasons and spatially defined regions. For spatial aggregation, we adopt the 16 biogeochemically homogeneous sub-regions of the Mediterranean Sea as defined in Salon et al. (2019) and shown in Fig. 2.

190 **2.3 Observational datasets and validation metrics**

In situ observations from BGC-Argo network (Argo, 2025; GDAC Coriolis) for year 2019 (Fig. 2), which includes 11 BGC-Argo floats with oxygen, chlorophyll and nitrate data sensors, 12 with chlorophyll and oxygen, and 13 with only oxygen, are used for model validation. Validation consists of RMSD (root mean square difference) and bias values computed for the 16 sub-basin subdivision (Salon et al., 2019) shown in Fig. 2. Three selected floats (6902903, 6902904 and 6903249, whose
195 2019 tracking are displayed in Fig. 2) are used for specific analysis of the fine-scale representation of the water column

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properties. Additionally, process-based metrics derived by profile analysis, such as NITR2, DCM, WBL and SOM, are used for validation, given that they are critical indicators of ecosystem functioning and nutrient dynamics (Mignot et al., 2014; Organelli et al., 2014, Lavigne et al., 2015; Teruzzi et al., 2021).

The three floats, which cover the whole 2019 and have an almost stationary trajectory, are representative of different physical regimes of the Mediterranean basin: seasonal mixing and stratified regime (Rhodes Gyre and Tyrrhenian Sea) and permanently stratified one (Ionian Sea). The latter trajectory includes also a part along poorly resolved shelf; however the summer period is well covered in off-shore area.

In detail, for the three exemplar floats we investigated how the increase of the temporal resolution of physical forcing from daily (24-hour) to high-frequency (6-hour) affects vertical nitrate transport and net primary production. Using time series of vertical profiles extracted at the locations of BGC-Argo floats in the western, central, and eastern Mediterranean, we analysed how changes in nitrate fluxes are related to changes in net primary production across depths and seasons.

By focusing on the vertical alignment between nitrate fluxes, the nutricline and the DCM, this analysis aims to clarify how high-frequency physical variability modulates biological production in oligotrophic marine systems, and to provide guidance for the representation of physical forcing in coupled ocean models.

At basin scale, satellite data of surface ocean colour for the period 1 January 2019-31 December 2019 available through CMEMS were used to validate (i.e., RMSD) spatial-temporal variability of the simulated chlorophyll in the 16 sub-basins.

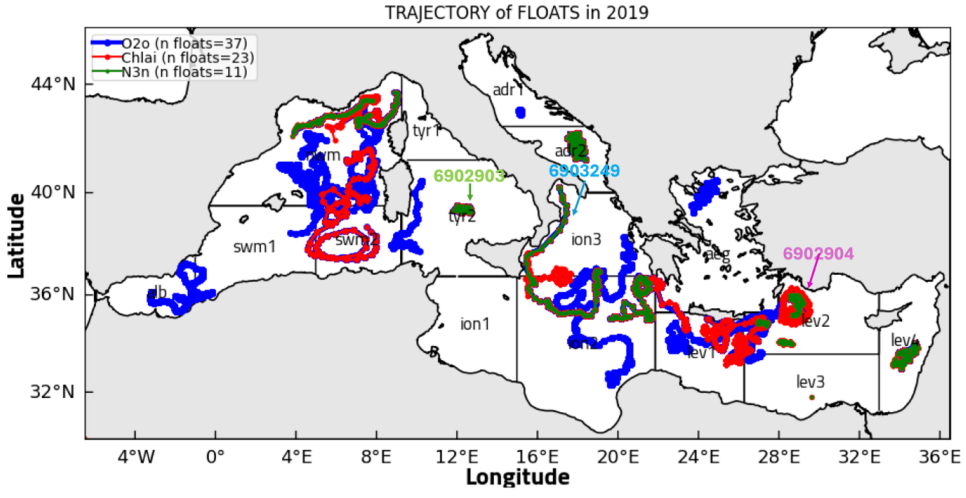

Figure 2: Trajectories of BGC-Argo floats of chlorophyll (red), nitrate (green) and oxygen (blue) available in the Mediterranean basin during the year 2019. The three floats selected for the analysis are evidenced. The map shows also the division of the Mediterranean basin the in 16 sub-basins: alb=Alboran; swm1, swm2=West and East southwester Mediterranean; nwm=northwestern Mediterranean; tyr1, tyr2=northern and southern Tyrrenian; ion1, ion2, ion3=western, southern and northern Ionian; adr1, adr2=northern and southern Adriatic; lev1, lev2, lev3, lev4=western, northern, southern and eastern Levantine respectively.

We extended the applicability of our approach by performing a basin-scale evaluation of the biogeochemical response to varying physical forcing frequencies. This analysis involved the computation of two-dimensional metrics that characterize the spatial distribution of biogeochemical tracers in the upper ocean. Specifically, we quantified the mean concentrations of nitrate, chlorophyll, and oxygen within the 0–200 m depth layer during both winter and summer seasons. This depth interval approximates the euphotic zone in the Mediterranean Sea (Estrada, 1996), thereby enabling the assessment of seasonal variability in biogeochemical properties under different temporal forcing regimes.

To further investigate spatial heterogeneity, we employed a percentile-based statistical framework to compare the 6H and 24H simulations. This approach facilitates the identification of sub-basin-scale differences and highlights regions exhibiting

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heightened sensitivity to the temporal resolution of physical forcing, as reflected in the distribution patterns of biogeochemical tracers.

3. Results

3.1 Diagnostics on physical forcing

Diagnostics metrics were evaluated for the two physical forcing datasets (6H and 24H) to assess potential changes in energy distribution and vertical mixing with the focus to identify shifts in the physical background state, particularly those influencing vertical transport and stratification, which are known to affect biogeochemical processes (e.g., Lévy et al., 2001; Mahadevan, 2016).

3.1.1 Total Kinetic Energy from transport

The timeseries of Total Kinetic Energy (KE_{TOTAL}), computed over the upper 200 m of the water column for the entire Mediterranean basin using the two forcing datasets (Fig. 3), exhibit a clear seasonal cycle: KE_{TOTAL} values are higher during winter and early spring (January to March) and reach a minimum in summer (June to September).

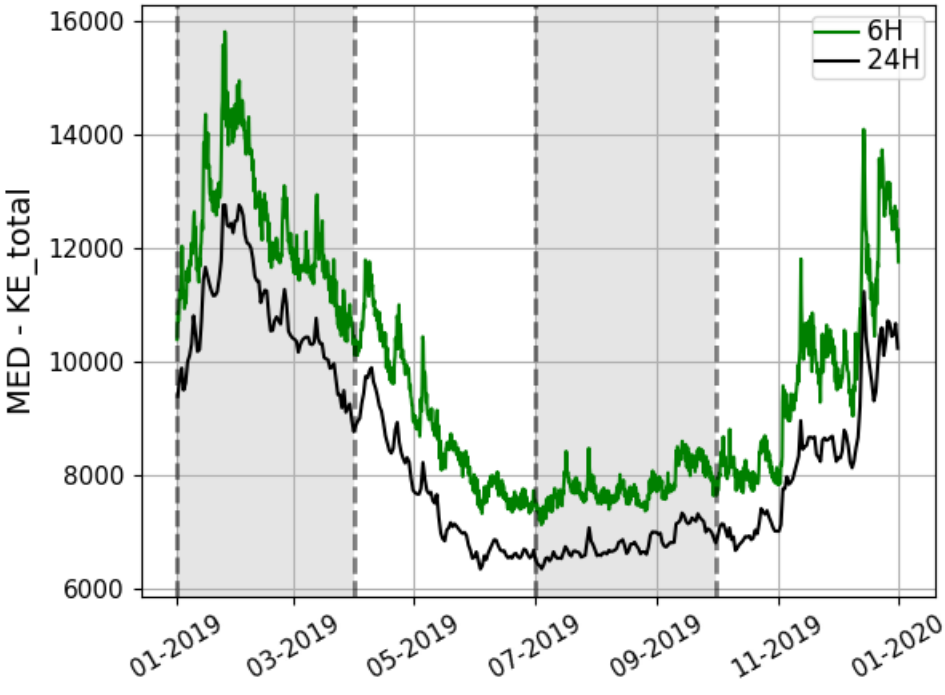

Figure 3: Time series of KE_{TOTAL} (daily mean) over the entire Mediterranean Sea basin for the 6H (green) and 24H (black) runs. Units are m^4/s^2. Gray shaded areas highlight winter (January–March) and summer (July–September) periods used for spatial analyses.

