



A Storm-driven Reversal of the Springtime North Atlantic CO₂ Sink

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Abstract. The North Atlantic Ocean is a major sink for atmospheric carbon dioxide (CO₂), particularly in spring when
10 phytoplankton blooms intensify CO₂ uptake. Its magnitude and variability affect how much anthropogenic CO₂ is sequestered. Yet short-term variability in this sink remains poorly constrained. Energetic events such as storms are rarely sampled, leaving their contribution to air-sea CO₂ exchange unresolved. Here we report a reversal of this sink during spring 2023, captured by validated measurements aboard a racing sailboat crossing a storm. Surface ocean CO₂ increased abruptly, reaching on average 34 µatm above atmospheric levels (magnitude comparable to the ~40 µatm undersaturation that typically sustains spring
15 uptake) as strong winds drove vertical mixing and Ekman suction that ventilated an unusually shallow carbon-rich subsurface reservoir. The anomaly was further amplified by a concurrent marine heatwave. Our observations provide evidence that storms can ventilate subsurface carbon reservoirs and temporarily reverse CO₂ fluxes even during peak biological drawdown. They reveal a mode of short-lived but intense carbon outgassing that is unresolved in coarse resolution models. As storms and marine heatwaves intensify under climate change, such events will become an increasingly important component of the ocean carbon
20 cycle and may weaken the North Atlantic CO₂ sink.



1 Introduction

The subpolar North Atlantic is one of the ocean's most efficient carbon sinks, accounting for approximately 15% of the global oceanic uptake of atmospheric carbon dioxide (CO₂) (Landschützer et al., 2013; Takahashi et al., 2009). This region is the most intense oceanic carbon sink per unit area (Mikaloff Fletcher et al., 2006), playing a key role in slowing the pace of human-induced climate change, and mitigating its effects (Friedlingstein et al., 2025; Landschützer et al., 2013; Olafsson et al., 2021). CO₂ uptake in the North Atlantic predominantly taking place in winter and spring and is driven by cold temperatures and high biological productivity. These processes are highly variable in space and time, resulting in strong coupling between physics and biology in shaping air-sea CO₂ exchanges.

Although extensively observed (Landschützer et al., 2013; Metzl et al., 2024; Reverdin et al., 2018; Takahashi et al., 2009), CO₂ uptake in this region remains uncertain, with discrepancies between models and observation-based estimates of the fugacity of CO₂ (fCO₂, the partial pressure of CO₂ corrected for the non-ideal gas behaviour) pointing to an incomplete representation of local processes (McKinley et al., 2017). Among these, the role of short-lived weather events, particularly extratropical storms, remains underexplored, despite their potential to temporarily enhance or suppress ocean-atmosphere gas exchange through intensified winds, and associated vertical mixing. This will become increasingly relevant as reanalysis and climate model data show an increasing storm frequency and intensity north of 50°N since the 1970s (Feser et al., 2015), and future climate scenarios project further intensification (Cheung and Chu, 2023; Priestley and Catto, 2022).

Storms modulate air-sea CO₂ flux through interconnected physical processes. High wind speeds enhance the gas transfer velocity, increasing the flux magnitude in either direction (Wanninkhof, 2014). At the same time, storm-driven changes in sea surface temperature (SST) and vertical mixing alter the surface ocean fCO₂, modulating the direction of the flux. The net outcome of a storm event therefore depends strongly on the pre-existing oceanic conditions, especially the vertical distribution of dissolved inorganic carbon (DIC) (Bates et al., 1998; Nickford et al., 2022). Storms may also entrain nutrients into the euphotic zone, potentially stimulating biological productivity and CO₂ drawdown (Ferreira et al., 2022; Fujii and Yamanaka, 2008; Rumyantseva et al., 2015). Yet, the impacts of storms on the subpolar North Atlantic air-sea CO₂ exchange remain undocumented and unobserved.

Here we present measurements from the racing sailboat *Malizia - Seaexplorer*, which recorded an episode of unexpected CO₂ while crossing the North Atlantic during the 2023 Ocean Race. The event occurred in late May, at the peak of the spring bloom when strong atmospheric CO₂ uptake is typically expected.



50 2 Results

2.1 Racing through the storm

As the racing sailboat *Malizia - Seaexplorer* crossed $\sim 55^\circ\text{N}$ in the North Atlantic on 25-26 May 2023, it recorded a sharp episode of CO_2 outgassing (Fig. 1). fCO_2 rose well above climatological mean levels (Landschützer et al., 2016), with a difference in fCO_2 between the ocean and the atmosphere (ΔfCO_2) averaging to $+34 \mu\text{atm}$ and peaking at $+70 \mu\text{atm}$ locally.

