Observed regional impacts of marine heatwaves on air-sea CO2 exchange

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May 30, 2024

Abstract

Marine heatwaves (MHWs) have devastating effects on ecosystems and impact regional air-sea CO2 exchange. Yet a global assessment of these regional impacts of MHWs on the air-sea CO2 exchange is missing. Here, we analyze thirty global observation-based air-sea CO2 flux datasets from 1990 to 2019. We observe minimal reduction in global oceanic CO2 uptake during MHWs. Regional variations are evident with the equatorial Pacific experiencing a 31% (spread across datasets: 3-49%) reduction in carbon release, suggesting that MHWs are the dominant drivers of strong air-sea CO2 flux anomalies in this region. In low- to mid-latitudes, MHWs cause a 29% (19-37%) decrease in air-sea CO2 uptake. Reduced dissolved inorganic carbon in the tropics weakens outgassing, while high ocean temperatures diminish uptake in the low-to-mid latitudes. In the North Pacific and Southern Ocean, enhanced carbon uptake occurs during MHWs, but uncertainties in pCO2 datasets limit a comprehensive assessment in these regions.
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Key Points:

- Marine heatwaves substantially affect local air-sea CO$_2$ fluxes via oceanic pCO$_2$ changes, but their global impacts remains minor.
- During MHWs, tropics decrease outgassing from lower DIC, while mid latitudes weaken uptake due to thermally induced rise in oceanic pCO$_2$.
- MHW events can trigger extreme CO$_2$ flux anomalies, notably in the eastern equatorial Pacific, Indian Ocean and Northeast Pacific.

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Abstract

Marine heatwaves (MHWs) have devastating effects on ecosystems and impact regional air-sea CO$_2$ exchange. Yet a global assessment of these regional impacts of MHWs on the air-sea CO$_2$ exchange is missing. Here, we analyze thirty global observation-based air-sea CO$_2$ flux datasets from 1990 to 2019. We observe minimal reduction in global oceanic CO$_2$ uptake during MHWs. Regional variations are evident with the equatorial Pacific experiencing a 31% (spread across datasets: 3–49%) reduction in carbon release, suggesting that MHWs are the dominant drivers of strong air-sea CO$_2$ flux anomalies in this region. In low-to-mid latitudes, MHWs cause a 29% (19–37%) decrease in air-sea CO$_2$ uptake. Reduced dissolved inorganic carbon in the tropics weakens outgassing, while high ocean temperatures diminish uptake in the low-to-mid latitudes. In the North Pacific and Southern Ocean, enhanced carbon uptake occurs during MHWs, but uncertainties in pCO$_2$ datasets limit a comprehensive assessment in these regions.

Plain language summary

Periods of unusually warm sea surface temperatures have recently been shown to impact the exchange of carbon dioxide between the surface ocean and overlying atmosphere. We find that extremely warm sea surface temperatures (marine heatwaves) have a small impact on the ocean’s overall ability to take up carbon dioxide from the atmosphere, but depending on the region the local exchange of carbon dioxide between the ocean and atmosphere can be substantially impacted. In tropical regions, the ocean’s usual release of carbon dioxide to the atmosphere is reduced during marine heatwaves due to lower dissolved inorganic carbon in the surface ocean. In low to mid latitude regions, the ocean’s uptake of carbon from the atmosphere is reduced during marine heatwaves due to the effect of warmer temperatures. A clear consensus on the impact of marine heatwaves in the North Pacific and Southern Ocean does not emerge due to data limitations. While heatwaves in the ocean can cause substantial changes in air-sea carbon dioxide exchange in some tropical areas and the Northeast Pacific, they are not the main reason for large monthly changes in globally integrated air-sea carbon dioxide exchange.

1 Introduction

Human-induced carbon dioxide (CO$_2$) emissions are the primary driver of climate change (IPCC, 2021), with the ocean playing a crucial role in mitigating global warming by taking up about a quarter of these emissions (Friedlingstein et al., 2023). An accurate quantification and understanding of the variability of air-sea CO$_2$ fluxes is essential for predicting future climate trends (Joos et al., 1999) and assessing the ocean ecosystem response (Gattuso et al., 2015).