This seasonality is consistent with the known behaviour of the Mediterranean general circulation, which is more energetic during winter due to increased atmospheric forcing and enhanced overturning circulation in the upper ocean layers (e.g., Sayol et al., 2023; Sorgente et al., 2011). While the systematically higher mean daily kinetic energy of 6H with respect to 24H arises from the mathematical properties of averaging nonlinear quantities (kinetic energy is proportional to the square of the velocity magnitude). The enhanced energy in the 6H forcing dataset reflects the ability of the tracer transport model to simulate short term (i.e., sub-daily) variability processes, which are removed in the dampened temporally coarser 24H run.

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This difference can be relevant especially during winter months, when, typically, episodic wind events and atmospheric pressure gradients strongly influence the upper-ocean dynamics (Gonçalves et al., 2021; Luzia et al., 2022).

In the 6H run, sub-diurnal scale processes can contribute to the system's total energy budget and can be crucial for correctly representing physical conditions that regulate biogeochemical transport and vertical mixing (Lévy et al., 2012a, 2012b; Mahadevan, 2006).

The seasonal spatial maps of KE_{TOTAL} of 24H (Fig. 4a and 4b) reflect the expected circulation features of the Mediterranean with large values along major current systems, such as the Algerian Current along the North African coast, the Northern Ionian Gyre and its seasonal reversals, the Rhodes Gyre in the Levantine Basin, the Northern Tyrrhenian jet, and the Aegean inflows, as well as boundary currents around Corsica and Crete during winter. These features are consistent with the persistent mesoscale circulation structures described by Menna et al. (2019b) and Pinardi et al. (2015). During summer (Fig. 4b), KE_{TOTAL} values are generally lower across the basin, reflecting a seasonal weakening of wind stress and stratification-driven suppression of vertical exchanges. However, energetic zones persist in the Sicily Channel, Alboran Gyres and the Cilician Basin, where local wind patterns and bathymetric constraints maintain active circulation. The differences between the two runs (Fig. 4c and 4d) confirm the general higher values in 6H showing relevant differences in areas dominated by transient forcing events such as the Algerian Current or the Rhodes and Ierapetra gyres in winter. In summer differences are generally lower than in winter and are limited to areas characterized by strong topographic constraints (i.e. Gibraltar and Sicily channel), as also indicated by the percentile analysis per subbasin (Fig. A1).

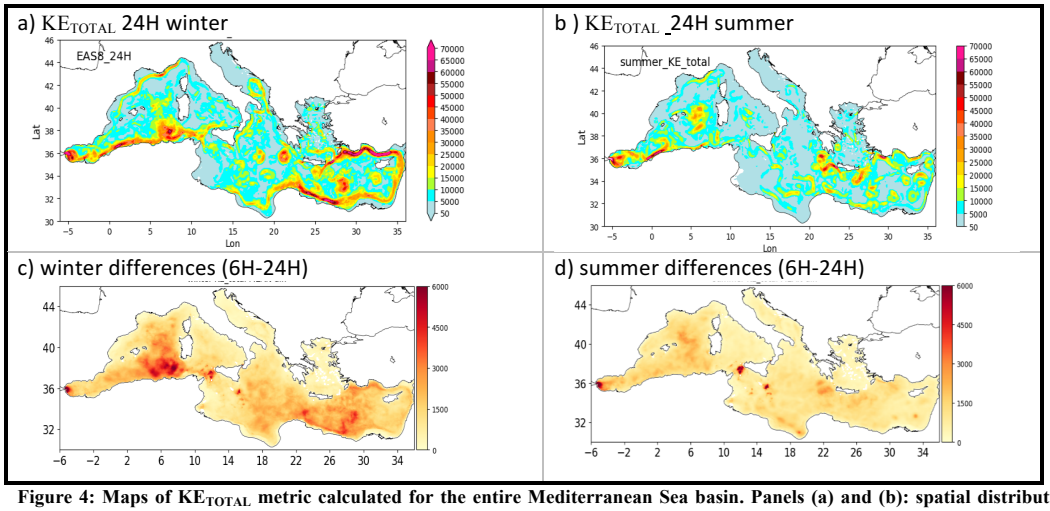

Figure 4: Maps of KE_{TOTAL} metric calculated for the entire Mediterranean Sea basin. Panels (a) and (b): spatial distribution of KE_{TOTAL} in the 24H run for winter (a) and summer (b). Panels (c) and (d): corresponding differences between 6H and 24H runs (6H − 24H) for winter (c) and summer (d). Units are $m^4 s^{-2}$.

3.1.2 Vertical vs Horizontal Dynamics: Insights from KE_{RATIO}

The KE_{RATIO} metric (Table 1) provides a dynamic proxy for vertical transport processes such as convection, upwelling, and entrainment, all of which are crucial for nutrient supply to the euphotic zone and therefore influence biogeochemical fluxes (e.g., Levy et al., 2001, 2012a; Estournel et al., 2005; Herrmann et al., 2008). The frequency distributions of KE_{RATIO} across the 16 sub-basins (Fig. 5 (a) and (b)) reveal a seasonal signal, with winter values up to one order of magnitude higher than in summer (i.e., 10^{-1} vs. 10^{-2}). This pattern reflects the enhanced role of vertical processes during the winter, when the water column is more weakly stratified, and conditions favor deep convection and subduction (Lascaratos et al., 1993; MEDOC Group, 1970). Superimposed on this seasonal variability, the comparison between the 6-hourly (6H) and daily (24H) forcing simulations shows a consistent increase in KE_{RATIO} in the higher-frequency forcing dataset, particularly in summer and in

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western sub-basins. Specifically, the median KE_{RATIO} increases by approximately half an order of magnitude in winter and up to a full order of magnitude in summer, indicating that sub-daily forcing dataset includes short-lived vertical accelerations that have potential implications for biogeochemical tracer dynamics such as nutrient injection and DCM variability (Levy et al., 2001; Auger et al., 2011).