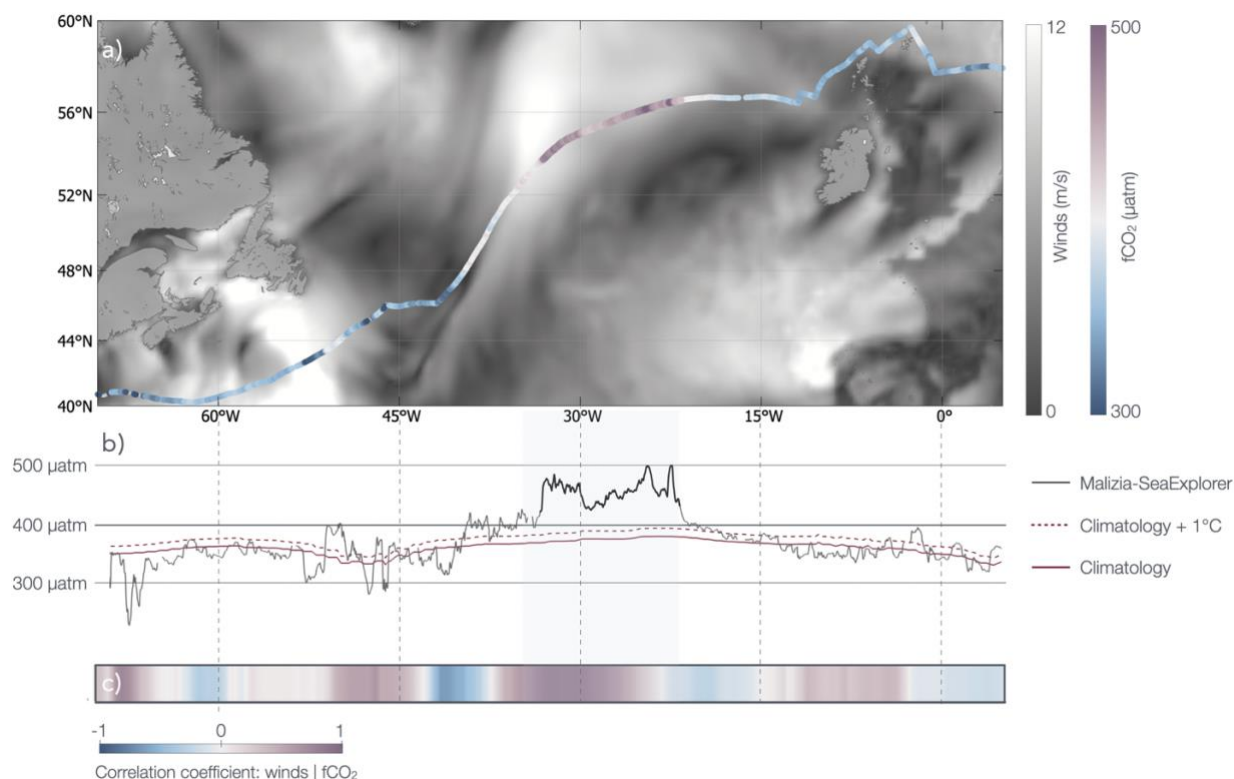


Figure 1: Surface ocean fCO_2 and wind forcing along the Malizia transect. (a) Track of *Malizia - Seaexplorer* from May 22 to 29, 2023, overlaid on ERA5 winds magnitude in black and white on May 26, 01h00 UTC. Track is color-coded by measured surface fCO_2 . (b) Observed along-track fCO_2 (1-minute resolution), compared with collocatated climatological fCO_2 for the month of May (Landschützer et al., 2016) and the same climatology adjusted for $+1^\circ\text{C}$ SST anomaly (following Takahashi et al., 1993). (c) Moving 26-hour correlation between ERA5 wind stress and measured fCO_2 along the track.

55 The measured levels of oceanic fCO_2 during the storm the sailboat passed that day contrast strongly with pre-storm conditions near $370 \mu\text{atm}$, which is well below the atmospheric values at the time (about $420 \mu\text{atm}$). This uptake is the typical behaviour of the subpolar North Atlantic in spring, as a result of the seasonal phytoplankton bloom, which draws down surface ocean fCO_2 .

60 As the boat progressed eastward, however, oceanic fCO_2 began to increase from 40°W onward, eventually exceeding atmospheric values around $35^\circ\text{W}/54^\circ\text{N}$. This transition marks a reversal from an oceanic carbon sink to a source. The most



abrupt $f\text{CO}_2$ increase from $\sim 400 \mu\text{atm}$ to $\sim 475 \mu\text{atm}$, coincided with the strongest wind regime ($>12 \text{ m s}^{-1}$, Fig. 1). The 26-hour moving correlation coefficient between wind stress and $f\text{CO}_2$ during this period reaching $r = 0.8$ (Fig. 1c) with a $p\text{-value} < 0.05$, pointing to physical forcing as the dominant driver of the flux anomaly.

65 This event occurred at the same time as an unprecedented marine heatwave in the North Atlantic. Between May and June 2023, SST anomalies in the region reached $+0.76^\circ\text{C}$ above the 1991 to 2020 mean, the highest on record for that time of year (Guinaldo et al., 2025), which has been shown to cause a decline in the Atlantic Ocean sink strength (Müller et al., 2025). Based on the measured SST from the sailboat, compared to climatological satellite SST, we find a positive anomaly of about 0.9°C during the crossing. To account for the decreased solubility with higher temperature, we compare in situ $f\text{CO}_2$ with both
 70 a monthly climatology and a version corrected for a $+1^\circ\text{C}$ SST anomaly, following Takahashi et al., (1993). Before and after the storm, the observed $f\text{CO}_2$ closely followed the 1982 to 2023 climatology (Landschützer et al., 2016) (Fig. 1b), supporting accuracy and consistency of the measurements. The strong correspondence with climatological conditions outside of the storm period supports the validity of the dataset. In contrast, the storm-induced anomaly exceeded the measurement system's expected uncertainty ($\pm 10 \mu\text{atm}$) (Landschützer et al., 2023; Steinhoff et al., 2025) by nearly an order of magnitude and
 75 strongly departed from the heatwave-adjusted climatology, indicating that the observed outgassing is a robust and significant signal.

