Near Inertial Oscillations and Vertical Velocities Modulating Phytoplankton After a Storm in the Mediterranean Sea

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Abstract: Understanding the impact of storms on phytoplankton dynamics is a complex and crucial issue, both on regional and global scales. Here we address this question by conducting a numerical modeling study to represent the physical forcing and phytoplankton response of an intense storm that occurred in the northwestern Mediterranean Sea in late spring 2019. This numerical study, employing the SYMPHONIE regional circulation model, covers and complements in situ observations gathered during the FUMSECK cruise. Our realistic numerical simulation unveils that the storm event triggered robust near-inertial oscillations (NIOs) in a two-layer system, spanning a 5000 km² area and persisting for a duration of 3-4 days. We demonstrate the oscillatory pattern of the NIOs vertical velocities. Notably, our modeled vertical velocities reach a maximum of 10^{-3} m s^{-1} and coincide with a substantial 1.3-fold increase in total chlorophyll concentration. These findings underline the significance of considering the vertical dynamics linked to NIOs induced by meteorological events that are projected to grow both in frequency and intensity in the context of ongoing climate change. The outcomes of this study contribute valuable insights into the intricate relationship between storms and phytoplankton, shedding light on the potential ecological consequences of future climate shifts, and emphasizing the need for more comprehensive investigations to address this complex issue effectively.

Keywords: Near Inertial Oscillations, Vertical Velocities, Storm, Mediterranean Sea

1. Introduction

Near-inertial frequency currents are the most energetic part of the ocean internal wave spectrum and are commonly observed throughout the ocean depth [1]. Inertial or near inertial oscillation (NIO) is a ubiquitous feature of oceanic motions, and can be found at all depths and latitudes of the global ocean. NIOs are generated by two distinct mechanisms: either by the propagation of long gravity waves within a stratified water column, or by the relaxation of a forcing by a strong local wind [2]. Studies based on idealistic models for open ocean oligotrophic regions have shown the impact on phytoplankton biomass and biogeochemistry of intermittent energetic movements forced by oscillatory winds of near inertial frequency [3, 4]. These studies show how these events can impact deep mixing layers, inducing intermittent nutrient supplies, and sustain phytoplankton growth.

In May 2019, the FUMSECK cruise (Facilities for Updating the Mediterranean Submesoscale - Ecosystem Coupling Knowledge, [5]) took place in the Ligurian Sea, and was marked by a short but very intense storm leading to inertial oscillation dynamics. This meteorological event can be qualified as exceptional with a semi-decennial to decennial occurrence for this period of the year in the Liguro-Provençal

region [6]. The storm forced the interruption of in situ sampling for 24 hours. In order to complement the in situ dataset, limited in time and space by its nature, we use a 3D realistic numerical ocean circulation model. The SYMPHONIE model [7] is particularly adapted to both the process and the area under study. It has proved useful and efficient in previous studies in the northwestern Mediterranean Sea to study phenomena such as deep convection and associated submesoscale frontal processes [8-10], shelf dense water formation and cascading along the slope [11-13] or, coupled to the biogeochemical model Eco3M-S, to assess biogeochemical budgets [14, 15]. In the present paper, the coupling with the Eco3M-S model allows us to observe the response of biogeochemical variables characterizing the primary productivity of the study area in response to physical forcing in the study area. Considering that changes in both the frequency and the intensity of Mediterranean storms are expected [16, 17], this knowledge is important for assessing the impact of climate change on the ecology and biogeochemistry of the Mediterranean Sea.

The inertial oscillations are commonly described by their horizontal velocity components. Nevertheless, the vertical component of the current generated by these oscillations can have important consequences on the biology of the euphotic layer. In this paper we describe the structure and evolution of near inertial motion generated by an intense late spring storm (of a few hours on 5 May 2019) in the northwestern Mediterranean Sea. The objective of this work is to highlight the importance of the vertical velocities generated by NIOs and the impact of this event on phytoplankton response.