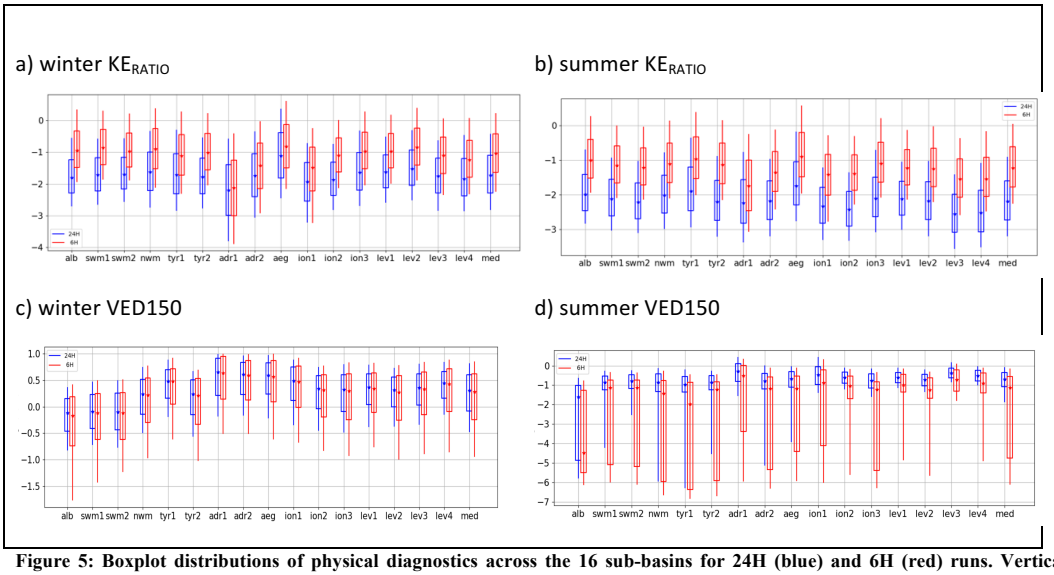

Figure 5: Boxplot distributions of physical diagnostics across the 16 sub-basins for 24H (blue) and 6H (red) runs. Vertical-to-horizontal kinetic energy ratio (KE_{RATIO}) in winter (a) and summer (b); vertically averaged vertical eddy diffusivity (VED150) in winter (c) and summer (d). Each boxplot shows the 10th, 25th, 50th (median, marked as an asterisk), 75th, and 90th percentiles. Quantities are expressed in log10.

Higher KE_{RATIO} values are particularly evident in the Sicily Strait area - ion1- and Adriatic Sea - adr1 and adr2 -, regions where complex bathymetric features—such as the Malta–Sicily escarpment and the steep bathymetry of the central Adriatic—induce strong coastal-open sea gradients and slope-induced vertical circulations. Such dynamics are known to promote cross-isobath exchange and vertical advection of water masses (Menna et al., 2019a; Rubino & Hainbucher, 2007), processes that are tightly linked to nutrient supply mechanisms.

Interestingly, a percentile analysis of the spatial pattern of KE_{RATIO} (Fig. A2) shows that low values are generally observed in regions dominated by gyres (e.g., Pelops, Southern Gyre System) or strong horizontal jets (e.g., Levantine Permanent Coastal Current and Sidra Libya Current), suggesting that energetic horizontal transport does not necessarily coincide with enhanced vertical exchanges.

3.1.3 Vertical Eddy Diffusivity

The analysis of the VED150 metric (Fig. 5c, 5d) reveals high median values in sub-basins known for intense convection and mixing, such as in the North West Mediterranean - nwm -, Tyrrhenian Sea - tyr1-, the Aegean Sea – aeg-, and the Adriatic Sea - adr1 and adr2 - (Herrmann et al., 2010; Schroeder et al., 2012; Cisneros et al., 2019) in winter. Conversely, during summer, VED150 median values are significantly lower and more uniform across sub-basins, consistently with increased stratification and reduced vertical exchange observed in the Mediterranean Sea during summer (Lavigne et al., 2015). Regions such as the ion1 (which includes the Gulf of Gabès, Adventure Bank, Malta Plateau) and the coastal zones of the central and northern Adriatic Sea—where shallow depths and continental shelf interactions enhance turbulence—still retain relatively higher values, though lower than their winter counterparts.

The boxplots of 6H dataset exhibits a wider range of VED150 variability, particularly toward lower percentiles (i.e., 10th and 25th), highlighting that higher temporal resolution forcing preserves transients of low-diffusivity conditions, whereas the

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24H forcing, by averaging over values of different magnitude within the daytime window, smooths out sub-daily variability and retains more persistent high mixing signals.

For example, winter mean VED150 values in the 24H run often exceed 0.3 $m^2 s^{-1}$, which corresponds to approximately −0.5 in log10 units, and therefore represents a very high value within the range of variability. This is indicative of sustained vertical mixing throughout the entire day length, which may facilitate the upward transport of nutrients and stimulate productivity. Conversely, in the 6H run, the same day may have shorter-lived spikes, resulting in lower cumulative vertical diffusivity and a reduced net effect on biogeochemical tracer redistribution.

3.2 Vertical variability compared to BGC-Argo float observations

To evaluate the impact of the temporal frequency of physical forcing on biogeochemical processes, while minimizing the risk of hiding vertical transport signals through horizontal averaging or vertical integration, vertical sections of model output are analysed along the trajectories of the three selected BGC-Argo floats. This approach also enables the use of BGC-Argo observations to validate the model and assess whether increasing the frequency of physical forcing improves or degrades model performance.

Hovmoeller's diagrams of Fig. 6 show that the model reproduces the key seasonal dynamics in agreement with previous studies and BGC-Argo observations (as can be found in Lazzari et al., 2012; Lavigne et al., 2015; Di Biagio et al., 2022; Tab. 3 and additional validation in appendix A). For instance, the first-row plots in Fig. 6 (a1, a2 and a3) show year-round nitrate accumulation at depth with wintertime surface replenishment and summer depletion. Phytoplankton dynamics are characterized by a winter surface chlorophyll bloom and a persistent DCM during summer (~80–100 m; Fig. 6b1, b2 and b3). Oxygen patterns (Fig. 6c1, c2 and c3) reflect winter surface blooms and enhanced subsurface production (the SOM) near the DCM during summer. Finally, primary production (Fig. 6d1, d2 and d3) exhibits high surface values associated with winter and early spring blooms, and moderate values throughout the water column down to the DCM depth during the onset of summer stratification.

The Hovmoeller plots of the differences (6H–24H; in Fig. 7) reveal distinct seasonal impacts. In winter, surface nitrate is lower in the 6H run, suggesting enhanced uptake by phytoplankton. An opposite positive anomaly occurs just below the surface, likely due to episodic entrainment events unresolved in the 24H run. Chlorophyll shows an earlier and sharper bloom in the 6H run, accompanied by increased surface oxygen and primary production, consistent with previous studies (Lévy et al., 2001; Auger et al., 2011) reporting stronger entrainment and short-lived phytoplankton events in higher variable physical dynamics.