2.2 The role of a subsurface carbon reservoir

To investigate the drivers of the outgassing event, we use the GLODAPv2 climatology (Lauvset et al., 2016) to characterize the background biogeochemical conditions beneath the track (Fig. 2). We identify a broad subsurface layer of positive $\Delta f\text{CO}_2$
 80 (calculated from DIC and total alkalinity using CO2SYS, see Section 2) extending from $\sim 1500 \text{ m}$ to $\sim 50 \text{ m}$ depth (Fig. 2a). Within this layer, $\Delta f\text{CO}_2$ exceeds $+60 \mu\text{atm}$ between 700 m and 200 m in the central North Atlantic, with the highest concentrations shoaling to $\sim 50 \text{ m}$ above the Mid-Atlantic Ridge between 35° and 30°W . This structure reflects the combined influence of DIC and total alkalinity (TA): the DIC distribution follows the same pattern as $\Delta f\text{CO}_2$, but its maximum lies $\sim 200 \text{ m}$ deeper (Fig. 2c). TA, by contrast, remains low across the water column between 35°W and 25°W ($< 2300 \mu\text{mol kg}^{-1}$; Fig.
 85 2d), elevating $f\text{CO}_2$ and shifting the maximum upward relative to DIC. This decoupling, also observed in other regions such as the Southern Ocean (Chen et al., 2022), highlights the importance of using $f\text{CO}_2$ (rather than DIC alone) to assess the influence of subsurface carbon reservoirs on potential surface CO_2 fluxes.

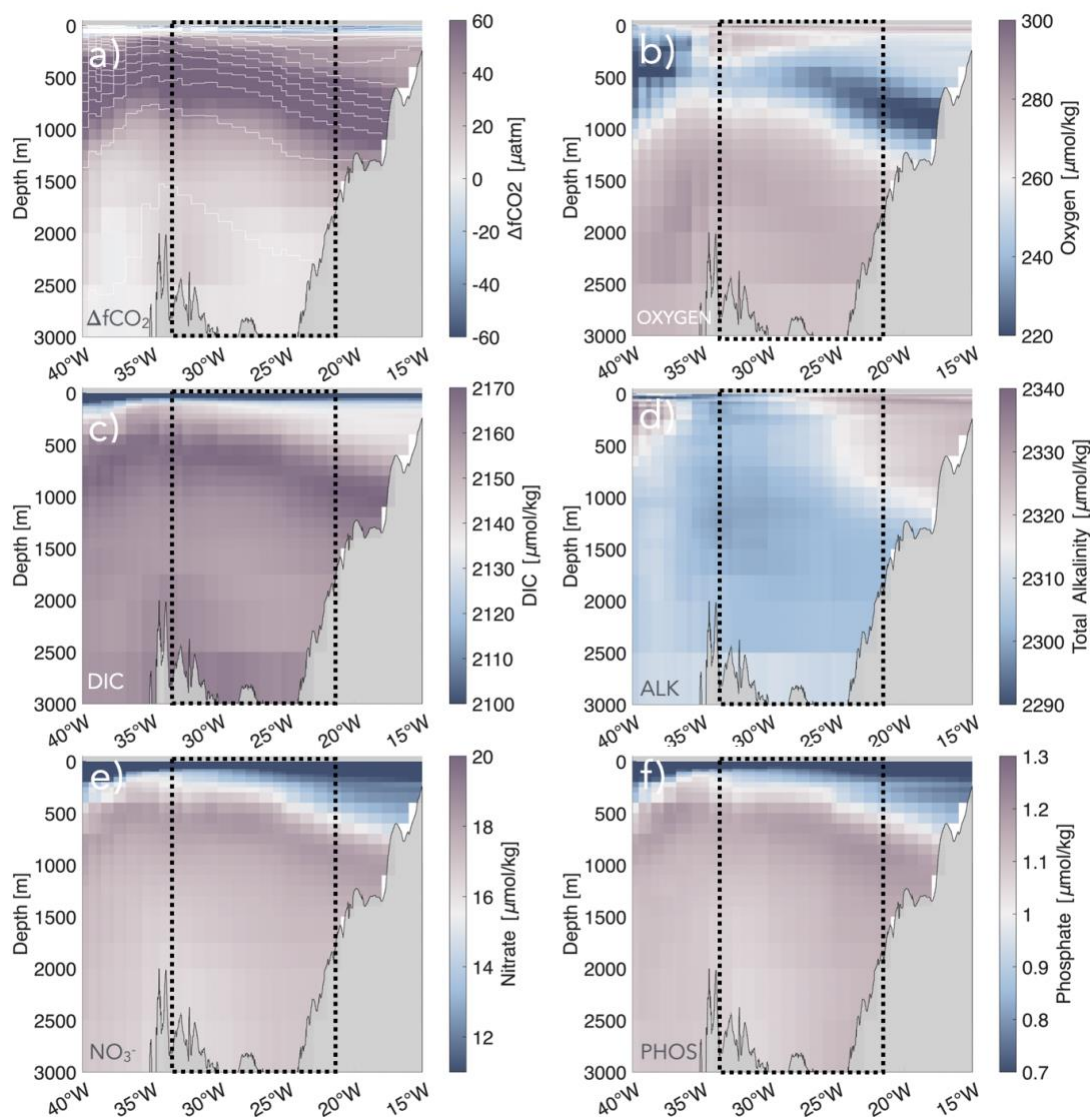


Figure 2. Along track vertical section of biogeochemical parameters. Depth sections along the ship track (0-3000 m) showing (a) $\Delta f\text{CO}_2$, (b) oxygen, (c) DIC, (d) total alkalinity, (e) nitrates and, (f) phosphates from the GLODAPv2 climatology. The dashed-box indicates the outgassing period. Isopycnals are represented by white contour lines on panel (a).