2. Materials and Methods

2.1. The Numerical Models

In this study we performed an offline coupling between the 3D regional ocean circulation model SYMPHONIE [7, 18, 19], and the biogeochemical model ECO3M-S [14], implemented for the whole Mediterranean Sea [19]. The version of the SYMPHONIE ocean circulation model is based on the Boussinesq and hydrostatic approximations discretized on a curvilinear Arakawa C horizontal grid and a hybrid generalized-sigma and step vertical grid. The numerical domain covers the whole Ligurian Sea with a resolution between 2 and 4.5 km, with 60 vertical levels, as described in [19]. The atmospheric forcing is calculated using bulk formulas applied to the ECMWF (European Centre for Medium-Range Weather Forecasts) hourly forecasts. Tidal forcing is taken into account, and the hydrodynamic model is initialized in April 2011 as described in [19]. Numerical simulations end on 20 May 2019.

The biogeochemical model Eco3M-S is a multi-nutrient and multi-plankton functional type model that simulates the dynamics of the pelagic planktonic ecosystem and the cycles of carbon, nitrogen, phosphorus, silicon, and oxygen. It was forced offline by hourly outputs of the hydrodynamic model. The advection and diffusion of the biogeochemical variables were calculated using the QUICKEST (QUICK with Estimated Streaming Terms) scheme [20] on the horizontal and with a centered scheme on the vertical.

2.2. Analysis of the Model Outputs and Sensitivity Tests

A comparison between modeled and observed data was performed with in situ physical and biogeochemical measurements from the FUMSECK cruise. The three components of the oceanic currents were directly measured with a Sentinel V50 Acoustic Doppler Current Profiler [21]. For the hydrological variables (temperature, conductivity, pressure), two CTD probes (shipborne SBE911 system and RBR concerto) were used. Chlorophyll concentration from the Eco3M-S model was compared with glider measurements performed during the FUMSECK cruise. The glider trajectory, deployed on 1 May 2019, crossed one of the modeled stations (station 4, Figure 1) twice before the storm, and was recovered on the morning of 6 May 2019. The in situ data calibration and glider trajectory are both described in [6].
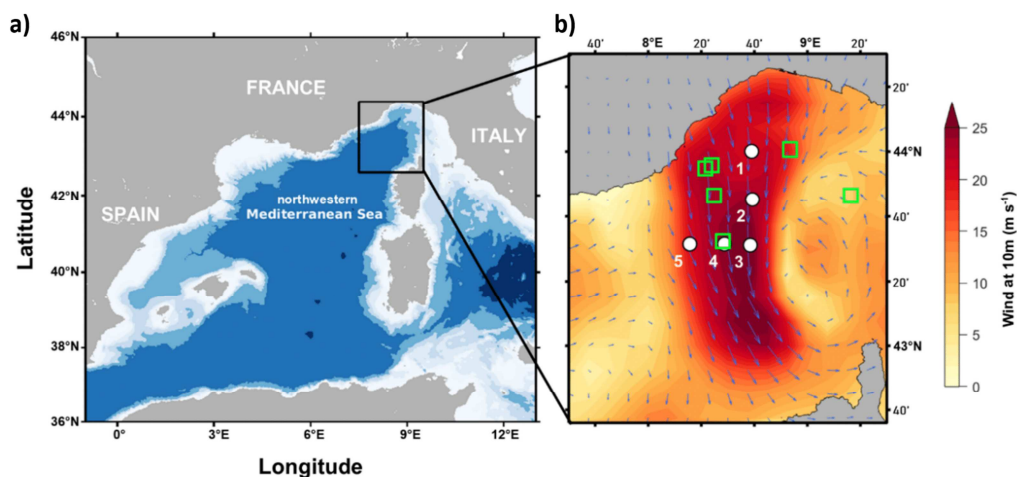
**Figure 1.** *(a) Map of the bathymetry of the northwestern Mediterranean basin. (b) Zoom on the Ligurian Sea with the position of the chosen model stations (white points). Winds intensity and direction (ECMWF forecasts) at 10 m for 5 May 2019, 07:30 am are represented respectively by the color of the map and by the arrows. The green squares represent the positions of in situ sampling used for comparison.*

We focused our study on stations located along the axis of the wind corridor generated by the storm as well as along its perpendicular axis (Figure 1, stations 1 to 5). All the five stations behave similarly, and we presented the results of station 4, corresponding to one of the in situ sampling before the storm (4 May 2019). We used the threshold method of de Boyer Montegut [22] defining the Mixed Layer Depth (MLD) as the depth at which the temperature difference from a reference near-surface depth fixed at 10 m reaches a threshold value of 0.2°C. Sensitivity tests were carried out to discern the impact of wind and tide on NIO triggering. To this end, four simulations were carried out in which wind and tidal forcing were either taken into account or not. These conditions were applied from January 2019.