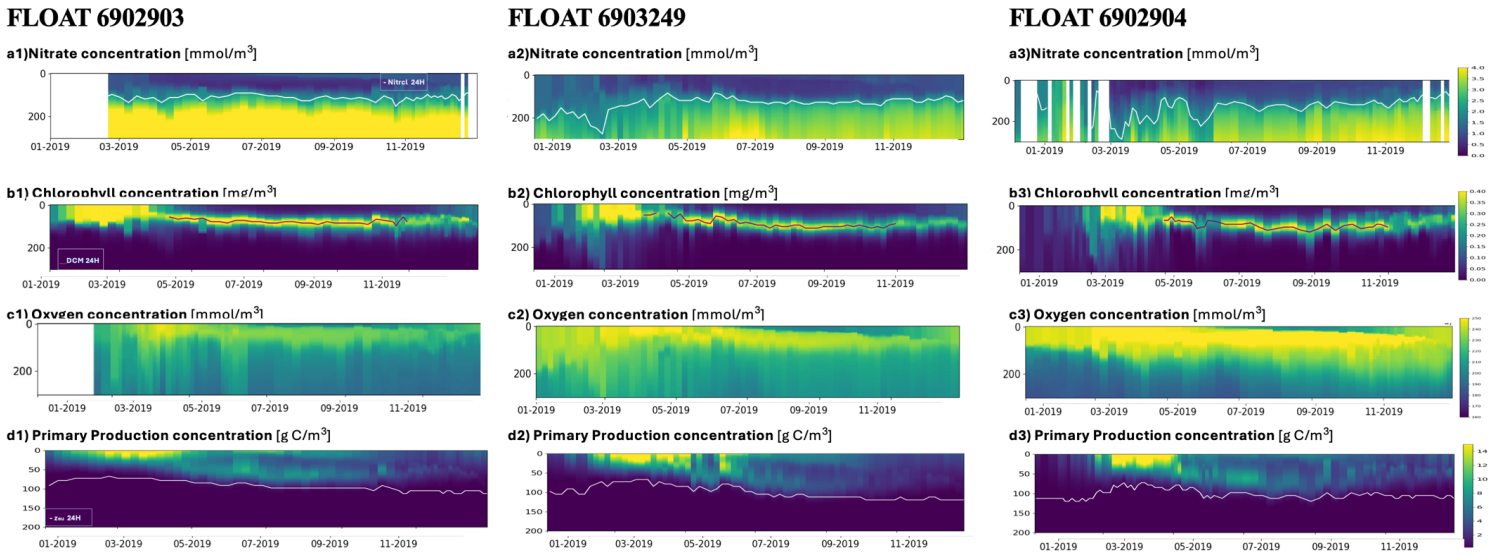

Figure 6: Hovmoeller's diagrams of BGC variables extracted from run 24H following the float ID 6902903 (left), 6903249 (central), 6902904 (right); from the top to the bottom: a) nitrate concentration, b) chlorophyll concentration, c) oxygen concentration and d) volumetric primary production.

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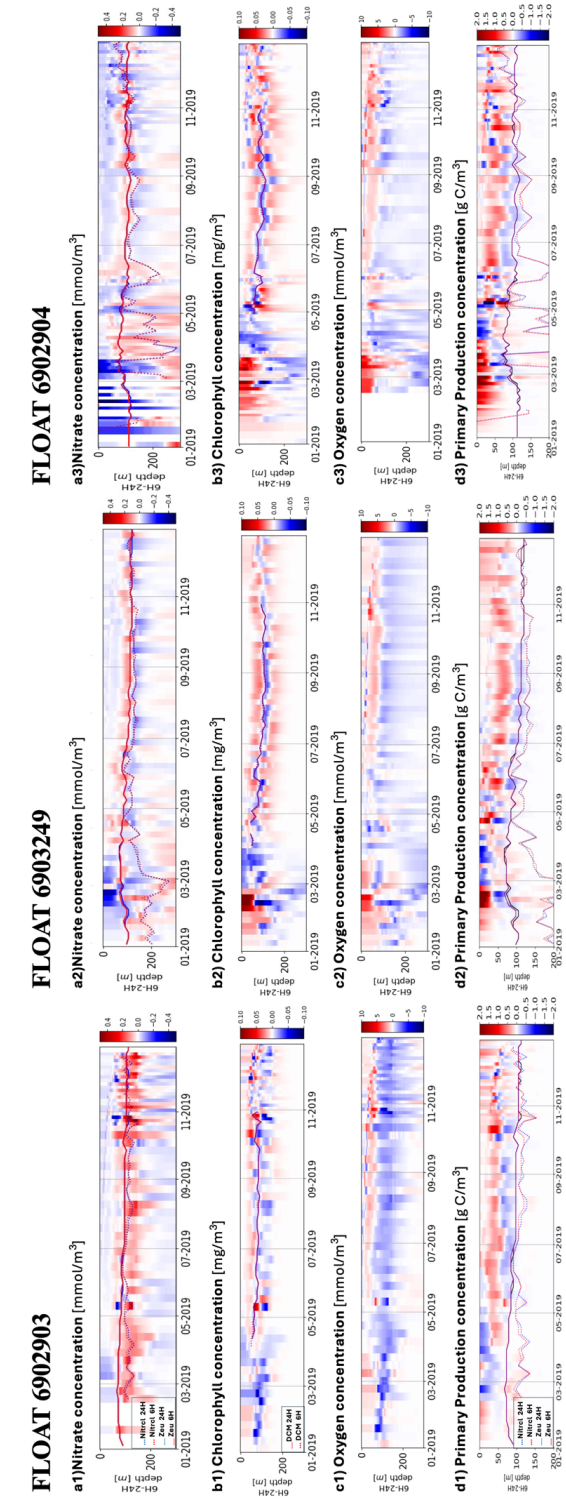

Figure 7 : Hovmoeller's diagrams of the 6H-24H differences of BGC variables extracted in the same position of the selected floats ID 6902903 (column 1, on the left), 6903249 (column 2, in the central), 6902904 (column 3, on the right); a) Nitrate concentration, b) Chla concentration; c) oxygen concentration and d) npp with the nitracline evidenced with the red line for 6H and blue line for 24H.

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In summer, differences are minor but systematic: the 6H run produces a broader DCM with reduced chlorophyll peak values, similarly to a distribution with greater variance but similar mean (see Fig.7 b1, b2, b3). Nitrate anomalies show a tripartite vertical pattern (Fig. 7 a1, a2, a3): (i) positive anomalies within the DCM due to reduced consumption, (ii) negative anomalies below the DCM linked to upward nutrient transport, and (iii) neutral to negative anomalies above the DCM, indicating increased uptake in the broadened productive layer. NITR2 (Fig. 6) slightly changes between 24H to 6H (Fig. 7) with the latter showing higher fluctuations consistently with the hypothesis that 6H is characterized by more sub-diurnal variability in vertical transport processes. In the 6H run, primary production and oxygen increase just above the DCM, reflecting the shallowing and broadening of the DCM layer in summer.

Table 2: Annual mean correlation, for both 24H and 6h runs, of vertical profiles [0-200m] along the three BGC ARGO floats trajectories of Fig. 6-7, for chlorophyll, nitrate and oxygen concentration (model vs BGC-Argo float records)

	24H			6H		
	6902903	6903249	6902904	6902903	6903249	6902904
Chlorophyll [mg m-3]	0.86	0.77	0.76	0.88	0.79	0.77
Nitrate [mmol m-3]	0.94	0.93	0.94	0.94	0.94	0.95
Oxygen [mmol m-3]	0.88	0.87	0.82	0.89	0.88	0.83

The comparison between the two simulations shows that the 6H run exhibits consistently higher skill performance (i.e., correlation between simulated and observed vertical profiles) than the 24H run (Tab. 2). Improvements, although not prominent, are present for all variables and floats, indicating that the higher-frequency physical forcing enhances the model's ability to reproduce the evolution of observed vertical structures in the upper 200 m.

3.3. Impact on biogeochemistry at basin scale

The previous analyses have highlighted how higher-frequency forcing alters nutrient supply and phytoplankton distribution, and how quality of biogeochemical variables generally improve along the float trajectories even if the presence of some inconsistencies indicates that higher forcing frequency does not automatically translate into greater accuracy. To generalize these findings at basin scale, we examined horizontal percentile-based distributions and quality of chlorophyll, nitrate, WBL depth and DCM properties (Fig. 8).