The vertical biogeochemical patterns on the transect reflect the wider characteristics of subpolar North Atlantic water masses. Waters advected into this region from the Labrador Sea are relatively fresh due to precipitations, river runoff and ice melt, which lowers TA through dilution (Fry et al., 2015). At the same time, subpolar waters formed at high latitudes are enriched in DIC due to solubility-driven CO_2 uptake (Davila et al., 2022; Perez et al., 2018), and the subpolar North Atlantic is highly productive biologically (Henson et al., 2009; Sverdrup, 1953). The resulting export of organic matter leads to subsurface



remineralization, evident in the observed DIC maximum and accompanying low oxygen ($\sim 250 \mu\text{mol kg}^{-1}$; Fig. 2b) and high phosphate and nitrate concentrations (Fig. 2e-f). These signals identify biological remineralization as the dominant source of elevated subsurface $\Delta f\text{CO}_2$ (Kwon et al., 2009). Such biologically derived carbon pools, positioned at relatively shallow depths are susceptible to episodic ventilation. The timing of the event (at the tail end of the spring bloom) suggests that recently remineralized carbon from the ongoing bloom may have accumulated above legacy winter signals, further shoaling the CO_2 -rich layer and increasing its exposure to vertical mixing.

In addition to the biogeochemical controls, regional ocean circulation patterns shape the accessibility of this subsurface carbon reservoir east of the Mid-Atlantic Ridge ($\sim 35^\circ\text{--}30^\circ\text{W}$, Fig. 3). Climatological velocity fields from the GLORYS12v1 reanalysis at 75 m depth reveal the presence of a cyclonic recirculation cell in this region. This feature coincides with a shoaling of the positive $\Delta f\text{CO}_2$ layer from $\sim 200\text{--}1000$ m elsewhere to ~ 50 m. The cyclonic recirculation generates a local upwelling, as indicated by the upward tilt of isopycnals (Fig. 2a). It lifts carbon-rich waters closer to the surface, reducing the mixing depth required to ventilate them. This shoaled anomaly also appears in the horizontal $\Delta f\text{CO}_2$ distribution at 75 m (Fig. 3), with values exceeding $+20 \mu\text{atm}$ in the region of the cyclonic circulation. The alignment of the outgassing event with this region suggests that local water masses and circulation jointly set the stage for this temporary CO_2 flux reversal.

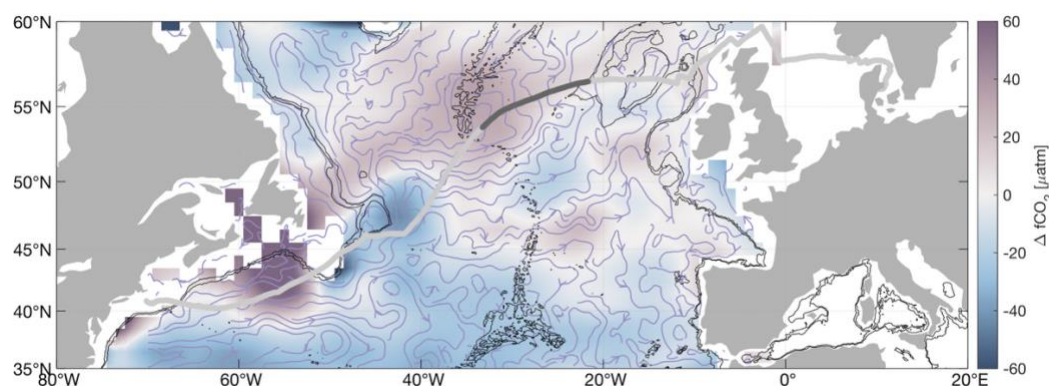


Figure 3. Subsurface $\Delta f\text{CO}_2$ and circulation in the North Atlantic. Background colours represent the climatological $\Delta f\text{CO}_2$ at 75 m from the GLODAPv2 climatology. Purple streamlines represent the horizontal circulation at 75 m, from GLORYS12v1 climatological reanalysis. The track of *Malizia - Seaexplorer* is overlaid in light grey for reference, with the outgassing area marked in darker grey.

2.3 Storm induced mixing

The observed reversal of the air-sea CO_2 flux suggests vertical entrainment of carbon-rich subsurface waters into the mixed layer, enabled by two complementary mechanisms: direct wind-driven mixing and wind stress curl-induced Ekman suction. In late spring, the subpolar North Atlantic typically features a shallow seasonal mixed layer, which has shoaled further in recent decades (England et al., 2025), and even more so in 2023, due to the ongoing marine heatwave.

To assess vertical mixing during the storm, we computed the mixing layer depth (XLD; see Section 2) using ERA5 (Hersbach et al., 2023) wind speeds and stratification data from both GLORYS12v1 (Fig. 4a). We distinguish here the MLD, zone of homogeneous water formed by the history of mixing, and the XLD, defined here as the zone in which wind-driven mixing is currently active. In all cases, XLD exceeded background MLD, indicating entrainment of deeper waters across the seasonal thermocline. This deep XLD aligns with the sharp increase in surface $\Delta f\text{CO}_2$, supporting a mechanism of upward carbon transport. In parallel, we detect positive Ekman suction velocities during the event (Fig. 4c), indicative of large-scale wind stress curl favouring upwelling and an upward tilt of the isopycnals. These two processes likely acted in concert to enhance vertical supply of subsurface carbon.

