



Upper-ocean physical and biogeochemical response to Hurricane Norbert in the eastern tropical Pacific

Javier González-Ramírez¹, Luis Soto-Mardones², Jushiro Cepeda-Morales³, Jasmín Granados-Amores¹, and Juan Ramón Flores-Ortega¹

¹Laboratorio de Oceanografía Física, Escuela Nacional de Ingeniería Pesquera, Universidad Autónoma de Nayarit, Bahía de Matanchén, Nayarit, México.

²Departamento de Física, Facultad de Ciencias, Universidad del Bío-Bío, Concepción, Chile.

³Laboratorio de Percepción Remota, Centro Nayarita para la Transferencia de Tecnología, Universidad Autónoma de Nayarit, Tepic, Nayarit, México.

Correspondence: Javier González-Ramírez (javier-gonzalez@uan.edu.mx)

Abstract. Tropical cyclones can strongly perturb the upper ocean through intense wind stress, vertical mixing, Ekman pumping, sea surface cooling, and nutrient injection into the euphotic zone. These processes enhance phytoplankton biomass generation and produce delayed chlorophyll-a responses after storm passage. Here, we investigate the physical and biogeochemical response of the Eastern Tropical Pacific to Hurricane Norbert, a category 4 hurricane that crossed the Mexican Pacific in October 2008. We combine tropical cyclone best-track data from IBTrACS, ERA5 wind forcing, CROCO physical–biogeochemical simulations, satellite-derived sea surface temperature and chlorophyll-a products, and Argo float profiles located near the hurricane track. The results show that Norbert generated strong positive Ekman pumping, mixed-layer deepening, surface nitrate enrichment, and a delayed increase in chlorophyll-a concentration along portions of the storm trajectory. The model reproduced the main structure of sea surface temperature cooling more clearly than the chlorophyll-a response, indicating that the physical response was more directly controlled by hurricane forcing, whereas the biological response was modulated by nutrient availability, pre-existing stratification, light conditions, and regional circulation. Argo profiles confirmed post-storm changes in the vertical thermal structure and mixed-layer depth. These results indicate that major hurricanes in the eastern tropical Pacific can generate significant but spatially heterogeneous biogeochemical responses through the coupling between wind-driven mixing, nutrient entrainment, and phytoplankton growth.

1 Introduction

Tropical cyclones are among the most energetic atmospheric disturbances affecting the upper ocean. Through intense wind stress, air–sea momentum exchange, vertical turbulent mixing, Ekman pumping, and near-inertial motions, these systems can rapidly modify the thermal, dynamical, and biogeochemical structure of the upper ocean (Price, 1981; D’Asaro et al., 2007; Zhang et al., 2021). The most widely documented physical response includes sea surface temperature cooling, mixed-layer deepening, vertical redistribution of heat, and changes in upper-ocean stratification (Liu et al., 2009; Zhang et al., 2021; Wurl and Meyerjürgens, 2024). These processes may also influence tropical cyclone intensity through ocean feedbacks, since the



entrainment of cooler subsurface waters into the mixed layer can reduce the oceanic heat available to sustain the storm (Price, 1981; Mei et al., 2012).

In addition to their physical effects, tropical cyclones can trigger substantial biogeochemical responses. Cyclone-induced mixing and wind-driven upwelling may inject nutrient-rich subsurface waters into the euphotic zone, enhancing phytoplankton biomass and increasing surface chlorophyll-a concentration (Babin et al., 2004; Liu et al., 2009; Zhang et al., 2021). However, the magnitude, timing, and persistence of this biological response are highly variable and depend on storm intensity, translation speed, residence time, pre-storm mixed-layer depth, nutricline depth, background stratification, mesoscale circulation, light availability, and the pre-existing biological state of the region (Lin et al., 2003; Babin et al., 2004; Ma et al., 2021; Chen et al., 2022). Consequently, the chlorophyll-a response to a hurricane cannot be interpreted solely as a function of wind intensity, but rather as the result of coupled physical and biogeochemical processes acting over different temporal and spatial scales.

Recent studies combining satellite observations, Argo profiles, and numerical simulations have improved our understanding of cyclone–ocean interactions in different ocean basins. In the Gulf of Mexico, Hurricane Michael produced marked biophysical changes, including sea surface cooling, mixed-layer deepening, and enhanced biological activity associated with nutrient entrainment (Nyadjro et al., 2021). In the South China Sea, consecutive typhoons generated strong vertical mixing and phytoplankton responses that varied according to the pre-existing oceanic conditions and the cumulative effect of successive storms (Ma et al., 2021). Similarly, satellite and modelling studies have shown that phytoplankton blooms following tropical cyclones are often controlled by the balance between nutrient supply, vertical mixing, light limitation, and post-storm restratification (Chen et al., 2022).

The eastern tropical Pacific (ETP) is a particularly relevant region for studying hurricane-induced upper-ocean responses because it is characterized by strong seasonal and interannual variability, complex coastal circulation, mesoscale activity, and pronounced biogeochemical gradients. The Mexican Pacific is also influenced by coastal upwelling, tropical cyclone activity, and subsurface oxygen-deficient waters, all of which can modulate the vertical distribution of nutrients and phytoplankton biomass. Despite this oceanographic complexity, the coupled physical and biogeochemical response to individual hurricane events in the ETP remains less documented than in other regions such as the Gulf of Mexico, the western North Pacific, and the South China Sea.

Hurricane Norbert, which developed in October 2008 and reached category 4 intensity, provides an opportunity to examine how a major hurricane modifies the upper ocean in the eastern tropical Pacific. Norbert followed a curved trajectory along the Mexican Pacific, producing intense wind forcing over a region previously affected during the same season by Hurricanes Elida and Fausto. This sequence of events provides a useful framework for assessing not only the direct response to Norbert, but also the potential role of preconditioning by earlier storms.

Here, we investigate how Hurricane Norbert modified the physical and biogeochemical structure of the upper ocean in the ETP. By combining wind-derived diagnostics, CROCO simulations, satellite products, and Argo profiles, we analyse the links between hurricane forcing, Ekman pumping, mixed-layer deepening, nutrient enrichment, and the subsequent chlorophyll-a response. The model results are evaluated against satellite-derived sea surface temperature anomaly and chlorophyll-a along



the storm track, while Argo observations provide an independent constraint on the vertical thermal adjustment after storm passage.

2 Materials and methods

2.1 Study area and hurricane events

60 The study was conducted in the ETP, with emphasis on the Mexican Pacific region affected by Hurricane Norbert in October 2008. This region is characterized by tropical cyclone activity, mesoscale variability, coastal upwelling, strong air–sea interaction, and pronounced physical and biogeochemical gradients.

Hurricane Norbert originated as a tropical depression on 4 October 2008, approximately 310 km off the coast of Oaxaca, Mexico, near 14° N and 99° W. It intensified into a hurricane on 7 October and reached category 4 intensity on 8 October, with
65 maximum wind speed close to 59 m s^{-1} and minimum central pressure near 945 mb. The storm followed a curved trajectory across the Mexican Pacific and made landfall on 12 October in northern Mexico, between the states of Sinaloa and Sonora. In addition to Norbert, Hurricanes Elida and Fausto, which developed in July 2008, were considered because they crossed part of the later trajectory of Norbert and may have contributed to preconditioning the upper ocean.

2.2 Hurricane track and intensity data

70 Hurricane track, intensity, maximum sustained wind speed, and minimum central pressure were obtained from the International Best Track Archive for Climate Stewardship database, IBTrACS (Knapp et al., 2010). Six-hourly hurricane positions were used to describe the temporal evolution of Hurricane Norbert and to define storm-centred spatial and temporal windows for the comparison between model outputs and satellite observations.