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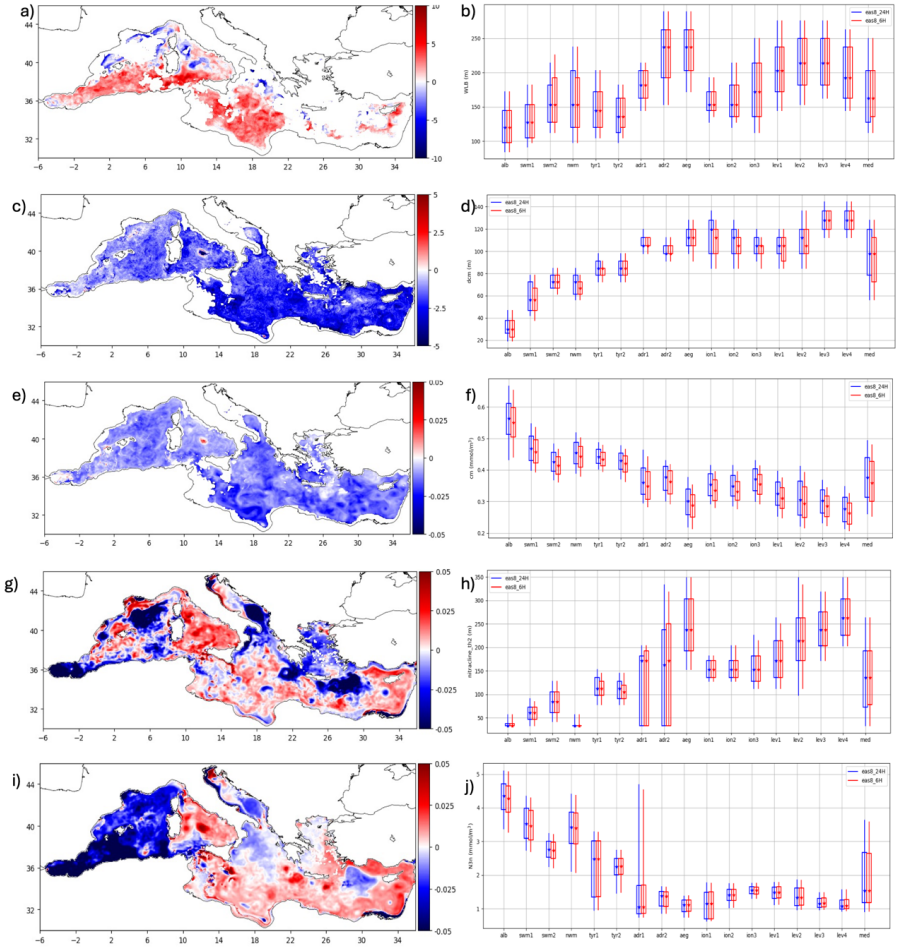

Figure 8: Maps of the seasonal mean runs difference (left column) and percentile distribution (right column) of the mean (a-b) WBL, (c-d) DCM depth (e-f) and the chlorophyll maximum (mg m^{-3}) value at DCM; in (g) map for the nitrate mean difference in winter; in (h) the percentile distribution of the nitracline 2 ([nitracline corresponding to the 2 mmol m^{-3} threshold) in winter; in (i) map for the nitrate mean difference in summer; in (j) the percentile distribution for the nitrate integral 0-200m depth. For the percentile analysis, runs 6H is in red and 24H run is in blue.

During winter, the WBL is slightly deeper in the 6H run in several western sub-basins (Fig. 8a), consistently with increased vertical eddy activity that increases nutrient vertical transport stimulating a thicker surface bloom layer, particularly in the South-western Mediterranean, Tyrrhenian and Ionian Seas (Fig. 8a).

In summer, when stratification and light–nutrient balance dominate the formation of DCM, the 6H run yields a shallower DCM (by ~5 m) with ~10% lower peak value of chlorophyll (Fig. 8c, 8d, 8e and 8f). With stronger vertical mixing, the productive layer is broadened, and the higher values appear diluted.

At a basin scale, the winter nitrate concentration in the 0-200 m has lower values in the areas of deep convection and higher values in the areas with low nitracline depth (Fig. 8g and 8h). In summer (Fig. 8i), the 6H simulation exhibits a decrease in the upper-layer nitrate concentration in the western areas, northern Ionian and Adriatic Sea and an increase in nitrate concentration in the eastern Mediterranean Sea.

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These basin-scale patterns are supported by VED150 variability, which show enhanced vertical diffusivity in 6H simulation (from O(10^{-7} m^2 s^{-1}) to O(1 m^2 s^{-1})), especially during winter convection and in topographically active regions (e.g., Gulf of Lions, Adriatic, Aegean), promoting nutrient entrainment and DCM redistribution.

In summary, basin-wide impacts reflect the vertical mechanisms identified earlier: winter blooms are deeper and thicker, while summer stratification produces a broader, shallower DCM with lower peaks and stronger nutrient drawdown.

3.4 Quality Assessment

Model outputs (6H and 24H) were compared with BGC-Argo float profiles across six Mediterranean macro-regions. Metrics include the RMSDs and Pearson correlations for chlorophyll, nitrate, and oxygen (Tables 3–5).

For chlorophyll, the 6H run improves model performance in approximately 80% of cases, showing lower RMSD values in the 0–30 m layer (Tab. 3). RMSDs in the 0–10 m and 10–30 m layers are generally lower in the 6H run across most basins, with the largest improvements observed in the southwestern (swm) and Adriatic (adr) regions. At greater depths (30–60 m and 60–100 m), differences remain small but still favor the 6H run, which more accurately captures the vertical structure of the DCM. Correlation coefficients also show gains, though modest, in 6H (i.e. 1-2 % in all sub-areas except nwm).

Table 3: RMSD of chlorophyll concentration [mg m^{-3}] for 24H (on the left) and 6H (on the right) versus corresponding BGC Argo floats per specific layers up to 150 m; the analysis is further subdivided in macro-regions where BGC floats transited in year 2019. Vertical correlation is calculated between model profiles and corresponding float profiles in each region; numbers of profiles included in the calculation are specified. Improvements (deteriorations) in the metrics are highlighted by blue (red) color. [mg/m3]. Macro-regions are defined as swm=swm1+swm2, nwm, tyr=tyr1+tyr2, adr=adr1+adr2, ion=ion1+ion2+ion3, lev=lev1+l3v2+l3v3+lev4

	RUN 24H						RUN 6H						
	RMSD [mg m-3]						RMSD [mg m-3]						
	0-10m	10-30m	30-60m	60-100m	100-150m	CORR	0-10m	10-30m	30-60m	60-100m	100-150m	CORR	N prof.
swm	0.092	0.091	0.099	0.1	0.056	0.71	0.087	0.087	0.103	0.103	0.055	0.72	36
nwm	0.122	0.126	0.188	0.1	0.048	0.87	0.123	0.126	0.188	0.099	0.047	0.87	276
tyr	0.051	0.049	0.039	0.074	0.044	0.88	0.051	0.048	0.039	0.07	0.042	0.89	72
adr	0.069	0.069	0.098	0.082	0.083	0.62	0.065	0.062	0.093	0.08	0.086	0.64	72
ion	0.061	0.058	0.062	0.08	0.089	0.78	0.062	0.06	0.064	0.081	0.086	0.80	192
lev	0.087	0.086	0.098	0.077	0.082	0.70	0.084	0.084	0.095	0.075	0.08	0.72	480

Table 4: Same as Table 3 but for Nitrate concentration [mmol m^{-3}].

	RUN 24H								RUN 6H								
	RMSD [mmol m-3]								RMSD [mmol m-3]								
	0-10m	10-30m	30-60m	60-100 m	100-150 m	150-300 m	300-600 m	CORR	0-10m	10-30m	30-60m	60-100m	100-150m	150-300m	300-600m	CORR	N prof.
nwm	0.94	0.82	0.60	0.93	0.71	0.74	0.71	0.97	0.92	0.80	0.61	0.92	0.74	0.73	0.71	0.97	132
tyr	0.97	0.84	0.61	0.98	1.64	1.35	0.47	0.95	0.96	0.82	0.60	1.01	1.72	1.35	0.47	0.94	72
adr	0.46	0.47	0.65	1.15	1.34	1.44	1.18	0.90	0.48	0.49	0.68	1.17	1.39	1.46	1.17	0.91	72
ion	0.60	0.59	0.60	0.73	0.80	0.83	0.96	0.94	0.60	0.59	0.59	0.73	0.82	0.83	0.94	0.94	144
lev	0.64	0.62	0.64	1.07	1.66	1.56	0.92	0.89	0.63	0.62	0.64	1.06	1.66	1.57	0.92	0.90	192

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Table 5: Same as Table 3 but for oxygen concentration [mmol m^{-3}].