In recent decades, prolonged periods of anomalously warm sea surface temperatures, known as marine heatwaves (MHWs; Pearce and Feng (2013); Hobday et al. (2016)), have occurred across all ocean basins (Frölicher & Laufkötter, 2018; Oliver et al., 2021), posing substantial risks to marine species, ecosystems and ecosystem services (Collins et al., 2019; Cheung & Frölicher, 2020; Hughes et al., 2017; Smale et al., 2019; Cheung et al., 2021). With global ocean warming, MHWs are becoming more frequent, intense, and prolonged (Oliver et al., 2018; Frölicher et al., 2018). Individual MHWs are generated by a combination of local oceanic and atmospheric processes including air-sea heat flux, horizontal and vertical temperature advection, and vertical mixing (Vogt et al., 2022; Bian et al., 2023), and are often associated with large-scale climate phenomena such as the El Niño Southern Oscillation (Oliver et al., 2021; Holbrook et al., 2019).

Recent research has highlighted the significance of MHWs in influencing regional oceanic pCO$_2$ and air-sea CO$_2$ fluxes (Arias-Ortiz et al., 2018; Mignot et al., 2022; Duke et al., 2023; Edwing et al., 2024). For example, Mignot et al. (2022) identified reduced oceanic
CO\textsubscript{2} release in the equatorial Pacific and decreased oceanic CO\textsubscript{2} uptake around 40°N in the North Pacific. Duke et al. (2023) examined the North Pacific subpolar gyre, revealing substantial anomalous oceanic uptake of CO\textsubscript{2} during recent MHWs due to limited wintertime entrainment and therefore lower oceanic pCO\textsubscript{2}. Additionally, Arias-Ortiz et al. (2018) suggested significant carbon release from seagrass carbon stocks to the atmosphere following the Western Australia 2011 MHW. Despite these insights, a comprehensive global assessment of MHWs impacts on air-sea CO\textsubscript{2} fluxes and their driving mechanisms is lacking. Moreover, understanding how CO\textsubscript{2} flux anomalies during MHWs compare to overall flux variability remains limited, hindering a comprehensive evaluation of the importance of MHWs for air-sea CO\textsubscript{2} flux variability.

In this study, we explore the impacts of MHW events on air-sea CO\textsubscript{2} exchange. Using an ensemble of observation-based pCO\textsubscript{2} and wind products spanning from 1990 to 2019, we initially assess the global and regional impacts of MHW events on air-sea CO\textsubscript{2} fluxes. Subsequently, we identify the underlying mechanisms driving flux anomalies during MHWs. Finally, we contextualize these anomalies within the broader spectrum of natural CO\textsubscript{2} flux variability to assess their relative significance in total regional CO\textsubscript{2} flux variability.

2 Methods

2.1 Observation-based data

To identify MHWs, we use the global observation-based daily-mean sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration (NOAA; Daily Optimum Interpolation Sea Surface Temperature OISST dataset v2.1, Huang et al., 2021). This comprehensive dataset combines in situ ship and buoy sea surface temperature observations with satellite-derived measurements from the Advanced Very High-Resolution Radiometer. Through interpolation, data gaps are filled to create a spatially and temporally complete representation of sea surface temperature. To ensure consistency with the CO\textsubscript{2} flux and oceanic pCO\textsubscript{2} data, the daily mean SST data is regridded from 0.25° × 0.25° to 1° × 1° and averaged from daily to monthly-mean values, spanning the period 1982 to 2021.

For the assessment of CO\textsubscript{2} flux anomalies during MHWs, we rely on CO\textsubscript{2} flux estimates derived from the SeaFlux version 2021.04 ensemble data product (Fay et al., 2021). This dataset integrates six global observation-based pCO\textsubscript{2} products, all based on the Surface Ocean Carbon Dioxide Atlas (SOCAT) pCO\textsubscript{2} dataset (Bakker et al., 2016), alongside five global wind reanalyses (Supporting Information Tables S1 and S2). Combined, we obtain 30 distinct air-sea CO\textsubscript{2} flux datasets at monthly intervals, covering the period 1990 to 2019 on a 1° × 1° grid. We only analyze CO\textsubscript{2} flux data in regions where data from all six observation-based pCO\textsubscript{2} products are available.