3. Results

In situ data were collected during the FUMSECK cruise over six vertical profiles (see locations of green squares in Figure 1) between the surface and 150 to 200 m depth, and presented in both [6] for the hydrological part and [21] for the hydrodynamic part. Here we compared the modeled outputs with these in situ datasets (Figure 2).
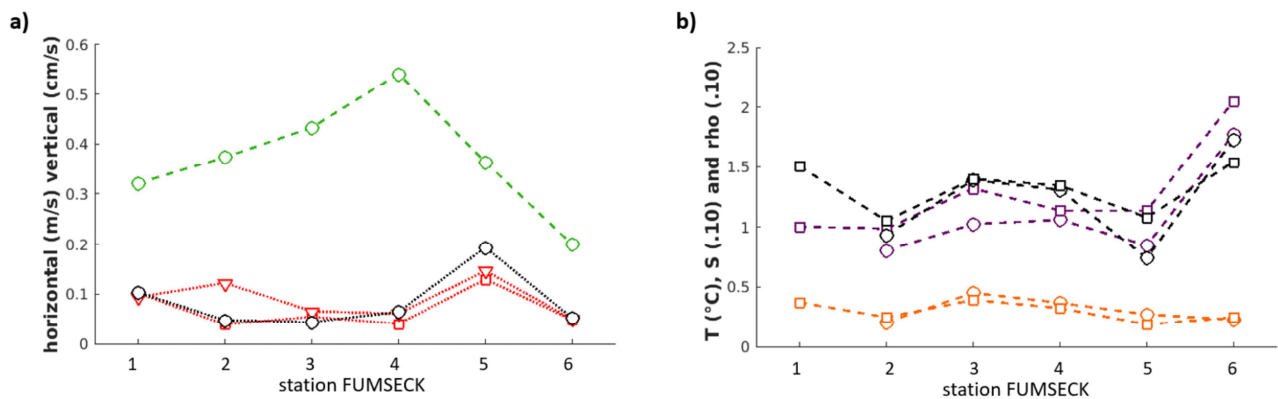
Figure 2. Representation of root mean square deviations (rmsd) between modelled data and in situ data measured at the 6 "vertical velocity" stations of the FUMSECK cruise. (a) rmsd of current data: u (red squares), v (red triangles), √(u² + v²) (black), and w (green). (b) rmsd of hydrology data: temperature (orange), salinity (× 10, purple), density (× 10, black). The square and round symbols represent the calculation based on in situ measurements from the CTD SBE 911 and RBR concerto respectively.
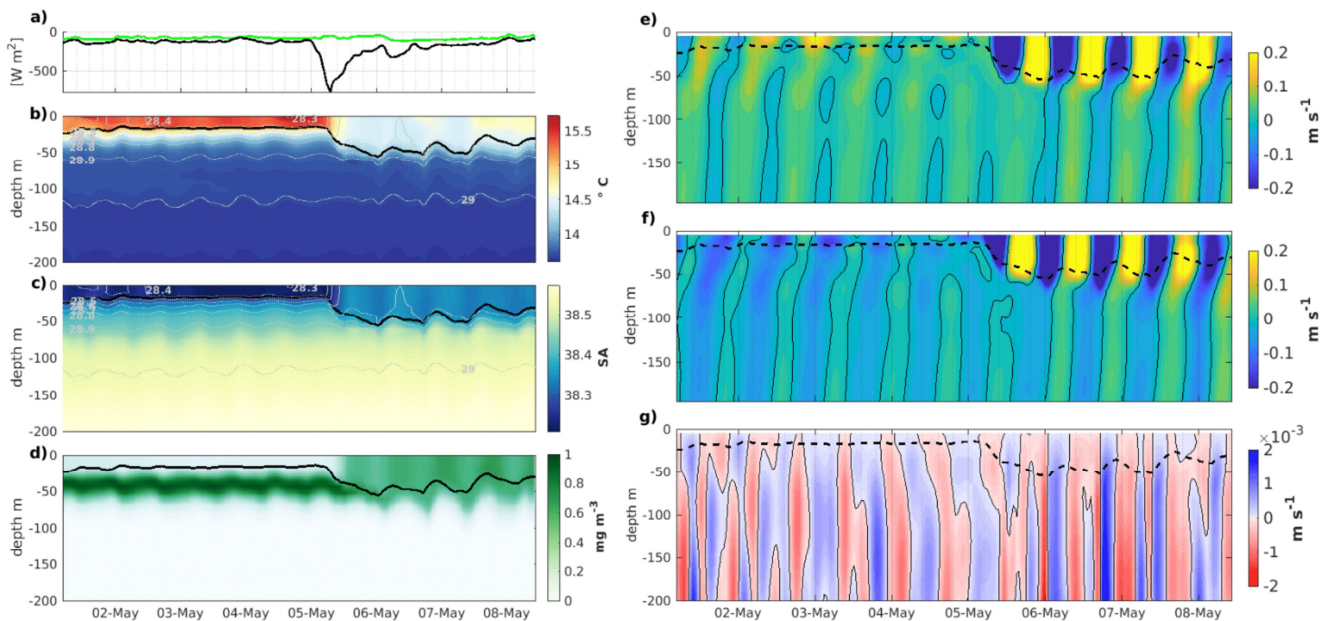
Figure 3. Modeled station 4: (a) total surface fluxes in black (latent and sensible heat fluxes) and longwave in green (negative sign corresponds to fluxes directed from the ocean towards the atmosphere), (b) temperature, (c) salinity, (d) total chlorophyll concentration, (e) eastward velocity component, (f) northward velocity component, and (g) vertical velocity component, with MLD in black dotted line for panel (b) to (g).