	RUN 24H						RUN 6H						
	RMSD [mg m^{-3}]						RMSD [mg m^{-3}]						
	0-10m	10-30m	30-60m	60-100m	100-150m	CORR	0-10m	10-30m	30-60m	60-100m	100-150m	CORR	N prof.
alb	8.5	6.7	23.0	10.4	12.3	0.81	7.5	5.8	13.5	11.6	12.8	0.81	144
swm	5.0	6.0	8.6	12.2	10.1	0.89	4.6	5.7	8.2	12.6	10.5	0.89	156
nwm	5.7	7.0	9.9	12.0	11.7	0.91	5.2	6.6	9.7	12.1	11.8	0.92	504
tyr	3.5	7.0	12.2	12.1	13.7	0.91	3.3	6.7	11.7	12.2	14.5	0.92	108
adr	6.0	10.6	8.8	13.8	11.2	0.5	5.9	10.3	8.7	13.8	11.1	0.52	120
ion	3.6	5.1	10.9	7.2	5.9	0.87	3.6	5.0	10.6	7.1	5.8	0.88	408
lev	7.7	11.1	13.0	11.5	10.8	0.81	7.4	10.7	12.6	11.4	10.6	0.82	540

For nitrate (Tab. 4), improvements of 6H with respect to 24H are minor (65% of cases) than those of chlorophyll. RMSD values differ by less than 0.02 mmol m^{-3} between runs, with the 6H run marginally reduces RMSD in surface and mid-depth layers in the nwm and tyr. Correlations remain very high (≥0.90), suggesting that while vertical redistribution is slightly altered, modelled concentrations remain consistent with observation profiles.

For oxygen, improvements are substantial (81% of cases). The 6H run reduces RMSD in the upper 30 m, where blooms dominate, and slightly enhances correlations. According to Table 5, in most macro-regions (e.g., swm, nwm, tyr, lev), the 6H run slightly reduces RMSD in the upper 30 m — which corresponds to the zone of primary production peak during blooms. The deeper layers (60–100 m and 100–150 m) exhibit nearly unchanged or slightly worse RMSD values in some macro-regions, although correlation coefficients improve slightly (e.g., from 0.91 to 0.92 in the Tyrrhenian). The Adriatic region shows minor changes, with a slightly better correlation in the 6H run (from 0.50 to 0.52).

These improvements reflect enhanced surface phytoplankton production and oxygen enrichment captured by the high-frequency forcing. This result is consistent with findings by Auger et al. (2011) and Ulses et al. (2021) who showed that short-timescale wind forcing enhances oxygenation in surface waters through intense vertical mixing period.

Overall, the 6H forcing consistently improves agreement with observations, particularly in upper layers (0–60 m) where short-term variability is most relevant; the deeper layers remain largely unchanged between the two runs. The benefit of sub-daily forcing is concentrated in near-surface and subsurface dynamics where vertical mixing and light/nutrient fluctuations are more sensitive to sub-daily ocean variability. The findings support earlier work (Levy et al., 2001, 2012a; Herrmann et al., 2008; Lavigne et al., 2015) on the importance of high-frequency ocean dynamics driven by wind stress and heat fluxes in regulating phytoplankton bloom onset, DCM formation, and nutrient entrainment.

3.4.2 Surface Chlorophyll Validation Against Satellite Observations

Surface chlorophyll patterns from the model were compared with satellite-derived products using RMSD and bias for the winter and summer seasons (Fig. 9).

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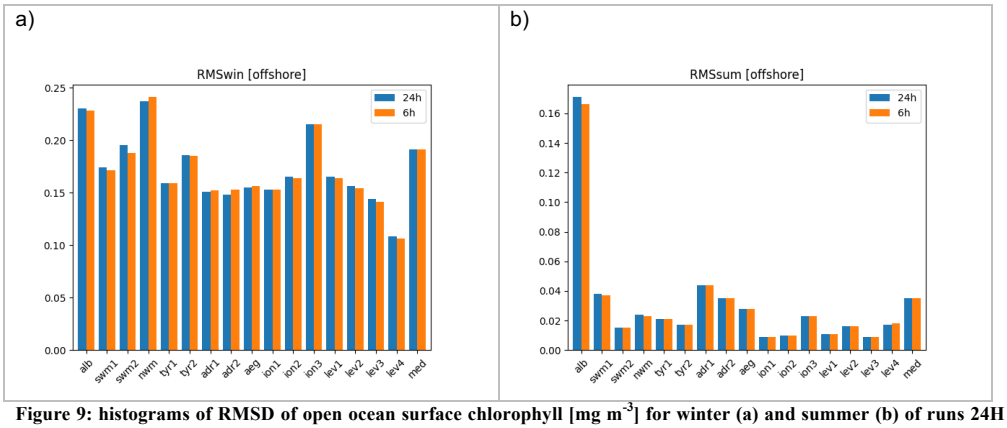

Figure 9: histograms of RMSD of open ocean surface chlorophyll [mg m^{-3}] for winter (a) and summer (b) of runs 24H (blue) and 6H (orange).

In winter (Fig. 9a), 9 out of 16 sub-basins in the 6H run show a RMSD reduction with respect to the 24H run, particularly in regions known for their intense mesoscale activity (swm1, swm2, tyr1 and lev3). Improvements are generally of the order of 5%. In the remaining sub-basins, three show no changes, and four report a worsening of about 3%. While the summer RMSDs are much lower than in winter, only three sub-basins show a reduction of RMSD, and the others report no changes (Fig. 9b) due to the weaker sensitivity of surface layers to vertical transport processes under strong stratification.

3.5 Net primary production

Net primary production (npp) integrates in a nonlinear way several processes such as nutrient availability, light penetration and vertical movement of biomasses, all of which are influenced by physical forcing. Panel a) of Fig. 10 show the annual averages of vertically integrated npp (0–200 m) for the 24H run and the annual difference with run 6H.

Values and spatial patterns of 24H are consistent with previous estimates (e.g., Bosc et al., 2004; Lazzari et al., 2012; Cossarini et al., 2021) showing meridional gradients with higher productivity in the northwestern and lower values in the oligotrophic Levantine basin (Fig. 10a).

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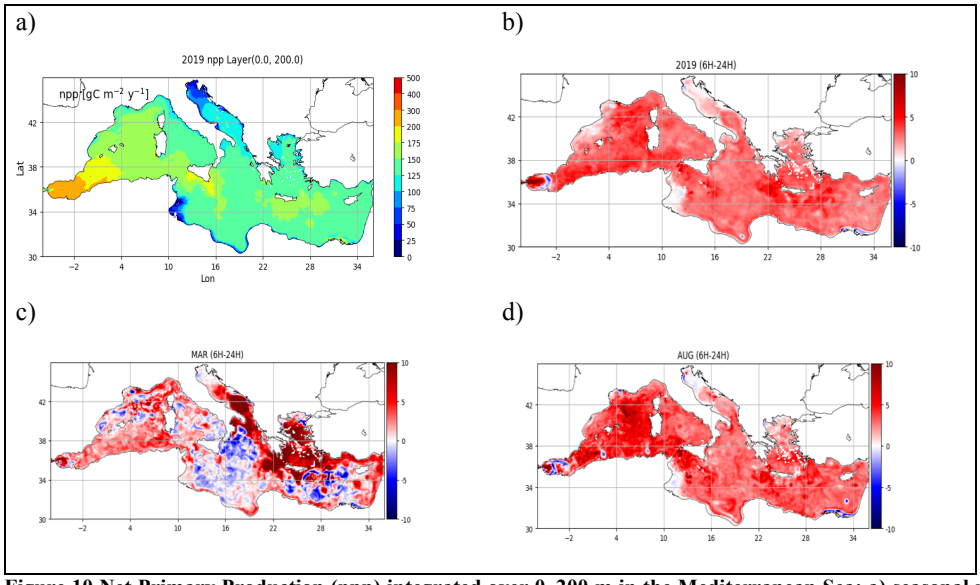

Figure 10 Net Primary Production (npp) integrated over 0–200 m in the Mediterranean Sea: a) seasonal means from the 24H simulation for year 2019 and b) difference with run 6H, in units of gC m⁻ ² yr⁻ ¹; c) spatial differences in npp between the 6H and 24H simulations (6H–24H) for for just the month of March (MAR) and d) August (AUG).