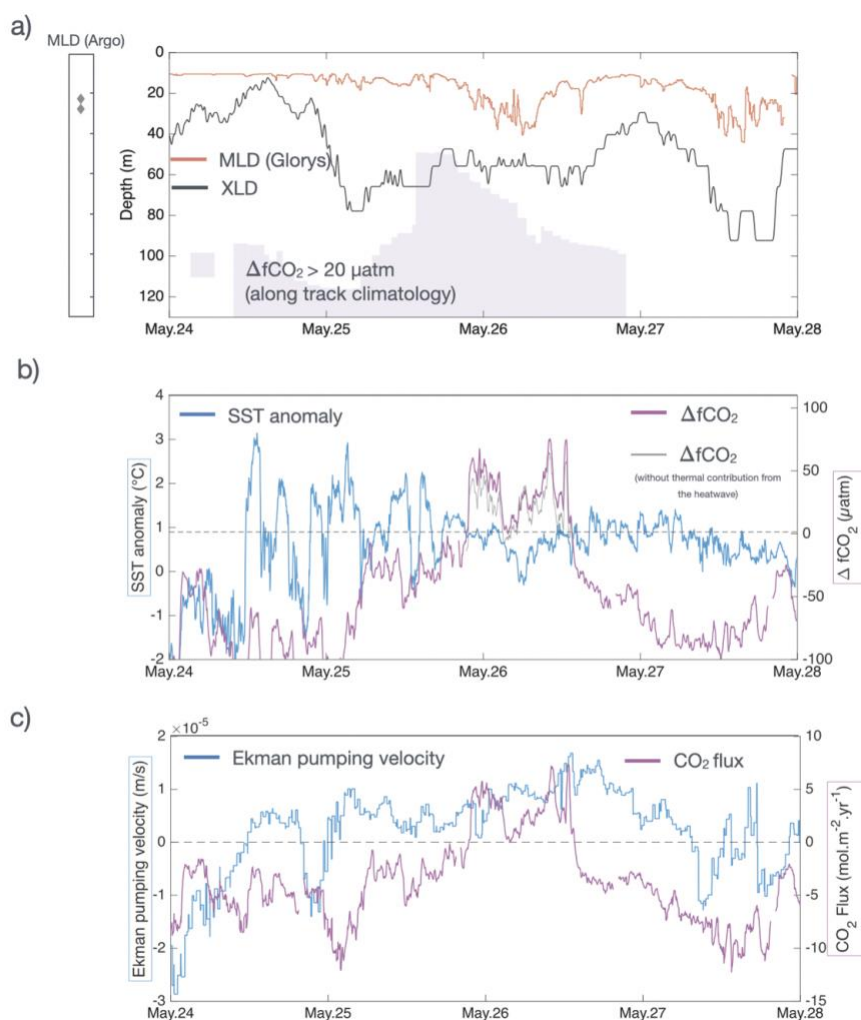


Figure 4. Storm-driven mixing and heatwave-enhanced surface $\Delta f\text{CO}_2$. (a) Time series of mixed layer depth (MLD, orange) from the GLORYS ocean reanalysis interpolated along the position of *Malizia-Seaexplorer*, shown together with the mixing layer depth (XLD, dark grey) computed from ERA5 winds. The daily (GLORYS) and hourly (ERA5) values are collocated onto the 1-minute ship trajectory. The



shaded purple patch represents the area where the climatological $\Delta f\text{CO}_2 > +20 \mu\text{atm}$ from GLODAPv2, co-located with the ship's position but invariant in time (i.e., not a time series). On the left side, diamonds show MLD estimates from two Argo floats located within the broader region (52–57°N, 40–25°W), sampled on 23 May 2023. (b) Time series of the sea surface temperature anomaly (blue), the $\Delta f\text{CO}_2$ (purple), and the $\Delta f\text{CO}_2$ adjusted to the CCI SST climatology using (Takahashi et al., 1993) (i.e. without the heat wave influence, grey). (c). Time series of the Ekman pumping velocities computed from hourly ERA5 winds collocated onto the 1-minute ship trajectory (blue) and the CO_2 flux (purple).

Surface temperature anomalies provide further evidence of deep storm-driven vertical mixing. We compared in-situ SST along the ship track to collocated satellite-derived climatology from the Climate Change Initiative (CCI) SST product. In front of the background marine heatwave, a local $\sim 1^\circ\text{C}$ SST drop was observed during the storm (Fig. 4b). To isolate the storm's signal from the anomalous background, we defined anomalies relative to a $+0.9^\circ\text{C}$ “heatwave baseline” (the mean SST anomaly for 25–26 May) rather than a standard zero-anomaly climatology. Against this reference, the SST decline remains visible, consistent with entrainment of cooler subsurface water into the surface layer and the switch from a carbon sink to a carbon source.

Despite the storm-driven entrainment of colder water from below, the SST anomaly in this period remained positive compared to the climatology (on average $+0.59^\circ\text{C}$ during the outgassing period). As a result, the usual solubility-driven cooling effect that often accompanies storms was largely absent. In a non-heatwave year, storm-induced cooling would likely have increased CO_2 solubility and partly offset any outgassing. Instead, the elevated background SST not only suppressed this compensating effect but also contributed positively to the flux anomaly. Based on the SST anomalies during the outgassing period and assuming a thermal dependence of $f\text{CO}_2$ on temperature of $4.23\%/\text{C}$ (Takahashi et al., 1993), we estimate that the change in temperature alone contributed $11.7 \mu\text{atm}$ on average (about one-third of the $34.0 \mu\text{atm}$ $\Delta f\text{CO}_2$ signal, Fig. 4b). This calculation indicates that the anomalously high SSTs amplified, but did not drive, the observed outgassing. The primary driver remains the chemical signature of the entrained subsurface waters (Fig. 2). Together, these multiple lines of evidence support a coherent interpretation: the storm vertically connected a shallow, carbon-rich reservoir to the surface, triggering a transient outgassing event amplified by the heat wave during a season that is usually dominated by CO_2 uptake (Fig. 4).

3 Conclusions

Our findings reveal an intense and previously undocumented reversal of the ocean carbon sink in the subpolar North Atlantic. Our observations, taken on-board the sailboat *Malizia-Seaexplorer* during a major racing event, capture a temporary reversal of the regional carbon sink and highlight a mechanism by which extreme weather and heatwaves—both expected to intensify with climate change—have a large impact on ocean-atmosphere CO_2 exchange.