2.3 Physical ocean model

75 The physical ocean circulation was simulated using the Coastal and Regional Ocean Community model, CROCO. CROCO is a regional ocean modelling system derived from ROMS and designed to represent mesoscale and coastal ocean dynamics using terrain-following vertical coordinates and split-explicit numerical schemes (Debreu et al., 2012). The model domain covered the eastern tropical Pacific between 10 and 35° N and 85 and 120° W. The model was configured with a horizontal resolution of 10 km, a 6 min time step, and 50 vertical sigma levels. Vertical stretching parameters were set to $\theta_s = 4.0$ and $\theta_b = 0.8$. The
80 simulation covered the period 2000–2010, allowing the 2008 hurricane season to be analysed within a broader oceanographic context. Initial and boundary conditions, as well as large-scale oceanic forcing, were derived from GLORYS ocean reanalysis (Lellouche et al., 2018).



2.4 Atmospheric forcing and Ekman pumping

Atmospheric forcing was obtained from ERA5 reanalysis, which provides global atmospheric fields suitable for air–sea interaction studies and tropical cyclone-related analyses (Hersbach et al., 2020). The 10 m wind velocity fields were used to calculate wind stress according to

$$\boldsymbol{\tau} = \rho_a C_d \mathbf{u}_{10} |\mathbf{u}_{10}|, \quad (1)$$

where $\boldsymbol{\tau}$ is wind stress, ρ_a is air density, C_d is the drag coefficient, and $\mathbf{u}_{10}$ is the 10 m wind velocity. An air density of 1.3 kg m^{-3} was adopted, and the drag coefficient was calculated following Wu (1982):

$$C_d = (0.8 + 0.065 |\mathbf{u}_{10}|) \times 10^{-3}. \quad (2)$$

Ekman pumping velocity was estimated from the wind-stress curl:

$$w_E = \frac{1}{f \rho_w} \nabla \times \boldsymbol{\tau}, \quad (3)$$

where w_E is the Ekman pumping velocity, f is the Coriolis parameter, and ρ_w is seawater density, set to 1025 kg m^{-3} . Positive values of w_E indicate upward motion associated with wind-driven divergence, whereas negative values indicate downward motion.

2.5 Biogeochemical model

The upper-ocean biogeochemical response was simulated using a nitrogen-based ecosystem model adapted from Gruber et al. (2006), with regional modifications and parameterizations following González-Ramírez et al. (2023). The model included nitrate, ammonium, phytoplankton, zooplankton, large detritus, and small detritus as state variables. Nitrate initial and boundary conditions were obtained from the World Ocean Atlas (Garcia et al., 2019), whereas ammonium, phytoplankton, zooplankton, and detrital compartments were initialized with small background concentrations. The simulated nitrate and chlorophyll-a fields were used to analyse the temporal and spatial evolution of the biological response after hurricane passage. Particular attention was given to the time lag between wind forcing, mixed-layer deepening, nitrate enrichment, and chlorophyll-a increase.

2.6 Satellite-derived sea surface temperature and chlorophyll-a

Satellite observations were used to evaluate the model representation of the surface ocean response. Daily gap-free sea surface temperature (Worsfold et al., 2024) and chlorophyll-a products (<https://doi.org/10.48670/moi-00281>) were selected to reduce the effect of missing data caused by cloud cover during hurricane conditions. Sea surface temperature anomalies were computed by subtracting a climatological mean from the daily SST fields. Chlorophyll-a concentration was used as an indicator of phytoplankton biomass and biological response to hurricane-induced mixing and nutrient supply.



110 2.7 Argo profiles and mixed-layer depth

Argo float profiles located near the Hurricane Norbert track were used to assess the vertical thermal response of the upper ocean. The selected floats were chosen according to their proximity to the hurricane trajectory and their temporal coverage before and after storm passage. Practical salinity, in situ temperature, pressure, latitude, and longitude were processed using the Gibbs SeaWater Oceanographic Toolbox following the TEOS-10 standard (McDougall and Barker, 2011). Practical salinity
 115 was converted to absolute salinity, and in situ temperature was converted to conservative temperature. Mixed-layer depth was calculated using a density threshold criterion of 0.03 kg m^{-3} relative to a reference depth of 10 m, following Holte and Talley (2009). The evolution of mixed-layer depth before and after Hurricane Norbert was used to identify hurricane-induced vertical mixing and the persistence of the post-storm oceanic response.

2.8 Model–observation comparison

120 The ability of the model to reproduce the observed surface response was evaluated by comparing simulated sea surface temperature anomalies and chlorophyll-a concentrations with satellite observations. For each six-hourly hurricane position, model and satellite fields were spatially averaged within a circular area of approximately 7850 km^2 , corresponding to a 100 km diameter, centred on the hurricane best-track position. Three statistical metrics were used to quantify model performance: Pearson correlation coefficient (r), root mean square error ($RMSE$), and bias:

$$125 \quad r = \frac{\sum_{i=1}^n (S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (S_i - \bar{S})^2 \sum_{i=1}^n (O_i - \bar{O})^2}}, \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (S_i - O_i)^2}, \quad (5)$$

$$BIAS = \frac{1}{n} \sum_{i=1}^n (S_i - O_i), \quad (6)$$

where S_i and O_i are the simulated and observed values, respectively; $\bar{S}$ and $\bar{O}$ are their respective means; and n is the number of paired data points. These metrics were calculated for two periods of intense tropical cyclone activity in 2008: 12–22
 130 July, associated with Hurricanes Elida and Fausto, and 3–12 October, associated with Hurricane Norbert.

3 Results

3.1 Storm evolution and oceanographic setting

Hurricane Norbert crossed a dynamically complex region of the ETP, following a curved trajectory from the southern Mexican Pacific toward the Baja California Peninsula. As shown in Fig. 1, the storm intensified while moving northwestward and



135 reached category 4 strength before weakening near landfall. Along this path, Norbert interacted with offshore waters, the coastal transition zone, and a background ocean state influenced by mesoscale variability and previous tropical cyclone activity. The tracks of Elida and Fausto, also shown in Fig. 1, provide important context for interpreting the ocean response to Norbert. Both storms crossed part of the region later affected by Norbert during the same hurricane season. Their earlier passage may have altered the upper-ocean thermal structure, stratification, nutrient distribution, and phytoplankton background state before
 140 October. This preconditioning is relevant because the biological response to a hurricane depends not only on storm intensity, but also on the pre-storm mixed-layer depth, nutricline position, light environment, and mesoscale circulation. Thus, the response to Norbert should be viewed as the combined result of direct hurricane forcing and the oceanographic conditions inherited from previous disturbances.

3.2 Wind-driven vertical response

145 Norbert generated a strong wind-driven response in the upper ocean. The Ekman pumping field (Fig. 2) shows that, during the early stage of the storm, positive values were mostly confined near the storm centre. As the hurricane intensified, the upward velocities increased and expanded along the trajectory, with the strongest values occurring between 8 and 11 October, when Norbert reached its highest intensity and approached the Baja California Peninsula. Localized Ekman pumping velocities exceeded $5 \times 10^{-4} \text{ m s}^{-1}$, indicating that the wind-stress curl was sufficiently strong to displace subsurface waters toward
 150 the euphotic zone. The corresponding vertical velocity field reinforces this interpretation. Rather than producing a smooth and continuous response along the track, Norbert generated alternating patches of upward and downward motion, as shown in Fig. 4. This spatial structure suggests that the hurricane wind field interacted with pre-existing mesoscale circulation and regional density gradients. Consequently, the potential for nutrient injection was not uniform along the storm path. The most favourable regions for upward nutrient transport were those where wind-driven divergence, background circulation, and upper-ocean
 155 stratification acted together to enhance vertical exchange.

3.3 Mixed-layer deepening and persistence of the physical perturbation

The mixed-layer response developed more gradually than the wind forcing itself. In the first days of Norbert, the simulated mixed-layer depth remained relatively stable over much of the affected region. A clearer deepening emerged after the strongest phase of the storm, especially along and behind the trajectory between approximately 17 and 25° N. This transition is evident
 160 as mixed-layer depths increase from values near 40 m before the storm to nearly 70 m after its passage (Fig. 3). This delay indicates that the upper ocean did not adjust instantaneously to the maximum winds. Instead, the response evolved through turbulent mixing, entrainment, and near-inertial motions that persisted after the storm centre had moved away. The deeper mixed layer is important for the subsequent biogeochemical response because it increased the likelihood of entraining nitrate-rich waters from below the pre-storm mixed layer. At the same time, deepening of the mixed layer may have reduced the
 165 average light exposure experienced by phytoplankton, helping to explain why the chlorophyll-a response was delayed rather than immediate.