The 6H run increases the annual npp of the Mediterranean Sea by approximately 3 g C m⁻ ² yr⁻ ¹ (Fig. 10b). Figures 10c and 10d illustrate that these increases are spatially heterogeneous depending by the season: during winter (March), the effects are more pronounced yet patchy, particularly in the Levantine Basin and marginal seas, whereas in summer (August), higher values and a smoother pattern are observed in the Western Mediterranean. The increase in npp in winter is largely concentrated in the upper 50 m (not shown here), which is in line with higher chlorophyll concentrations and increased nutrient availability due to enhanced vertical mixing (as shown by the VED150 distributions in Sect. 3.1.3).

These findings echo previous studies (e.g., Lavigne et al., 2015; Pasqueron de Fommervault et al., 2015; Mellard et al., 2011), which show that even small increases in winter mixing can extend the bloom period or deepen the winter mixed layer, favoring nutrient entrainment and light availability. On the other hand, enhanced summer npp in the 6H run occurs between 20–100 m, depending on the region (i.e. 20–60 m in the Western Mediterranean, and 40–100 m in the eastern Mediterranean Sea). These depths are located just above or within the DCM layer, where sub-daily vertical mixing variability can help the injection nutrients from below, without entirely disrupting the DCM structure.

This vertical redistribution of production, toward less shallower layers in winter and broader subsurface layers in summer (Sect. 3.2), confirms that primary production is sensitive not only to the total nutrient supply, but also to its vertical timing and location.

Furthermore, from an ecological and carbon-cycle perspective, even a modest 2–3 g C m⁻ ² yr⁻ ¹ increase in npp, when integrated over the entire Mediterranean Sea (~2.5 million km²), translates into a net increase in carbon fixation of ~0.5–0.8 Tg C yr^{-1} that can have downstream effects on organic matter export, bacterial remineralization, and oxygen demand in deeper layers, though further analysis would be needed to evaluate these effects.

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4. Discussion

The biogeochemical dynamics are strongly influenced by vertical transport processes (Levy et al., 2001; Mahadevan, 2016). Our simulations demonstrate that enhancing the temporal frequency of ocean dynamics forcing the biogeochemistry from 24-hour (24H) to 6-hour (6H) frequency, while keeping the spatial resolution fixed, induces relevant changes in transport processes, which propagate into the BGC system mainly through vertical dynamics. In particular, kinetic energy intensification affects chlorophyll, nitrate, and oxygen vertical dynamics, redistributing key ecosystem properties such as the DCM, the nitracline depth, and the winter mixed layer depth (MLD). This redistribution results in changes to the vertically integrated npp, although horizontal patterns remain largely unaffected.

Our analysis shows that different physical processes dominate in different seasons: vertical advection during winter and vertical diffusion during summer. In particular, during winter the use of 6H forcing led to an approximate 15% increase in vertical advective transport energy, while the contribution from vertical diffusion decreased. Better representation of convective mixing events, supplying nutrients to the surface, produced a patchy increase of npp.

In summer, the 6H forcing introduced sub-daily variability in vertical diffusion (Fig. 5) that enabled pulses of nutrients to penetrate the DCM layer, thereby sustaining phytoplankton growth even in oligotrophic conditions. These mechanisms are consistent with previous findings (Lévy et al., 2001; Omand et al., 2015; Gruber et al., 2011), which emphasized the role of vertical transport in driving sub-seasonal productivity variability.

Our results showed that the increased forcing frequency has a larger positive impact on the model quality in winter than in summer at surface (Fig 9, Tabs.3-5). The reductions in RMSD in some regions suggest that 6H forcing can improve surface bloom timing and amplitude during dynamically active periods (e.g., winter-spring transition). Regions like the Southwestern Mediterranean (swm), known for intermittent frontal activity and mesoscale eddies (Menna et al., 2019a), appear more sensitive to enhanced temporal resolution of ocean dynamics. The benefits of 6H forcing are less evident in highly stratified or oligotrophic regions (e.g., central Levantine, lev2), where vertical transport processes have weaker surface impacts. These results confirm that sub-daily forcing affects bloom timing and amplitude in dynamical regions, but it has a limited impact under strongly stratified conditions, where surface chlorophyll is often dampened by biological response timescales and light-driven adaptation, in agreement with Herrmann et al. (2010) and Auger et al. (2011). In general, there is no single universal relationship between energy of ocean dynamics and productivity: increasing ocean kinetic or eddy kinetic energy can either enhance or suppress net primary production (npp), depending strongly on region and mechanism (Gruber et al., 2011; Lu et al., 2018).

Indeed, our work confirms that the relationship between vertical dynamics and productivity, which are related to variations in nutrient transport, depends on the season and on the region.

A productivity enhancement arises from intermittent vertical nutrient entrainment events that episodically inject nutrients from subsurface layers into the euphotic zone. Rather than responding linearly to mean nutrient fluxes, phytoplankton productivity appears to be particularly sensitive to high-frequency physical variability that intensifies vertical exchanges across the nutricline. The biological response to vertical transport exhibits a pronounced depth dependence. Maximum sensitivity is not observed at the surface, where nutrients are generally depleted, but rather near the nutricline and within the deep euphotic layers, where small perturbations in vertical

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transport substantially modify nutrient availability. This vertical structure of the response highlights the importance of resolving fine-scale physical dynamics to accurately represent biogeochemical feedback. Similar mechanisms linking mesoscale and sub-mesoscale dynamics to enhanced nutrient supply and productivity have been documented in observational and modelling studies (e.g., McGillicuddy et al., 1998; Mahadevan et al., 2012). Seasonal modulation further regulates the magnitude of the response. During summer stratification, when vertical mixing is strongly suppressed and nutrient limitation intensifies, episodic mixing events become disproportionately important for sustaining productivity. Under these conditions, transient physical disturbances can penetrate the nutricline and stimulate short-lived but significant increases in primary production (Fig. 6 and 7). This mechanism is particularly evident in oligotrophic regions such as the eastern Mediterranean Sea, where chronic nutrient limitation—especially phosphorus limitation—renders ecosystem productivity highly sensitive to pulsed nutrient inputs (Krom et al., 1991; Moutin and Raimbault, 2002).

The regional variability observed in the model results reflects differences in stratification intensity, nutricline depth, and background trophic state. In the ultra-oligotrophic eastern Mediterranean, productivity appears tightly coupled to the frequency and intensity of intermittent nutrient injections (not shown), reinforcing the need to adequately represent high-frequency physical variability in coupled physical–biogeochemical models. Overall, these findings support the growing body of evidence indicating that episodic and small-scale physical processes play a critical role in regulating marine primary production, particularly in strongly stratified and nutrient-depleted environments.