These comparisons based on root mean square deviation (rmsd) pointed out that the modeled hydrology variables were in good agreement with the in situ measurements, with rmsd inferior to 0.5°C for temperature, 0.15 for absolute salinity and 0.2 kg m^{-3} for density. These agreements have been demonstrated in other studies using the SYMPHONIE model

and including the entire northwestern Mediterranean Sea [9, 23]. The general circulation in the study area simulated by the model was in good agreement with the in situ data. This circulation is generally cyclonic and characterized by a strong westward-flowing coastal current [24]. The comparison indicated that the intensity of the horizontal components of the numerical current velocity was of the same order of magnitude as the in situ one. The numerical vertical velocities reached a maximum of 10^{-3} m s^{-1}. They were in the range of the observed data whose precision, with the methodology used during the FUMSECK cruise, was several 10^{-3} m s^{-1}. The in situ chlorophyll concentration integrated on 200 m depth was 2 - 3 times its numerical counterpart, with a relatively limited variation over time. Hence we used the model for its ability to reproduce the biological temporal variability.

The effect of the storm on the water column for the modeled station 4 was analyzed through different parameters: hydrological (temperature and salinity), physical (heat flux and currents) and biological (total chlorophyll concentration), gathered in Figure 3. We note a deepening and an oscillation of the mixed layer (ML) and a dilution of the Deep Chlorophyll Maximum (DCM) a few hours after the storm. This ML deepening was a direct result of the mixing induced by the wind, leading to a loss of heat from the ocean to the atmosphere (more than 250 W m^{-2}). The strong constraint of the storm led to the destratification of the first 60 m of the water column associated with a decrease in surface temperature, the disappearance of the DCM and finally to homogeneous chlorophyll within the ML. We noted an asymmetry in the oscillation of the calculated MLD: the ML deepens slower than it ascents. A salinity oscillation was also observed (Figure 3 c), with ML salinity decreasing when MLD thickness increased and inversely.