3.4 Vertical velocity response

The simulated vertical velocity response showed that Hurricane Norbert generated a spatially structured perturbation of the upper ocean rather than a uniform signal along its trajectory (Fig. 4). During the intensification and mature stages of the storm, upward velocity anomalies reached values of approximately $1.5\text{--}2.5 \times 10^{-4} \text{ m s}^{-1}$ in localized cores near the hurricane track. These positive anomalies indicate wind-driven divergence and the upward displacement of subsurface waters. They were commonly bordered by negative anomalies of similar magnitude, ranging from about -0.5 to $-1 \times 10^{-4} \text{ m s}^{-1}$, associated with convergence and downward motion. The resulting pattern consisted of alternating upwelling and downwelling cells embedded within a broader field of weaker vertical velocities, generally below $0.5 \times 10^{-4} \text{ m s}^{-1}$ away from the storm-induced cores.

This patchy and filamentary structure suggests that the vertical response was shaped by the interaction between the hurricane wind field and the pre-existing oceanic circulation. In particular, the strongest anomalies appeared where storm-induced divergence likely reinforced mesoscale uplift or local density gradients, whereas neighbouring regions experienced compensating downward motion. This behaviour has important implications for the biogeochemical response, because the upward supply of nitrate-rich subsurface waters would not occur uniformly along the entire storm trajectory. Instead, nutrient injection and subsequent biological enhancement would be favoured in localized regions where positive vertical velocities, mixed-layer deepening, and a shallow nutricline acted together. The heterogeneous vertical velocity field therefore provides a physical explanation for the spatially variable nitrate enrichment and delayed chlorophyll-a response observed after the passage of Norbert.

3.5 Surface nitrate enrichment

Before Norbert intensified, surface nitrate concentrations were low across most offshore waters. After the storm moved northwestward and generated stronger vertical exchange, nitrate increased along portions of the hurricane trajectory and near coastal regions. The evolution shown in Fig. 5 suggests that nitrate enrichment was not simultaneous with the first wind forcing, but became more evident after the strongest phase of the storm with values $\sim 6 \text{ mmol m}^{-3}$. This timing supports a physically driven mechanism in which hurricane-induced mixing and upward vertical motion supplied subsurface nutrients to the surface layer. The enrichment persisted after storm passage (13 October to 3 November), indicating that Norbert produced a biogeochemical perturbation that lasted beyond the period of maximum winds. However, nitrate did not increase uniformly along the entire track. Its spatial variability suggests that local stratification, nutricline depth, mesoscale circulation, and coastal influence modulated the efficiency of nutrient entrainment.

3.6 Chlorophyll-a response and biological adjustment

The chlorophyll-a response followed the nitrate enrichment with a clear temporal delay. Enhanced chlorophyll-a concentrations appeared mainly after the strongest wind forcing and were most evident in regions where nitrate had previously increased as shown in Fig. 6. This sequence indicates that the biological response was mediated by nutrient supply rather than by wind forcing alone. The response was spatially heterogeneous, with values ranging between ~ 0.3 and 1.5 mg m^{-3} . Some portions of the storm track showed clear chlorophyll-a enhancement, whereas others exhibited only weak or delayed changes. This



variability indicates that nutrient availability was necessary but not sufficient to determine the magnitude of the phytoplankton response. Light limitation, mixed-layer depth, phytoplankton growth rates, grazing, mesoscale advection, and the pre-existing chlorophyll-a distribution likely contributed to the observed pattern. In this sense, the chlorophyll-a field should be interpreted as the integrated result of physical forcing, nutrient enrichment, and ecosystem adjustment.

3.7 Model-satellite comparison

The comparison between modelled and satellite-derived fields shows that the simulation captured the broad temporal variability associated with the 2008 hurricane season. Both observations and simulations reflected surface changes during the Elida–Fausto period and after the passage of Hurricane Norbert, although the degree of agreement differed between SST anomalies and chlorophyll-a concentration. The model reproduced SST anomalies more consistently than chlorophyll-a concentration (Fig. 7, a-d). The mean differences between modelled and satellite-derived fields were approximately $\sim 0.5^\circ\text{C}$ for SST anomalies and $\sim 0.4\text{ mg m}^{-3}$ for chlorophyll-a concentration. This better agreement for SST is expected, as surface cooling is closely linked to vertical mixing and the entrainment of cooler subsurface waters. The correlations for SST anomalies were approximately 0.71 during the Elida–Fausto period and 0.59 during Norbert (Fig. 7, f), suggesting that the model captured the main structure of the surface physical response. The comparison was more variable for chlorophyll-a. Although the model reproduced part of the observed variability, with correlations of approximately 0.705 during the Elida–Fausto period and 0.445 during Norbert (Fig. 7, e), differences in amplitude and timing remained evident. These discrepancies likely reflect the greater complexity of the biological response and the limitations of both modelled and satellite-derived chlorophyll-a. Ocean-colour estimates can be affected by cloud contamination, atmospheric correction uncertainties, coloured dissolved organic matter, suspended particles, and the presence of subsurface chlorophyll maxima. In addition, phytoplankton growth, mortality, grazing, and photoacclimation introduce biological time scales and nonlinear responses that are more difficult to reproduce than the more direct physical signal represented by SST.

3.8 Along-track coupling between nitrate and chlorophyll-a

The along-track evolution of nitrate and chlorophyll-a provides a more integrated view of the physical-biogeochemical coupling during the 2008 hurricane season. In Fig. 8, nitrate increases appear first around specific storm positions, followed by chlorophyll-a enhancement. This temporal ordering supports the interpretation that vertical nutrient injection was a key mechanism driving the biological response. The Norbert period produced a stronger and more persistent signal than the Elida–Fausto period. During Elida–Fausto, enrichment in nitrate and chlorophyll-a was more localized, whereas Norbert generated a broader and longer-lasting response. This contrast suggests that Norbert encountered oceanographic conditions that were more favourable for nutrient entrainment and phytoplankton growth. Nevertheless, the earlier storms may have contributed to the October response by modifying stratification, nutrient availability, or the background chlorophyll-a field before Norbert arrived.



230 3.9 Subsurface thermal and chlorophyll-a structure

The Argo profiles provide independent evidence that Norbert modified the vertical structure of the upper ocean. The temperature profiles show post-storm cooling and vertical redistribution of heat within the upper tens of metres. In the locations of profiles 4900323 and 3900605, which were closer to the hurricane path, it was possible to observe a diminution of the upper ocean layer from ~ 23 to 28°C in the 4900323 profiler and from ~ 22 to 28°C in the profile 3900605, we also observed
 235 the mixed layer deepened after the passage of the storm in both panels (Fig. 9, b and c), which was consistent with the simulated mixed-layer evolution. Although the spatial and temporal coverage of the available Argo profiles was limited, these observations support the interpretation that Norbert generated a measurable subsurface physical response.

The simulated vertical chlorophyll-a profiles (Fig. 10) indicate that the biological response was not restricted to the surface. Some storm positions show subsurface chlorophyll maxima between approximately 10 and 40 m depth, whereas other locations
 240 remain comparatively low throughout the upper water column. This vertical variability suggests that hurricane-induced mixing affected both the concentration and depth distribution of phytoplankton biomass. In some cases, the response reflected the vertical redistribution of an existing subsurface chlorophyll maximum, with values ranging between ~ 0.4 and 0.8 mg m^{-3} as we can observe in Figure 10, d-f; in others it is involved new phytoplankton growth (Fig. 10, d-f) supported by nitrate enrichment provided from P30 to P60 with nitrate values from ~ 2 to 4 mmol m^{-3} as we can observe in Figure 8 panel d.