This event occurred at the height of the spring bloom, a period typically marked by strong oceanic CO_2 uptake, yet surface $f\text{CO}_2$ increased by over $34 \mu\text{atm}$ above atmospheric levels, reversing the expected flux. This anomaly was only detectable thanks to the unique platform and timing of the observations, demonstrating how sailboats can reveal processes missed by



conventional platforms. While current measurement uncertainties in instruments operated on sailboats exceed those on research vessels (Steinhoff et al., 2025), we show here that the event captured exceeds the instrument uncertainty by an order of magnitude. By combining in-situ data with ocean reanalyses and climatological biogeochemical observations, we attribute the anomaly to storm-driven vertical mixing that ventilated a hidden subsurface reservoir of remineralized carbon (Fig. 5). While our interpretation of the signal relies in part on climatological data and model reanalyses, these various data products provide multiple, independent lines of evidence supporting our conclusions. Importantly, the storm also happened during the record-breaking marine heatwave in 2023 (England et al., 2025). The warmer ocean further enhanced the outgassing through reduced solubility (Müller et al., 2025). These results show how episodic physical forcing can momentarily disrupt the North Atlantic carbon sink and even reverse it into a source. As we expect such extreme events (storms and heat waves) to intensify in the future climate, they might further hinder the efficient CO₂ uptake in this region.

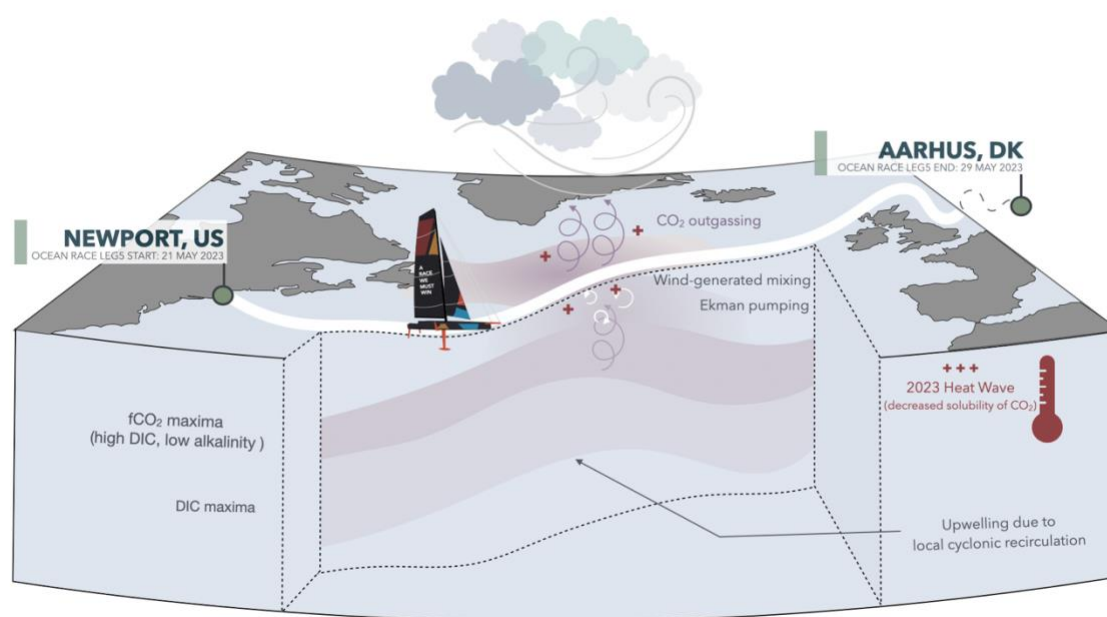


Figure 5. Schematic summarizing key physical and biogeochemical mechanisms driving a CO₂ release in the North Atlantic during a storm in late May 2023: storm-induced mixing and Ekman suction entraining CO₂-rich waters into the mixed layer; subsurface high fCO₂ reservoir through a combination of high DIC and low TA and vertically uplifted through regional ocean circulation; 2023 marine heatwave enhanced stratification and background fCO₂.

This event highlights a broader limitation in how we monitor and model ocean carbon fluxes. While storm-driven CO₂ outgassing has been reported in the Southern Ocean (Nicholson et al., 2022; Toolsee et al., 2024) no comparable signal has been documented in the subpolar North Atlantic. Previous study in the Gulf Stream region have instead reported enhanced CO₂ uptake associated with wintertime storms (Nickford et al., 2022). A search of the SOCAT database (Bakker et al., 2016)



confirms the absence of similar springtime outgassing in this region. This gap likely reflects both the region's high variability (Schuster and Watson, 2007) and the scarcity of observations during storms. As a result, similar events may have occurred undetected, or may be emerging more prominently as a consequence of climate-driven changes in storm activity (Priestley and Catto, 2022) and ocean warming. Either possibility calls for a rethinking of both observing strategies and assumptions about North Atlantic CO₂ fluxes and their potential future changes.

These findings underscore the importance of capturing short-term events in our efforts to understand and predict the ocean's role in the global carbon cycle. Research vessels usually avoid storms, leading to a potential bias in global databases towards calm conditions. While we here report a single event, its magnitude and context suggest that storm-induced flux reversals may occur more often than previously recognized. A simple scaling illustrates the potential magnitude of such events. Assuming a mean flux anomaly of $\sim 1.5 \text{ mol m}^{-2} \text{ day}^{-1}$ (Fig. 4C) sustained over 2-3 days across a typical storm footprint (10^5 - 10^6 km^2), the resulting carbon release could reach approximately 5-50 TgC per event, depending on storm duration and spatial extent. While highly uncertain, this estimate suggests that repeated storm-driven reversals may contribute non-negligibly to regional carbon flux variability. Because intense storms frequently traverse regions with strong vertical carbon gradients in the subpolar North Atlantic, similar ventilation events may occur more frequently than currently documented.