The storm intensified each current component by a factor of 2 to 3 (Figure 3 e to g). However, the horizontal components were intensified only in the ML, while the vertical component was intensified from the surface to beyond 200 m. The wind peak during the storm not only intensified the three current components, but also triggered horizontal current ellipses. They are typical of near inertial oscillations, with clockwise rotation (Coriolis force in the Northern Hemisphere) whose period is very close to the inertial period at this latitude ($T_{NIO} = 16.7$ h vs. $T_{inertial} = 17.4$ h at 43.53 °N, $T_{NIO} = 0.96$ $T_{inertial}$). The first complete period of current ellipses for each of the five stations modeled was illustrated in Figure 4. The current ellipses were triggered starting with station 2 and then station 3 at 7:00 am and 9:00 am respectively on 5 May. NIO triggering continued at 10:00 am of the same day at stations 1 and 4, then at 12:00 am at station 5. Oscillations were triggered concentrically, with a marked westward propagation; the epicenter being located directly below the wind vein, as shown in Figure 4. The windy episode produced by the storm thus triggered NIOs over an area of around 5000 km² in the course of 5 hours. East of the wind vein (corresponding to stations 1 to 3, Figure 1) the model showed no inertial oscillation of the water mass.
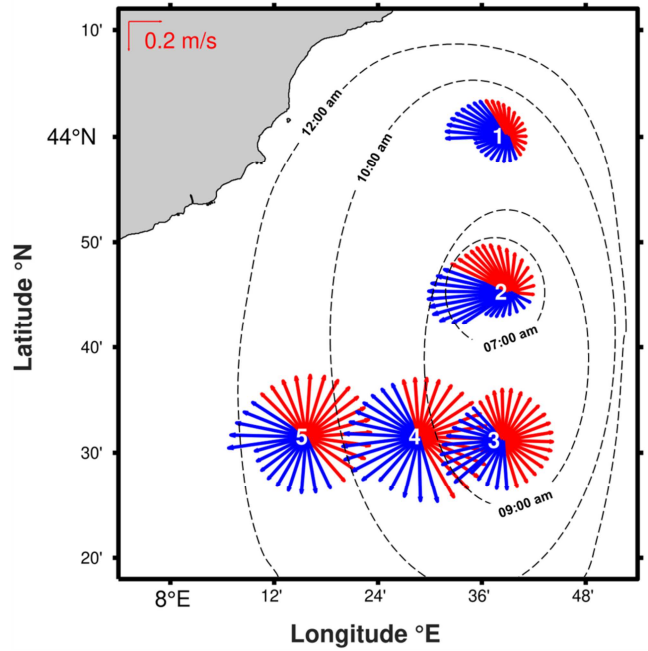
Figure 4. *Near inertial oscillations at 30 m, vectors of horizontal currents shown over their first period, with upward / downward vertical velocity in blue / red. The trigger time for each of the current ellipses is schematized by the dotted lines, for 5 May 2019.*

In the vertical plane, we observed a horizontal oscillation of a two-layer system in phase opposition, more intense in the upper layer than in the lower one, associated with a homogeneous vertical oscillation on the 0 - 200 m layer (Figure 3 g). The frequency of oscillation, slightly higher than the inertial period ($f_{NIO} = 1.04$ f_C Coriolis frequency), means that the oscillation system was not strictly horizontal but slightly tilted, by less than one degree (from the dispersion relationship of internal gravity wave), with respect to the horizontal gravimetric plane. Therefore, wave propagation at this angle ($\theta < 1$ °) implies an associated vertical component (i e. $w = tan(\theta) \times U \approx 0.01 \times 0.1 = 1 \times 10^{-3}$ m s^{-1}), corresponding to the order of magnitude of the modeled vertical velocities. This produced an intensification of the vertical component of the current, with a sinusoidal oscillation synchronized with the horizontal components (Figure 3 e to g). We observed that this effect on the vertical velocity did not occur immediately after the triggering of the two-layer horizontal oscillation system, but after a slight relaxation time of the order of 8 to 9 hours (i e. roughly half the Coriolis period).