To analyze the drivers of CO\textsubscript{2} flux anomalies during MHWs, we use the LIARv2 alkalinity regression algorithm (Carter et al., 2018). This algorithm utilizes salinity data from the Hadley Centre (EN4.2.2; Good et al., 2013) in conjunction with sea surface temperature data to compute total alkalinity on a 1° × 1° grid. Dissolved Inorganic Carbon (DIC) is then calculated with CO2SYS (Humphreys et al., 2022) using the estimated total alkalinity, pCO\textsubscript{2} from the six different SeaFlux pCO\textsubscript{2} data products, temperature, salinity, and monthly mean climatologies of phosphate and silicate from the World Atlas 2018 (WOA18; Boyer et al., 2018; Garcia et al., 2019).

2.2 MHW definition and air-sea CO\textsubscript{2} flux anomalies

A MHW is identified when the local linearly detrended monthly-mean SST surpasses the local seasonally-varying 90th percentile of SST. The seasonally varying 90th percentile is calculated for each calendar month separately and is based on linearly detrended monthly-
mean SST data spanning from 1982 to 2021. The threshold is set to capture extreme temperature anomalies while ensuring a sufficiently large sample size of MHW months for robust statistical analyses. In contrast to the prevailing approach in MHW studies (Hobday et al., 2016; Le Grix et al., 2021), we define MHWs here on monthly anomalies rather than daily anomalies to be consistent with temporal resolution of the CO₂ flux products.

We calculate the monthly mean air-sea CO₂ flux anomalies during MHWs by initially linearly detrending the air-sea CO₂ flux over the period 1990 to 2019. Subsequently, the anomalies during MHWs are derived as deviations from the climatological seasonal cycle of monthly-mean CO₂ fluxes during MHWs.

We divide the global ocean into eight study regions (Figure 1a, and Supporting Information Table S3) given the diverse characteristics of air-sea CO₂ flux, such as strong or weak CO₂ sink or source regions. To assess whether the product-ensemble-mean air-sea CO₂ flux during MHWs significantly differs from the mean CO₂ flux, we conduct a standard two-sample t-test globally and for each study region, using the 5% significance level (Wilks, 2019).

2.3 Decomposition of air-sea CO₂ flux anomalies into drivers

To determine the driving mechanisms behind the air-sea CO₂ flux anomalies during MHWs, we conduct a first-order Taylor series decomposition of the air-sea flux components. This analysis allows us to quantify the contribution of the solubility, gas transfer velocity, oceanic pCO₂, and atmospheric pCO₂ to the overall air-sea CO₂ flux anomaly during MHWs.

SeaFlux computes the net air-sea CO₂ flux (F_{air-sea}) via the adapted bulk formula established by Wanninkhof (1992):

\[ F_{air-sea} = k_w \cdot \text{sol} \cdot (pCO_2,a - pCO_2,o), \]  

where \( k_w \) is the gas transfer velocity (in units m s\(^{-1}\)), \( \text{sol} \) is the solubility of CO₂ in seawater (mol m\(^{-3}\)µatm\(^{-1}\)), \( pCO_2,a \) represents the partial pressure of atmospheric CO₂ in the marine boundary layer (µatm), and \( pCO_2,o \) is the partial pressure of surface ocean CO₂ (µatm). Note that the bulk formula is adapted to omit sea ice regions as not all data products encompass these regions.

The first order Taylor series decomposition of the air-sea CO₂ flux anomalies during MHWs (referred to hereafter as \( \Delta F_{air-sea} \)) is as follows:

\[ \Delta F_{air-sea} \approx \frac{\partial F_{air-sea}}{\partial k_w} \cdot \Delta k_w + \frac{\partial F_{air-sea}}{\partial \text{sol}} \cdot \Delta \text{sol} + \frac{\partial F_{air-sea}}{\partial pCO_2,o} \cdot \Delta pCO_2,o + \frac{\partial F_{air-sea}}{\partial pCO_2,a} \cdot \Delta pCO_2,a \]  

The right hand side of equation (2) represents the contributions of the gas transfer velocity, solubility, and oceanic and atmospheric partial pressure of CO₂. The delta values represent the mean anomalies of the variables during MHWs and the partial derivatives are calculated with the temporal mean values.