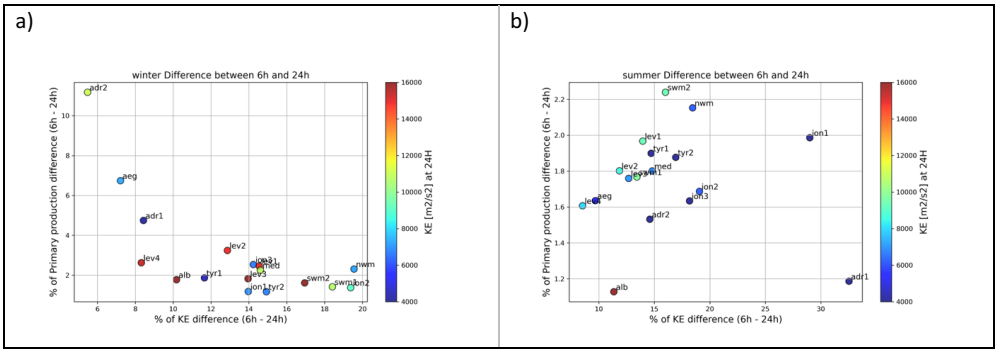

Figure 11: Winter (a) and summer (b) relationship between npp and KE_{TOTAL} for the model system when forcing changes from 24H (orange dot) to 6H (blue dot). Each dot represents the pair of the mean seasonal values for (KE_{TOTAL}, npp), for each subbasin.

To support the nonlinear relationship between ecosystem productivity and energy of ocean dynamics, Figure 11 shows that in winter a KE_{TOTAL} increasing range by 6–20% is associated with a weak response of npp, generally lower than 4%, and spatially scattered. Only western sub-basins exhibit a moderate positive relationship between increases in KE_{TOTAL} and in npp, while most of the regions shows little sensitivity of biological production to enhanced energy due to the high frequency physical forcing. This indicates that, under wintertime conditions, when the upper ocean is weakly stratified and nutrient-replete, additional kinetic energy does not translate efficiently into enhanced biological productivity. In contrast, summer exhibits a coherent and statistically significant coupling between positive variations of KE_{TOTAL} and of npp (correlation ≈ 0.7). The transition from

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24-hour to 6-hour forcing frequency leads to KE_{TOTAL} increases of 10–30% and to concomitant npp enhancements of up to ~20% in several basins. This robust relationship highlights that under strongly stratified, nutrient-limited summer conditions, sub-daily physical forcing substantially strengthens mesoscale and sub-mesoscale dynamical activity, thereby enhancing vertical and lateral nutrient fluxes into the euphotic zone and stimulating phytoplankton production.

These results emphasize that biological productivity is sensitive not only to nutrient availability but also to the amount and structure of energy available for vertical and horizontal transport. As previously demonstrated by Lévy et al. (2001, 2012a), the spatial resolution of the physical model can control the production of sub-mesoscale motions that shape nutrient pathways. Our findings extend this idea by showing that also the temporal resolution of the physical dynamics plays a critical role in shaping these biogeochemical responses.

While the analysis could have included higher frequencies (e.g. 4-hours or 2-hours) to further enhance the representation of the physical-biogeochemical interactions toward online coupling, our experiment was constrained by the computational feasibility as this would have required a 4-fold increase in memory usage and storage for the physical fields. Additionally, our physical-biogeochemical model system uses offline atmospheric forcing at 6-hour frequency, rather than a fully coupled ocean-atmosphere system, which could better represent transient events like storms and their feedback on mixing and productivity (Liu et al., 2019), though impacting onto the computational needs related to operational production.

5. Conclusions

Through numerical experiments, this study demonstrates that the sub-daily temporal forcing frequency of ocean dynamic fields resolution of physical forcing is a critical factor for biogeochemical models to accurately represent the variability of primary production in the Mediterranean Sea, particularly when mesoscale dynamics are resolved. We quantify a variable link between the energy of transport processes associated with temporal variability of ocean dynamics and the observed increase in primary production.

Enhancing the temporal resolution of physical forcing from daily to sub-daily frequencies not only improves the basin-scale agreement of the biogeochemical model with in-situ and satellite observations but also increases the realism of vertical processes at the mesoscale, as evidenced by comparisons with individual float profiles. A better representation of short-lived mixing and convective events drives significant changes in bloom dynamics, DCM structure, and nutrient availability, with distinct seasonal responses. In winter, higher frequency forcing enhances advective processes that promote nutrient upwelling and bloom initiation, while in summer, intensified diffusion in subsurface layer leads to a broader DCM layer and increased subsurface productivity.

By strengthening the consistency between physical and biogeochemical components, these findings contribute to the ongoing improvement of the Mediterranean biogeochemical analysis and forecast model system within the EU Copernicus Marine Service.

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6. Appendix A

Additional plots for KE_{TOTAL} and KE_{RATIO} spatial distribution.

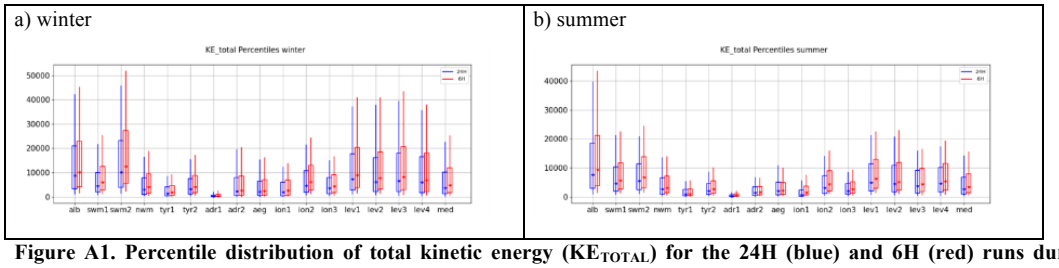

Figure A1. Percentile distribution of total kinetic energy (KE_{TOTAL}) for the 24H (blue) and 6H (red) runs during winter (a) and summer (b) across 16 Mediterranean sub-basins and for the basin as a whole (med). For each boxplot, the asterisk indicates the median value (50th percentile), while the lower and upper bounds of the box represent the 25th and 75th percentiles, respectively. The whiskers extend to the 10th and 90th percentiles, capturing the spread of sub-seasonal variability. Units are expressed in $m^4 s^{-2}$.

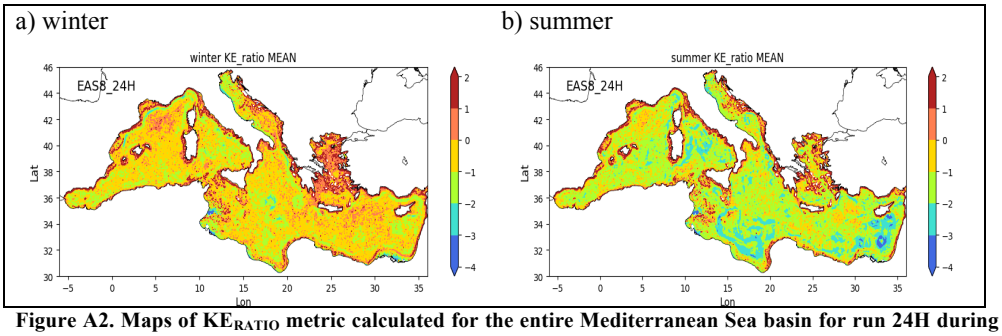

Figure A2. Maps of KE_{RATIO} metric calculated for the entire Mediterranean Sea basin for run 24H during (a) winter and (b) summer. Quantities are expressed in log10.

Data availability

This work has been conducted using EU Copernicus Marine Service Information; in particular, the satellite data used for the simulation validation were obtained from the Copernicus Marine Service (CMEMS) Ocean Colour Thematic Assembly Centre (OC-TAC).

The BGC-Argo data used for the analysis were collected and made freely available by the International Argo Program and the national programs that contribute to it. (https://argo.ucsd.edu, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System.

Author contributions

LF, GC and SS conceived the idea. GB performed the simulations. LF and GB validated the simulations. LF conducted the formal analysis. SS and GC supervised the work. LF wrote the first draft with contributions from all co-authors. All the authors discussed the submitted manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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