The variability in power spectrum of the various sensitivity test simulations was noticeable. Both the wind and no-tide simulations as well as the realistic one have the highest power at the sub-inertial 16.7 h period (Figure 5), mentioned previously. The sensitivity tests showed that the tidal phenomenon, and in particular its semi-diurnal harmonic (12.3 h), contributed to the intensification of vertical velocities during the triggering of NIOs by the wind.
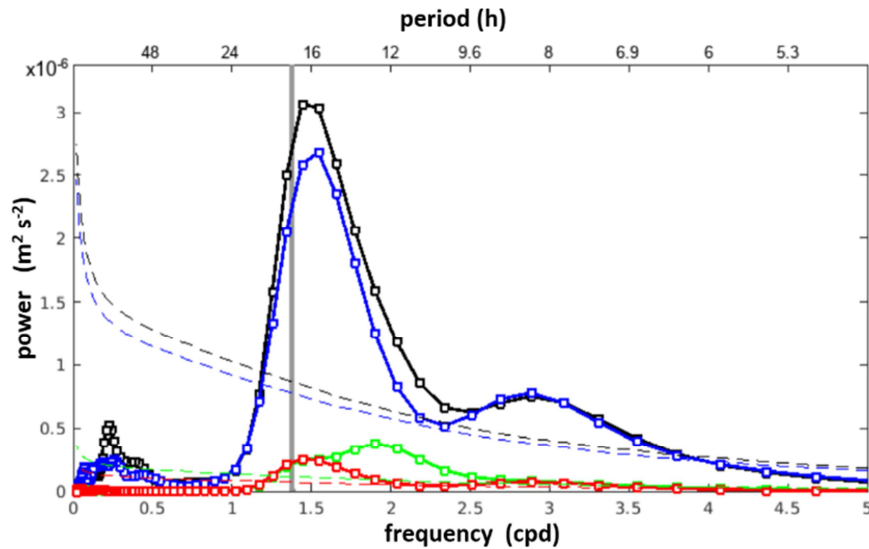
Figure 5. *0 - 200 m averaged global wavelet spectrum of vertical velocities (station 4) from four different simulations: wind + tide in black, wind + no tide in blue, no wind + tide in green, and no wind + no tide in red; with in gray: inertial frequency (also inertial period) for the model station's latitude (43.5 − 44 °N). The dotted lines represent the cone of influence of each simulation, following the wavelet analysis method of [25].*

4. Discussion

The vertical velocity oscillation generated by NIOs modulated the variation in total chlorophyll concentration during the first 24 hours, with an increase in integrated total chlorophyll concentration that persisted for several days (Figure 6 a). The increase in surface chlorophyll concentration was related to two associated processes: i) the mixing of the DCM with advection of chlorophyll from the DCM toward the surface, and ii) a significative increase (factor 1.3 between 5 and 7 May) of the total chlorophyll concentration integrated over the first 200 m.
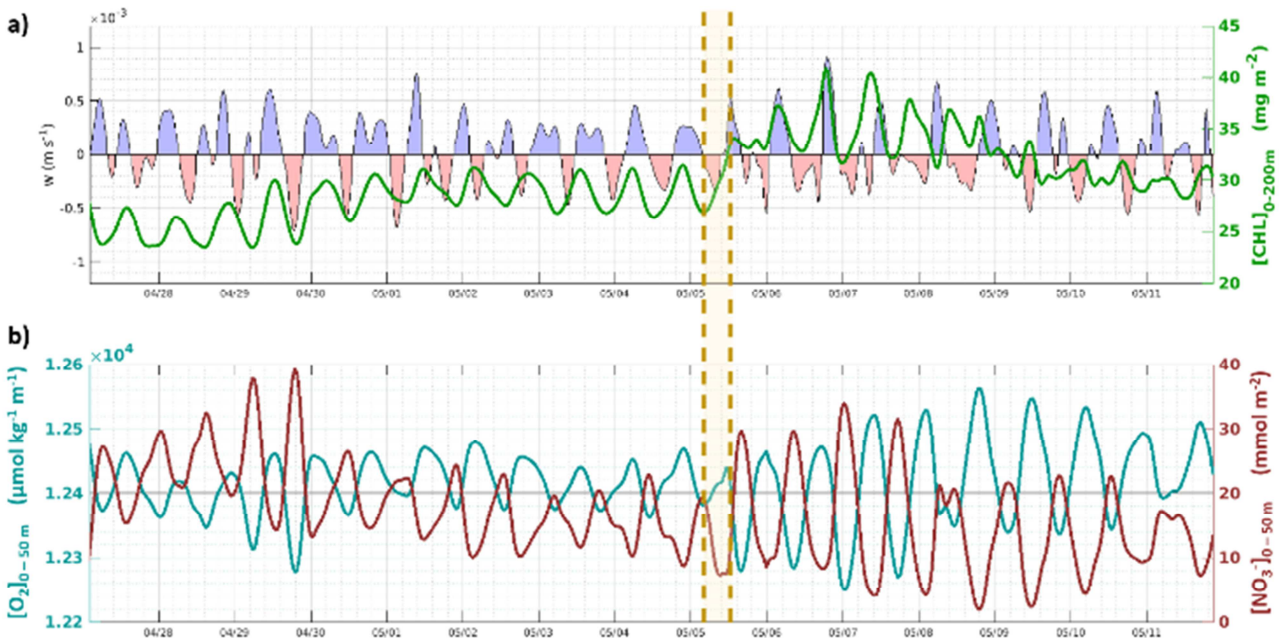
Figure 6. *(a) Chlorophyll concentration integrated between 0 - 200 m depth, superimposed on numerical vertical velocities at 40 m, at station 4. (b) Dissolved oxygen and nitrate concentrations integrated over 0 - 50 m depth at station 4. The period of storm activity is shown in yellow.*