Episodic flux reversals such as the one documented here are unlikely to be resolved in coarse-resolution observing networks, Earth System Models or monthly climatologies, and may therefore be systematically underrepresented in global carbon budgets (Friedlingstein et al., 2025). As climate change accelerates, storms and marine heatwaves are projected to increase in both number and intensity (England et al., 2025; Feser et al., 2015; Priestley and Catto, 2022), and the interplay between surface warming, subsurface carbon reservoirs, and storm-induced mixing will likely grow more complex, with consequences for both regional and global CO₂ fluxes. By demonstrating the utility of unconventional observing platforms, this study also highlights new avenues for expanding ocean carbon monitoring. Low-emission data from sailing vessels like *Malizia - Seaexplorer* offer a promising complement to existing networks, particularly in under-sampled and dynamic regions. Integrating and resolving such episodic events into Earth System Models will be essential to improve projections of the ocean carbon sink under climate extremes. In a rapidly changing climate, capturing the "weather" of the carbon cycle and not just its climate may be essential to improve flux estimates, better constrain models, and inform carbon policy based on a fuller picture of ocean-atmosphere CO₂ exchange.



Appendix A: Data and Methods

A1 Sea surface $f\text{CO}_2$ and temperature observations

The sailing vessel *Malizia - Seaexplorer* is equipped with a SubCtech OceanPack Race system, a membrane-based equilibrator with a non-drying gas loop, designed for autonomous underway CO_2 measurements in harsh offshore conditions (Landschützer et al., 2023). The system continuously records sea surface temperature (SST), salinity, pressure, and the molar fraction of CO_2 ($x\text{CO}_2$) in equilibrated headspace air. From $x\text{CO}_2$, SST, and pressure, the fugacity of CO_2 ($f\text{CO}_2$) in surface seawater is calculated following standard thermodynamic routines (Pierrot et al., 2009), and the quality check has been adapted for sailboats (Olivier et al., 2025). The $f\text{CO}_2$ reflects the effective partial pressure of CO_2 in seawater, accounting for non-ideal gas behaviour, and is the standard quantity used to describe gas exchange with the atmosphere. The difference between oceanic and atmospheric $f\text{CO}_2$ ($\Delta f\text{CO}_2$) determines the direction and magnitude of air-sea CO_2 fluxes.

The system is expected to perform within an uncertainty of $\pm 10 \mu\text{atm}$ for $f\text{CO}_2$, based on an extensive sensor intercomparison experiment (Steinhoff et al., 2025), and the data are averaged over 1-minute intervals. The dataset has been quality-controlled and is available in the Surface Ocean CO_2 Atlas (SOCAT) (Bakker et al., 2016). Calibration is performed daily using two reference gases: a zero- CO_2 gas and a non-zero span gas to account for sensor drifts.

The atmospheric $f\text{CO}_2$ is derived assuming a constant atmospheric $x\text{CO}_2$ value representative of late May 2023 conditions, combined with SST from *Malizia - Seaexplorer* and ERA5 hourly atmospheric pressure (Hersbach et al., 2023). We used the atmospheric $x\text{CO}_2$ of 423.88 ppm measured by the National Oceanic and Atmospheric Administration (NOAA) station at Portsmouth, USA (McKain et al., 2024) on May 23, 2023 which showed excellent agreement (to the second decimal place) with values from the Stórhöfði station in Iceland (Lan et al., 2025), the second closest to the *Malizia - Seaexplorer* track.

Air-sea CO_2 fluxes were calculated using the $\Delta f\text{CO}_2$ computed from shipboard oceanic $f\text{CO}_2$ and atmospheric $f\text{CO}_2$ described above, combined with ERA5 hourly wind speeds co-located along the ship track. The gas transfer velocity (k) was calculated as a quadratic function of wind speed at 10 m (Wanninkhof, 2014), and SST and salinity from the sailboat were used to compute solubility following (Weiss, 1974). The flux is thus given by $F = k \times \text{sol} \times \Delta f\text{CO}_2$, where sol is the CO_2 solubility in seawater (Weiss, 1974). Fluxes are reported as 1-minute averages matching the $f\text{CO}_2$ resolution. We acknowledge that uncertainties in the gas transfer velocity parameterization (e.g., wind dependence, bubble effects during storms) may contribute to the total uncertainty in the air-sea CO_2 flux, beyond the measurement error in the seawater $f\text{CO}_2$ alone. Given the short timescale of the event, we prioritize relative changes and anomalies in air-sea CO_2 flux over absolute flux magnitudes and focus the study on $\Delta f\text{CO}_2$. To contextualize the observed $f\text{CO}_2$ values, we compare them to the monthly climatology of Landschützer et al. (Landschützer et al., 2016) based on SOCAT and neural network interpolation for the period 1986 to 2023. The climatology is centred around the average year of data and corrected for anthropogenic trends by adding $+1.8 \mu\text{atm yr}^{-1}$, allowing direct comparison with 2023 conditions (Fig. 1).



A2 Subsurface $f\text{CO}_2$ and $\Delta f\text{CO}_2$

To estimate $f\text{CO}_2$ in the subsurface ocean (Fig. 2.), we use total alkalinity (TA) and dissolved inorganic carbon (DIC) data from the GLODAPv2 climatology (Lauvset et al., 2016), calculated with the MATLAB version of CO2SYS v3.1.5.9 (Sharp et al., 2020). The GLODAPv2 gap-filled fields are on a uniform $1^\circ \times 1^\circ$ grid and 33 standard depth surfaces. Subsurface $f\text{CO}_2$ is estimated as a potential $f\text{CO}_2$, i.e., the fugacity that a water parcel would have if adiabatically brought to the surface, using potential temperature and atmospheric surface pressure. Required nutrients (phosphate, silicate) are also taken from GLODAP, and we apply the Lueker et al. (2000) (Lueker et al., 2000) carbonate system constants.