245 4 Discussion

The response to Hurricane Norbert reveals a coherent sequence of coupled physical and biogeochemical processes in the eastern tropical Pacific. The storm first imposed intense wind forcing on the upper ocean, producing wind-stress curl, Ekman pumping, vertical mixing, and mixed-layer deepening. These processes then favoured the upward transport of nitrate-rich subsurface waters into the euphotic zone, creating conditions for a delayed increase in chlorophyll-a. The response, how-
 250 ever, was not spatially uniform. Instead, it varied along the storm track, reflecting the influence of pre-existing stratification, mesoscale circulation, nutricline depth, and the vertical distribution of phytoplankton biomass. This behaviour is consistent with the broader understanding of tropical cyclone-ocean interaction. Strong wind stress and near-inertial motions can deepen the mixed layer, cool the surface ocean, and entrain subsurface waters into the mixed layer. The results for Norbert show this physical response clearly: Ekman pumping was strongest during the most intense phase of the storm, while the mixed layer
 255 continued to deepen after the storm had moved away. This delayed adjustment is important because the biological response depends on the accumulated effect of mixing and nutrient supply rather than on instantaneous wind intensity alone. The nitrate response provides the clearest link between the physical perturbation and the biological signal. Surface nitrate increased after the strongest wind forcing and was most evident in regions where mixed-layer deepening and upward motion also developed. This supports the interpretation that Norbert injected nutrient-rich waters into the upper ocean. Similar mechanisms have been
 260 described in other hurricane-affected regions. Walker et al. (2005) showed that Hurricane Ivan generated strong upwelling, surface cooling, and chlorophyll-a enhancement within cold-core cyclones in the Gulf of Mexico, demonstrating that mesoscale circulation can amplify the biological response to hurricane forcing. This comparison is especially relevant for Norbert be-



cause the simulated vertical velocity field also showed patchy structures that suggest modulation by mesoscale variability. The delayed chlorophyll-a response after Norbert is also consistent with previous studies. In oligotrophic and stratified regions, hurricane-induced blooms typically require a sequence of processes: wind-driven mixing must first reach nutrient-rich waters, nutrients must then become available in the euphotic zone, and phytoplankton biomass responds over biological growth time scales. Babin et al. (2004) showed that surface chlorophyll increases in hurricane cold wakes can persist for 2-3 weeks, while Liu et al. (2009) attributed the Katrina-induced bloom to the combined effect of a pre-existing cold eddy and the slow passage of the storm. The Norbert case follows this same conceptual framework, but with a response that is strongly shaped by the eastern tropical Pacific's regional stratification and biogeochemical gradients. The spatial heterogeneity of the Norbert response is particularly important. Although the hurricane generated intense winds along much of its trajectory, chlorophyll-a did not increase uniformly. This indicates that storm intensity alone cannot explain the biological response. The background ocean state must also be considered. Lin (2012) showed that only a fraction of typhoons in the western North Pacific generate detectable phytoplankton blooms and that cyclone-induced primary production contributes only modestly to global ocean carbon uptake. This reinforces the interpretation that even intense tropical cyclones do not always produce strong biological responses; rather, blooms occur where storm forcing coincides with favourable oceanic conditions. The vertical structure of chlorophyll-a further complicates the interpretation of the surface signal. The profiles in Fig. 10 suggest that part of the post-storm response occurred below the surface, with subsurface chlorophyll maxima developing or shifting between approximately 10 and 40 m. This is relevant because satellite ocean-colour sensors primarily observe the near-surface layer and may not fully capture changes in vertically integrated biomass. Chai et al. (2020) used BGC-Argo observations in Biogeosciences to show that apparent surface chlorophyll enhancement after typhoon passage can partly reflect vertical redistribution of an existing deep chlorophyll maximum rather than a substantial increase in total phytoplankton biomass. The Norbert results are consistent with this caution: the observed and simulated surface chlorophyll-a increase likely represents a combination of new growth supported by nitrate enrichment and redistribution of pre-existing subsurface biomass. The better model performance for SST anomalies than for chlorophyll-a is therefore expected. SST responds directly to vertical mixing, entrainment, and heat redistribution, whereas chlorophyll-a integrates physical, biological, and optical processes. Differences between simulated and observed chlorophyll-a may arise from uncertainties in satellite retrievals, unresolved small-scale circulation, simplified ecosystem dynamics, or the inability of surface observations to resolve subsurface chlorophyll maxima. The model nevertheless captures the main physical-biogeochemical sequence: surface cooling and mixed-layer deepening were followed by nitrate enrichment and a delayed chlorophyll-a response. The Argo profiles strengthen the interpretation of the physical response. Although limited in number, they show post-storm cooling and mixed-layer modification consistent with the simulated fields. This agreement suggests that the modelled nitrate and chlorophyll-a changes were physically plausible, because they occurred in a region where independent observations confirm that the upper ocean was disturbed by the storm. The combined use of satellite observations, Argo profiles, and a physical-biogeochemical model is therefore essential: satellites provide spatial coverage, Argo constrains the subsurface thermal response, and the model links wind forcing, vertical exchange, nitrate supply, and biological variability within a dynamically consistent framework. The comparison between the Elida-Fausto period and Norbert also suggests that storm history may have influenced the October response. Previous storms can modify stratification, deepen or erode the mixed



layer, alter nutrient distributions, and change the background chlorophyll-a field. In the present case, Elida and Fausto crossed part of the region later affected by Norbert, making preconditioning a plausible contributor to the stronger and more persistent response observed during October. Although the available diagnostics do not allow this contribution to be isolated completely, the seasonal sequence of storms should be considered when interpreting the magnitude and distribution of the Norbert signal. Overall, Hurricane Norbert produced a physically driven but biologically modulated response in the eastern tropical Pacific. The main pathway was wind-driven vertical exchange: Ekman pumping, vertical mixing, and mixed-layer deepening increased the availability of nitrate in the upper ocean, and this nutrient enrichment supported a delayed chlorophyll-a response. The biological impact was strongest where physical forcing coincided with favourable local conditions, including shallow nutrient-rich waters, mesoscale uplift, and suitable light conditions after storm passage. These findings show that major hurricanes in the eastern tropical Pacific can produce significant but spatially heterogeneous biogeochemical responses, and they emphasize that surface chlorophyll-a anomalies should be interpreted together with vertical structure, nutrient fields, and the pre-existing ocean state.

5 Conclusions

This study analysed the upper-ocean physical and biogeochemical response to Hurricane Norbert in the eastern tropical Pacific using IBTrACS hurricane data, ERA5 wind forcing, CROCO physical–biogeochemical simulations, satellite-derived SST and chlorophyll-a products, and Argo float observations. Hurricane Norbert generated strong wind-driven Ekman pumping, with localized upward velocities during the period of maximum storm intensity. This mechanism favoured the uplift of sub-surface waters and contributed to nutrient enrichment in the upper ocean. The mixed layer deepened after the storm passage, increasing from approximately 40 m to nearly 70 m in some regions. This delayed response indicates that vertical mixing and oceanic adjustment persisted after the maximum wind forcing. Surface nitrate concentrations increased along portions of the hurricane trajectory after storm passage, providing favourable conditions for phytoplankton growth in the post-storm period. Chlorophyll-a concentration increased after nitrate enrichment, indicating a delayed biological response to hurricane-induced nutrient supply. However, the response was spatially heterogeneous and depended on local oceanographic conditions. The model reproduced the main features of SST cooling more clearly than the chlorophyll-a response. This suggests that the physical response was more directly controlled by hurricane forcing, whereas the biological response was modulated by additional ecological and optical processes. Argo float profiles supported the simulated physical response, showing changes in vertical thermal structure and mixed-layer depth after the passage of Hurricane Norbert. These findings demonstrate that major hurricanes in the eastern tropical Pacific can produce significant but spatially variable physical and biogeochemical impacts. The integrated use of numerical modelling, satellite observations, and Argo profiles provides a robust framework for understanding the mechanisms linking hurricane forcing, vertical mixing, nutrient entrainment, and phytoplankton response.