Furthermore, the nitrate and dissolved oxygen concentrations represented by the model respond in two distinct times to the storm (Figure 6 b). Firstly, the intensification of vertical velocities by the triggering of NIOs increases the variability of integrated concentrations in the first 200 m, and more specifically in the 0 - 50 m layer. Secondly, when the maximum chlorophyll concentration is reached, the average nitrate concentration decreases and that of oxygen increases, despite vertical velocities maintaining the amplitude of their variability.

These results explain the observations by [6], who described the dilution effect of DCM but did not observe any increase in the integrated biomass, since the cruise had to end before the increase could occur. Moreover, [6] highlighted an increase in surface concentration of nitrates and particulate organic carbon. This fact, if combined with our numerical simulations showing a cooling of the surface water, an intensification of vertical velocities, an increase in chlorophyll concentration and a synchronization of oscillation of the latter two, allow us to show how the vertical velocities generated by NIOs generated a favorable environment for phytoplankton development.

In their study, [26] analyzed a series of hurricanes generating inertial oscillations and highlighted the establishment of inertial pumping associated with an isopycnal displacement of at least 10 m. Although the storm during FUMSECK cruise was not comparable in intensity to the hurricanes described, we found the same characteristics of deepening and oscillation of the MLD, with isopycnal displacement of 10 - 15 m. These authors also insisted on the impact of hurricanes on the upper ocean biogeochemistry as well as on the global nutrient and carbon budgets. Considering that changes in both the frequency and the intensity of Mediterranean storms are expected [16, 17], in the future it will be necessary to evaluate the impacts of these weather events, both locally and on a global scale. Such a storm can be considered as an important case study of the physical – biogeochemical coupling, especially under stratified surface oligotrophic conditions, as in the Ligurian Sea.

5. Conclusion

The upper-ocean responses to an intense late spring storm have been described. This study, based on a regional hydrostatic ocean circulation model, provided a three-dimensional dynamic of near inertial oscillations generated by an intense and rarely occurring meteorological event, compensating for the lack of in situ sampling during the storm. The numerical vertical velocities reached a maximum of 10^{-3} m s^{-1}, in the range of the FUMSECK cruise data precision. They were significantly intensified by the storm and oscillated at the near inertial frequency in synchronization with the horizontal components of the current. This approach highlighted a phenomenon of amplification of the horizontal and vertical velocities, as well as the intensification of the vertical component of the quasi-inertial oscillations in a two-layer system, generally described in the horizontal plane only. We emphasize the need to take into account the influence of these high-frequency vertical velocities on biology and biogeochemistry. Indeed, the analysis of the biogeochemical response to these dynamics results in an increase of the chlorophyll concentration, in phase with vertical velocity oscillations, that is not solely a dilution of the Deep Chlorophyll Maximum in the mixing layer. These results underline the importance of considering the vertical dynamics associated with NIOs induced by events that are becoming increasingly frequent and intense in a context of global change.

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Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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