As the GLODAP dataset represents a climatological mean around 2002, we estimate the corresponding atmospheric $f\text{CO}_2$ in 2002 as $368 \mu\text{atm}$ to compute $\Delta f\text{CO}_2$. This reference allows direct comparison between observed surface anomalies and the underlying subsurface reservoir from two decades prior. To estimate the atmospheric reference $f\text{CO}_2$ in 2002, we used the atmospheric $p\text{CO}_2$ values provided in the Landschützer et al., (2016) product, treating $f\text{CO}_2$ as approximately equal to $p\text{CO}_2$, given the negligible correction factor under these conditions. These values are derived from the NOAA ESRL marine boundary layer $x\text{CO}_2$ product (<https://www.esrl.noaa.gov/gmd/ccgg/mbl/>), combined with SST (Reynolds et al., 2002) and sea level pressure (Kalnay et al., 1996), following the formulation of Dickson (2007). We extracted the monthly atmospheric $p\text{CO}_2$ values for 2002, collocated them along the ship track, and averaged the result, obtaining a reference value of $368 \mu\text{atm}$. While this provides a consistent and reasonable baseline, the estimate carries inherent uncertainties, which is why our interpretation does not rely on differences of just a few microatmospheres, but rather on broader patterns and magnitudes of anomalies.

A3 Mixed and mixing layer depth

Mixed layer depth (MLD) is taken from the daily GLORYS12v1 (hereafter GLORYS) reanalysis, using the mixed layer thickness variable collocated along the 1-minute resolution track of the *Malizia – Seaexplorer* (Fig. 3a). GLORYS has a horizontal resolution of $1/12^\circ$ and 50 vertical levels. In this product, MLD is defined as the depth at which density increases by 0.01 kg m^{-3} relative to the surface. To ensure consistency, we applied the same density criterion to the two Argo profiles with both temperature and salinity data, available between 22 and 27 May 2023 within the domain $40^\circ\text{--}20^\circ\text{W}$, $50^\circ\text{--}58^\circ\text{N}$.

The mixing layer depth (XLD, Fig. 3a) is an estimation of the upper ocean layer affected by wind induced mixing following Nicholson et al.,(2022). The friction velocity u^* defined as $u^* = \sqrt{\tau/\rho_{sw}}$, where ρ_{sw} is the density of seawater taken at 1025 kg m^{-3} and τ is the wind stress estimated using ERA5 wind speeds. According to similarity theory, wind forcing, expressed via the friction velocity u^* , influences the dissipation rate of turbulent kinetic energy (ϵ), following $\epsilon = \frac{u^{*3}}{\kappa z}$ where $\kappa = 0.41$ is the von Karman constant and z is the depth below the surface. The XLD was then estimated as the depth at which ϵ falls below $10^{-8} \text{ m}^{-2} \text{ s}^{-3}$ (Nicholson et al., 2022). This wind-driven XLD is subject to substantial uncertainties, due to both the assumptions inherent in the similarity theory and the input data used. In particular, the estimate depends strongly on the wind stress from ERA5 reanalysis, which may underestimate or smooth extreme wind events. Moreover, the threshold of ϵ is empirically chosen and may not correspond precisely to physical layer boundaries during rapidly evolving storm conditions. As a result, XLD



values should be interpreted qualitatively, as an indicator of the relative depth and timing of wind-driven mixing events, rather than as precise quantitative estimates of vertical mixing.

A4 Sea surface temperature anomalies

We assessed SST anomalies by comparing shipboard SST measurements with the daily climatology from the CCI SST product (Embury et al., 2024), collocated along the ship track (Fig. 3b). Using satellite-derived SST instead of in-situ measurements yields similar anomaly patterns, supporting the robustness of the observed signal.

A5 Moving correlation between wind and $f\text{CO}_2$

To explore the relationship between wind speed and surface ocean $f\text{CO}_2$, we computed a moving correlation along the ship track (Fig. 1c). We used a sliding window of 1560 data points (26 h) to calculate the Pearson correlation coefficient between $f\text{CO}_2$ and the wind magnitude from ERA5 collocated along the ship track. At each step, only valid data pairs were retained for the correlation, when both values existed.

Code and data availability

The atmospheric $x\text{CO}_2$ data from Portsmouth, USA (<https://gml.noaa.gov/data/dataset.php?item=nha-co2-aircraft-pfp>) and Stórhöfði, Iceland (<https://gml.noaa.gov/data/dataset.php?item=ice-co2-flask>) are made freely available by NOAA. The underway data from *Malizia* - *Seaexplorer* is available on the SOCATv2025 database: <https://socat.info/index.php/version-2025/>. The biogeochemical climatology from the GLODAP database is openly available at <https://glodap.info/index.php/mapped-data-product/>. The wind speed and sea level pressure data from ERA5 is available at: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>. The satellite climatological sea surface temperature product from the Climate Change Initiative is available at: <https://catalogue.ceda.ac.uk/uuid/62800d3d2227449085b430b503d36b01/>. The GLORYS12v1 reanalysis can be accessed at: https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description. The Argo profiles number 4902439 and 4902495 can be downloaded from: <https://dataselection.euro-argo.eu>. Key analysis and figures codes will be accessible via a Zenodo repository upon publication.

Author contributions

L.O. conceptualized the study and wrote the manuscript with substantial input from F.A.H. and P.L. All authors contributed to the interpretation of the results and the review of the manuscript. Data were acquired by B.H., and project funding was provided by F.A.H. and P.L..



Competing interests

One of the co-authors is a member of the editorial board of BG.

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