Data availability. IBTrACS tropical cyclone data are available from NOAA/NCEI. ERA5 atmospheric reanalysis data are available from the Copernicus Climate Data Store. Satellite-derived sea surface temperature and chlorophyll-a products are available from the Copernicus Marine Service. Argo float profiles are available from the Argo Global Data Assembly Centres. Model outputs generated in this study can be made available by the corresponding author upon reasonable request.

Author contributions. JGR and LSM designed the study, configured and analysed the physical–biogeochemical simulations, processed the satellite and Argo data, and wrote the initial manuscript draft. JCM contributed to the conceptual development of the study, interpretation of the physical oceanographic processes, discussion of hurricane-induced mixing, and manuscript revision. JGA and JRFO contributed to data processing, figure preparation, and interpretation of the biogeochemical response. All authors contributed to the final version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. The authors gratefully acknowledge the Laboratorio Nacional de Cómputo de Alto Desempeño (LANCAD) for providing the computational resources allocated through project 28-2022, which supported the development of this study. This work also benefited from data and products provided by the European Union Copernicus Marine Service, ERA5 reanalysis, IBTrACS tropical cyclone records, and Argo float observations. The authors thank all institutions and data providers whose open-access resources made this research possible. During the preparation of the manuscript, the authors used generative AI (ChatGPT, developed by OpenAI) only to assist with English language editing, sentence structure, and readability. The authors reviewed and verified the final text and remain fully responsible for the scientific content of the manuscript.



345 References

- Babin, S., Carton, J., Dickey, T., and Wiggert, J.: Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert, *Journal of Geophysical Research: Oceans*, 109, 2004.
- Chai, F., Wang, Y., Xing, X., Yan, Y., Xue, H., Wells, M., and Boss, E.: A limited effect of sub-tropical typhoons on phytoplankton dynamics, *Biogeosciences Discussions*, 2020, 1–16, 2020.
- 350 Chen, Y., Pan, G., Mortimer, R., and Zhao, H.: Possible mechanism of phytoplankton blooms at the sea surface after tropical cyclones, *Remote Sensing*, 14, 6207, 2022.
- D’Asaro, E. A., Sanford, T. B., Niiler, P. P., and Terrill, E. J.: Cold wake of hurricane Frances, *Geophysical Research Letters*, 34, 2007.
- Debreu, L., Marchesiello, P., Penven, P., and Cambon, G.: Two-way nesting in split-explicit ocean models: algorithms, implementation and validation, *Ocean Modelling*, 49, 1–21, 2012.
- 355 Garcia, H. E., Boyer, T. P., Baranova, O. K., Locarnini, R. A., Mishonov, A. V., Grodsky, A. e., Paver, C. R., Weathers, K. W., Smolyar, I. V., Reagan, J. R., et al.: *World ocean atlas 2018: Product documentation*, 2019.
- González-Ramírez, J., Pares-Sierra, A., and Cepeda-Morales, J.: Chlorophyll response to wind and terrestrial nitrate in the western and southern continental shelves of the Gulf of Mexico, *Frontiers in Marine Science*, 10, 1034638, 2023.
- Gruber, N., Frenzel, H., Doney, S. C., Marchesiello, P., McWilliams, J. C., Moisan, J. R., Oram, J. J., Plattner, G.-K., and Stolzenbach, K. D.:
 360 Eddy-resolving simulation of plankton ecosystem dynamics in the California Current System, *Deep Sea Research Part I: Oceanographic Research Papers*, 53, 1483–1516, 2006.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al.: The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, 2020.
- Holte, J. and Talley, L.: A new algorithm for finding mixed layer depths with applications to Argo data and Subantarctic Mode Water
 365 formation, *Journal of Atmospheric and Oceanic Technology*, 26, 1920–1939, 2009.
- Knapp, K. R., Kruk, M. C., Levinson, D. H., Diamond, H. J., and Neumann, C. J.: The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data, *Bulletin of the American Meteorological Society*, 91, 363–376, 2010.
- Lellouche, J.-M., Le Galloudec, O., Greiner, E., Garric, G., Regnier, C., Drevillon, M., Bourdalle-Badie, R., Bricaud, C., Drillet, Y., and Le Traon, P.-Y.: The Copernicus Marine Environment Monitoring Service global ocean 1/12 physical reanalysis GLORYS12V1: description and quality assessment, in: *American Geophysical Union, Ocean Sciences Meeting*, 2046, pp. OM14B–2046, 2018.
- 370 Lin, I., Liu, W. T., Wu, C.-C., Wong, G. T., Hu, C., Chen, Z., Liang, W.-D., Yang, Y., and Liu, K.-K.: New evidence for enhanced ocean primary production triggered by tropical cyclone, *Geophysical Research Letters*, 30, 2003.
- Lin, I.-I.: Typhoon-induced phytoplankton blooms and primary productivity increase in the western North Pacific subtropical ocean, *Journal of Geophysical Research: Oceans*, 117, 2012.
- 375 Liu, X., Wang, M., and Shi, W.: A study of a Hurricane Katrina-induced phytoplankton bloom using satellite observations and model simulations, *Journal of Geophysical Research: Oceans*, 114, 2009.
- Ma, C., Zhao, J., Ai, B., Sun, S., Zhang, G., Huang, W., and Wang, G.: Assessing responses of phytoplankton to consecutive typhoons by combining Argo, remote sensing and numerical simulation data, *Science of the Total Environment*, 790, 148086, 2021.
- McDougall, T. J. and Barker, P. M.: Getting started with TEOS-10 and the Gibbs Seawater (GSW) oceanographic toolbox, *Scor/iapso WG*,
 380 127, 1–28, 2011.



- Mei, W., Pasquero, C., and Primeau, F.: The effect of translation speed upon the intensity of tropical cyclones over the tropical ocean, *Geophysical Research Letters*, 39, 2012.
- Nyadjro, E. S., Wang, Z., Reagan, J., Cebrian, J., and Shriver, J. F.: Bio-physical changes in the Gulf of Mexico during the 2018 Hurricane Michael, *IEEE Geoscience and Remote Sensing Letters*, 19, 1–5, 2021.
- 385 Price, J. F.: Upper ocean response to a hurricane, *Journal of Physical Oceanography*, 11, 153–175, 1981.
- Walker, N. D., Leben, R. R., and Balasubramanian, S.: Hurricane-forced upwelling and chlorophyll a enhancement within cold-core cyclones in the Gulf of Mexico, *Geophysical Research Letters*, 32, 2005.
- Worsfold, M., Good, S., Atkinson, C., and Embury, O.: Presenting a long-term, reprocessed dataset of global sea surface temperature produced using the OSTIA system, *Remote Sensing*, 16, 3358, 2024.
- 390 Wu, J.: Wind-stress coefficients over sea surface from breeze to hurricane, *Journal of Geophysical Research: Oceans*, 87, 9704–9706, 1982.
- Wurl, O. and Meyerjürgens, J.: Intense Cooling of the Upper Ocean with the Merging of Tropical Cyclones: A Case Study in the Southeastern Indian Ocean, *Tellus*, 76, 2024.
- Zhang, H., He, H., Zhang, W.-Z., and Tian, D.: Upper ocean response to tropical cyclones: A review, *Geoscience Letters*, 8, 1, 2021.

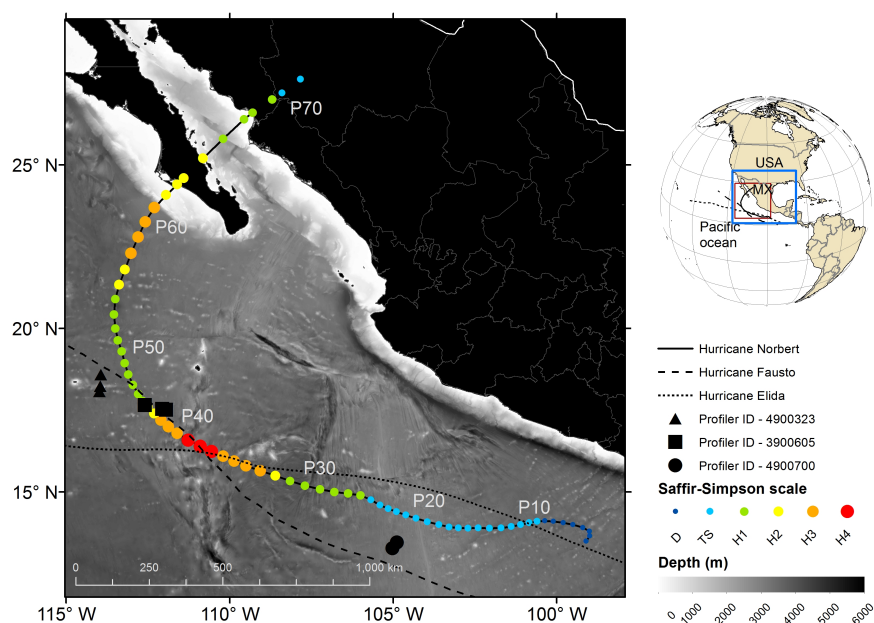


Figure 1. Figure 1. Model domain and hurricane trajectories in the eastern tropical Pacific. The solid line indicates the track of Hurricane Norbert, with six-hourly storm positions coloured according to the Saffir–Simpson category. Dashed and dotted lines indicate the partial trajectories of Hurricanes Fausto and Elida, respectively. Black symbols show the position of the Argo floats used to evaluate the vertical response of the upper ocean.

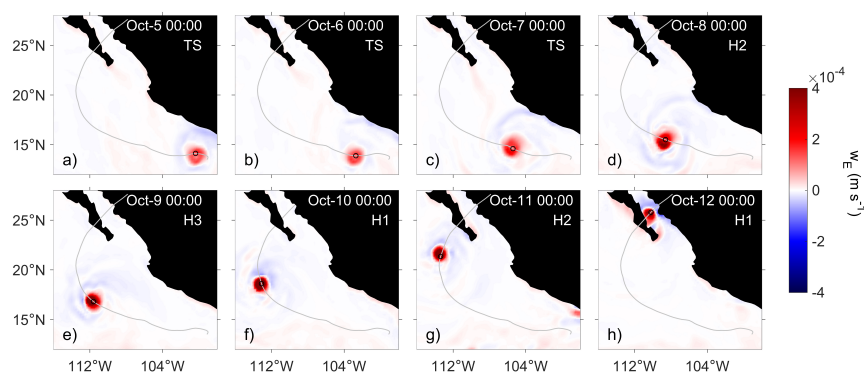


Figure 2. Figure 2. Ekman pumping velocity induced by the wind-stress curl of Hurricane Norbert from 5 to 12 October 2008. Positive values indicate upward motion associated with wind-driven divergence, while negative values indicate downward motion. The hurricane trajectory is shown in grey and the black circle indicates the storm position for each date.

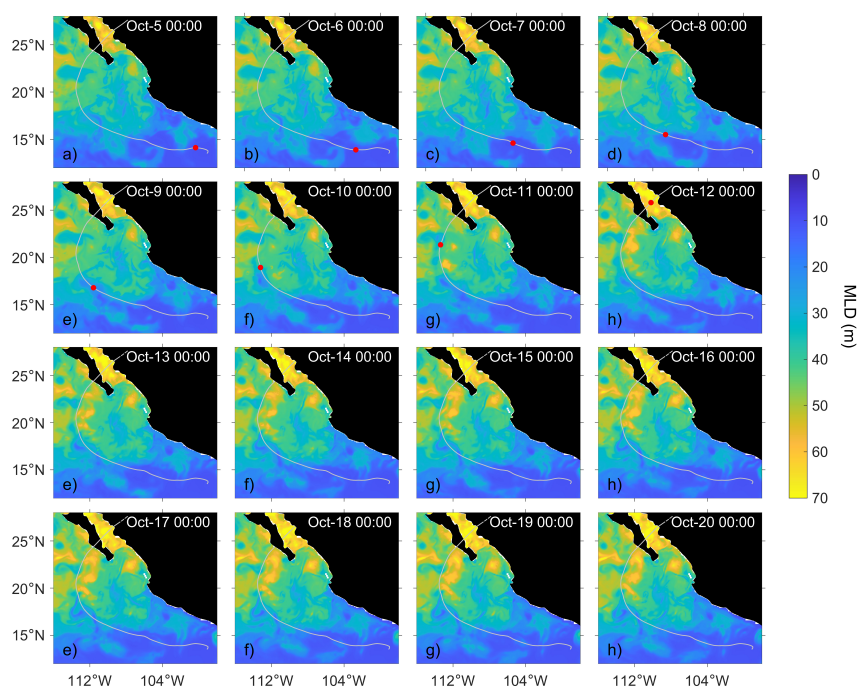


Figure 3. Figure 3. Evolution of simulated mixed-layer depth from 5 October to 20 October. The grey line represents the track of Hurricane Norbert and the red dot indicates the storm position on each date. Larger mixed-layer depth values indicate enhanced vertical mixing after hurricane passage.

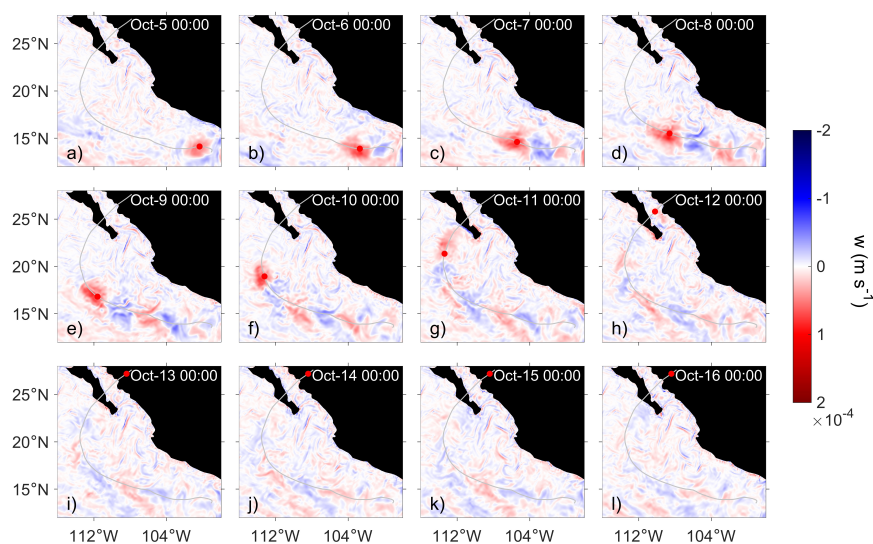


Figure 4. Figure 4. Simulated vertical velocity during and after the passage of Hurricane Norbert. Positive values indicate upward motion and negative values indicate downward motion. The spatial pattern reveals the heterogeneous vertical response of the upper ocean to hurricane forcing.

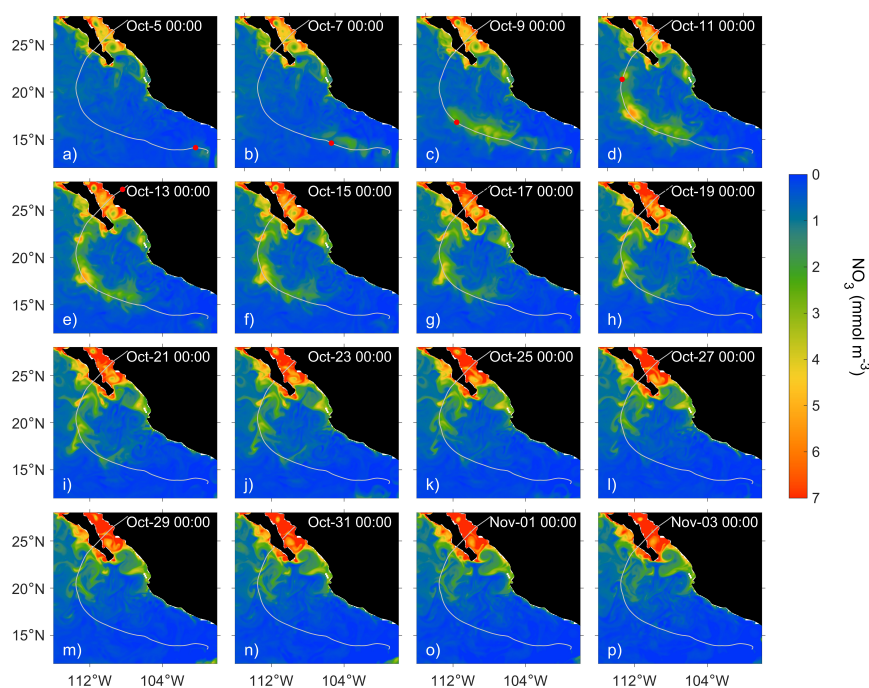


Figure 5. Figure 5. Evolution of simulated surface nitrate concentration from 5 October to 20 October. The grey line indicates the trajectory of Hurricane Norbert and the red dot shows the storm position on each date. Enhanced nitrate concentrations after storm passage indicate nutrient enrichment associated with vertical mixing and upward motion.

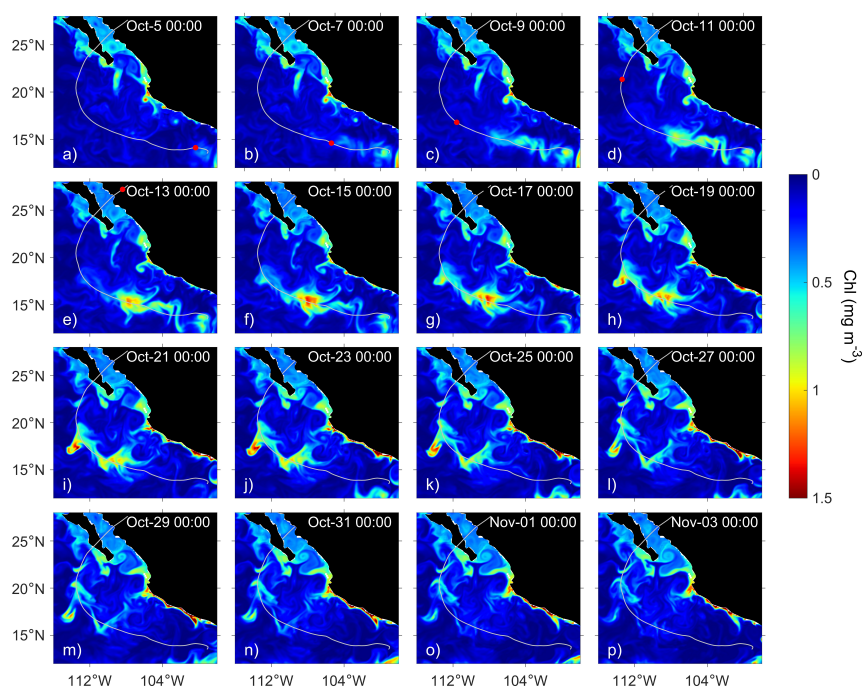


Figure 6. Figure 6. Evolution of simulated surface chlorophyll-a concentration from 5 October to 20 October. The grey line indicates the trajectory of Hurricane Norbert and the red dot shows the storm position on each date. Increased chlorophyll-a concentrations after storm passage indicate a delayed biological response to hurricane-induced nutrient enrichment.

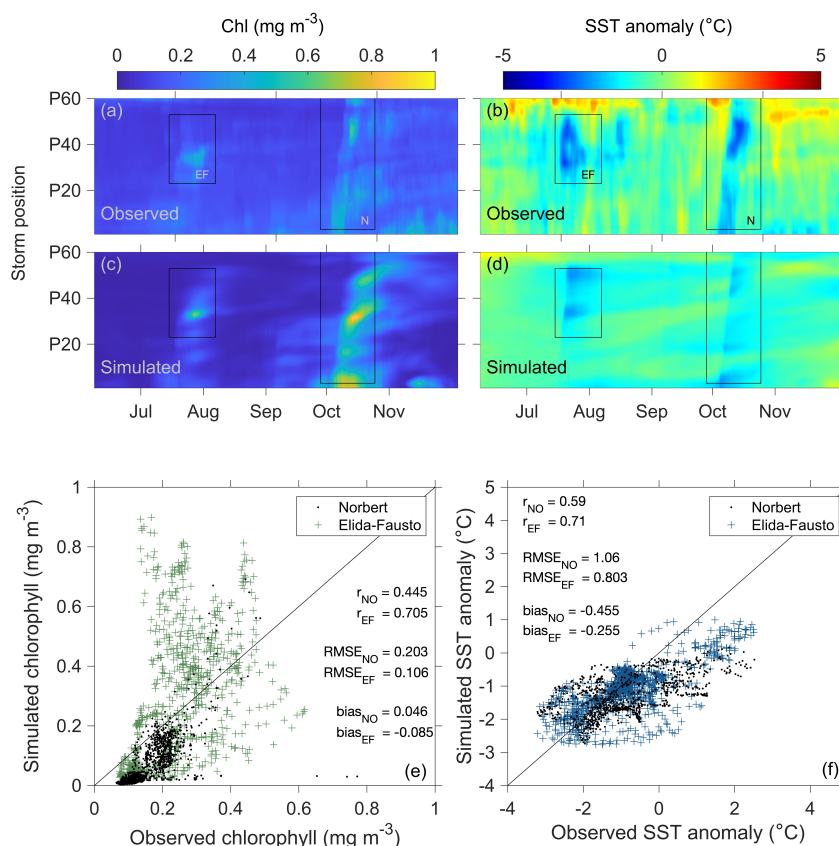


Figure 7. Figure 7. Observed and simulated surface chlorophyll-a concentration and sea surface temperature anomaly along the trajectory of Hurricane Norbert and previous 2008 storms. Upper panels show observed and simulated chlorophyll-a and SST anomaly as a function of storm position and time. Lower panels show model-observation comparisons for chlorophyll-a and SST anomaly during the Elida-Fausto and Norbert periods, including correlation, RMSE, and bias statistics.

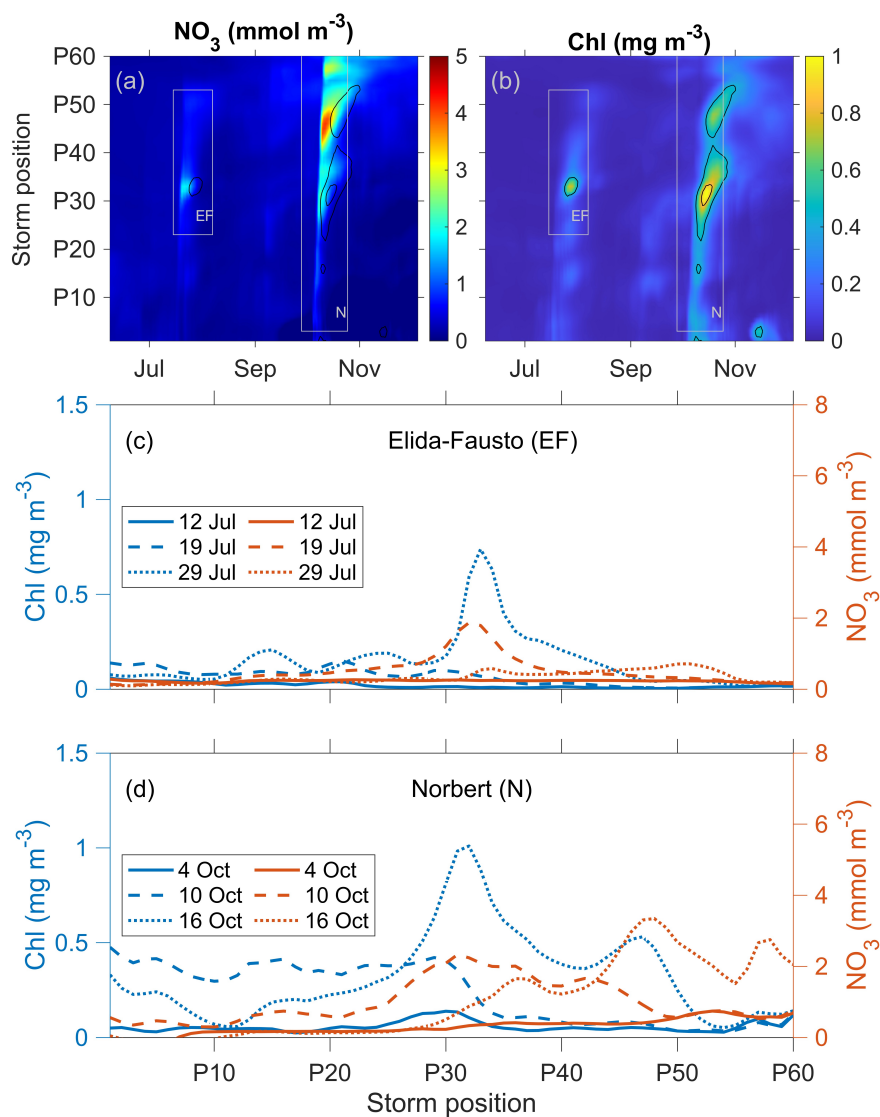


Figure 8. Figure 8. Along-track evolution of simulated surface nitrate and chlorophyll-a concentrations during the 2008 hurricane season. Upper panels show the temporal distribution of nitrate and chlorophyll-a across storm positions. Lower panels show mean nitrate and chlorophyll-a concentrations along the storm trajectory for selected dates during the Elida–Fausto and Norbert periods.

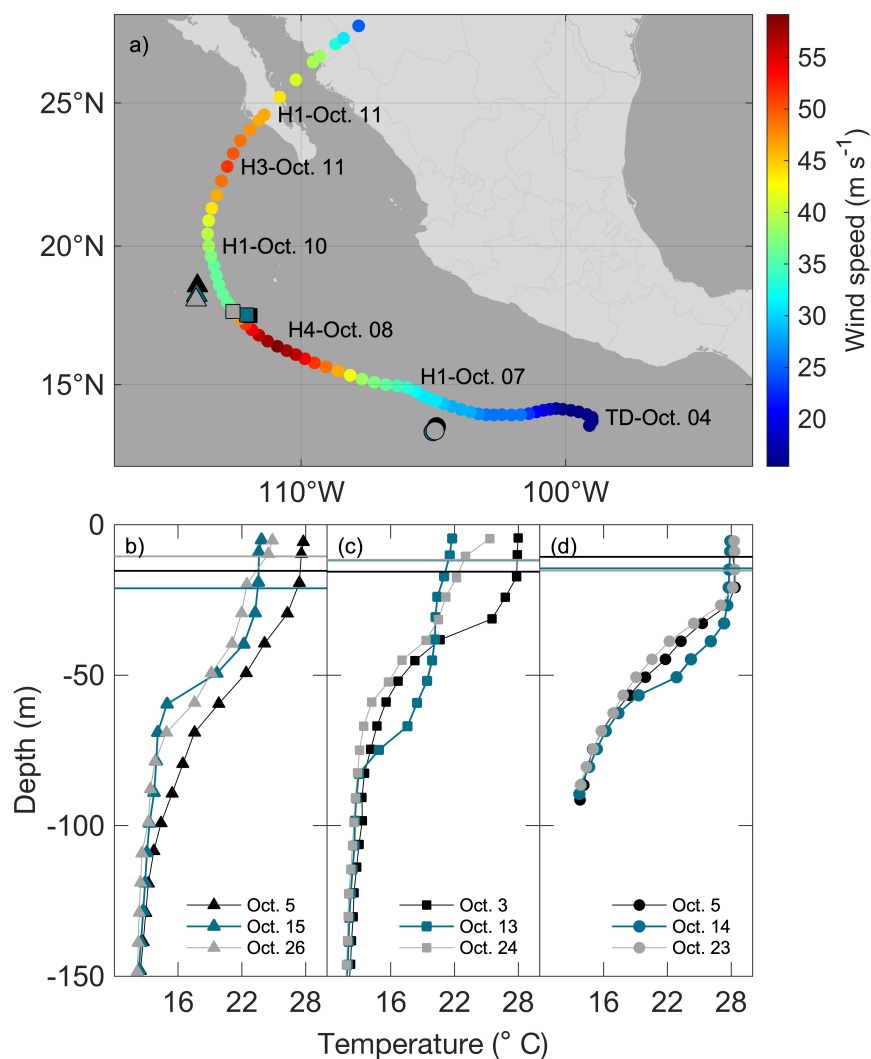


Figure 9. Figure 9. Hurricane Norbert trajectory, wind speed, and Argo float temperature profiles. Triangle, square and circle figure represent locations of profiles 4900323, 3900605 and 4900700, respectively. The upper panel shows six-hourly storm positions coloured by wind speed and the locations of Argo floats near the hurricane track. Lower panels show temperature profiles before and after storm passage, with horizontal lines indicating mixed-layer depth estimated from density criteria.

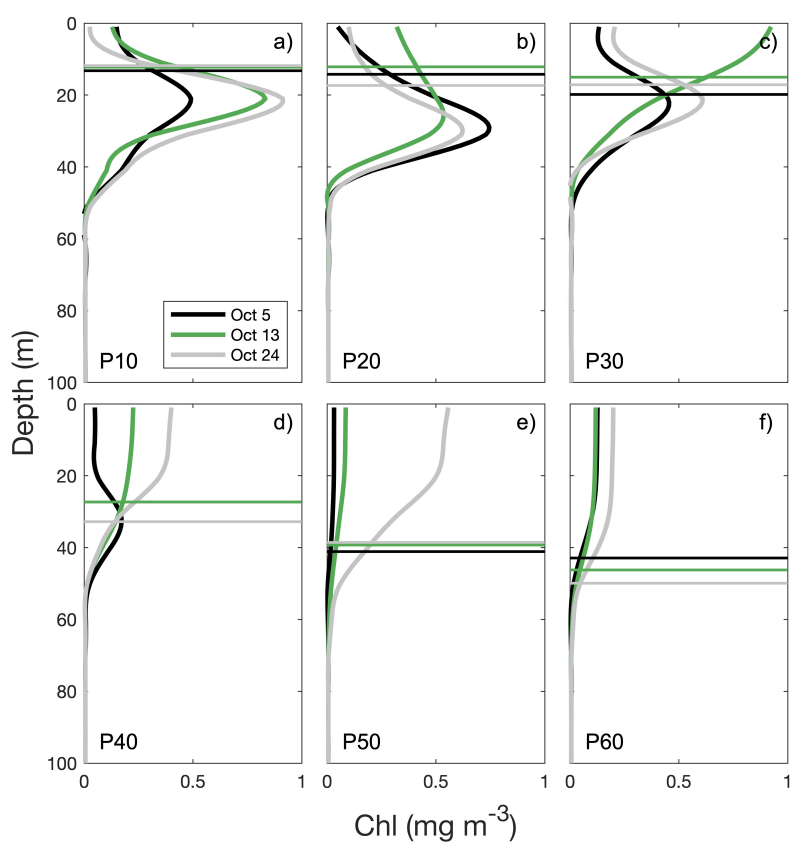


Figure 10. Figure 10. Vertical distribution of simulated chlorophyll-a concentration at six storm positions along the Hurricane Norbert trajectory. Profiles are shown for selected dates before and after storm passage. Horizontal lines indicate mixed-layer depth, and colours represent the temporal evolution of chlorophyll-a concentration.