The oceanic pCO₂ anomalies are further decomposed as:

\[ \Delta pCO_2,o \approx \frac{\partial pCO_2,o}{\partial DIC} \cdot \Delta DIC + \frac{\partial pCO_2,o}{\partial ALK} \cdot \Delta ALK + \frac{\partial pCO_2,o}{\partial T} \cdot \Delta T + \frac{\partial pCO_2,o}{\partial S} \cdot \Delta S \]  

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where oceanic $pCO_{2,o}$ is a function of sea surface dissolved inorganic carbon (DIC), alkalinity (ALK), temperature (T), and salinity (S). The 'mocsy 2.0' Fortran 95 routine (Orr & Epitalon, 2015) is used to calculate the partial derivatives, evaluated at temporal mean values for S, T, DIC, ALK, phosphate, and silicate.

### 3 Results

#### 3.1 Global and regional response of air-sea CO$_2$ fluxes during MHWs

Globally, we observe a small reduction in the oceanic uptake of CO$_2$ by an average of $-0.04$ mol C/m$^2$/yr during MHWs, with values ranging from 0.01 (anomalous uptake) to $-0.11$ mol (anomalous release) C/m$^2$/yr depending on the dataset used (Figure 1b). This reduction corresponds to approximately 8% (3 to 19%) of the net global oceanic uptake of CO$_2$ during the time period from 1990 to 2019. In most regions, the CO$_2$ flux - whether into or out of the ocean in the climatological mean - is diminished during MHWs. Consequently, the air-sea CO$_2$ flux anomaly pattern during MHWs is reversed from the climatological mean CO$_2$ flux pattern (Figure 1a).

Although the global CO$_2$ flux response during MHWs is minor, we observe substantial CO$_2$ flux responses on the regional scale. The CO$_2$ uptake in the North Atlantic and the low-mid latitude regions in both the northern and southern hemispheres is reduced by an average of $-0.10$ mol C/m$^2$/yr (-0.24 to -0.00), -0.17 mol C/m$^2$/yr (-0.22 to -0.11), and $-0.12$ mol C/m$^2$/yr (-0.18 to -0.04), respectively. In the equatorial Pacific, CO$_2$ outgassing is reduced by an average of 0.30 (0.03 to 0.48) mol C/m$^2$/yr. However, this general pattern of reduced air-sea CO$_2$ fluxes does not apply to the North Pacific and the Southern Ocean. In these regions, CO$_2$ uptake is even stronger during MHWs (North Pacific: 0.14 (-0.12 to 0.30); Southern Ocean: 0.09 (-0.05 to 0.22) mol C/m$^2$/yr). In the equatorial Atlantic and the equatorial Indian Ocean, MHW events have minimal to no effect on the air-sea CO$_2$ fluxes.

The spread in the air-sea CO$_2$ flux anomalies during MHWs across all observation-based products is considerable (Figure 1b). The primary contributors to this spread are the pCO$_2$ datasets, as indicated by the contrast between the purple and black ranges in Figure 1b. Minimal variation is observed between CO$_2$ flux anomalies calculated with the average pCO$_2$ product and different wind products (not shown), further underscoring the role of pCO$_2$ reconstructions as the primary source of uncertainty. As a result, significant CO$_2$ flux anomalies during MHW are only detectable in four of the eight study regions: the equatorial Pacific, the low-to-mid latitudes in both hemispheres, and the Southern Ocean. While statistical significant changes are observed in the Southern Ocean, a comprehensive assessment is hindered by the absence of the pCO$_2$ data, particularly during austral winter (Landschützer et al., 2016; Gray et al., 2018).

#### 3.2 Drivers of air-sea CO$_2$ flux changes during MHWs

To detect the drivers of air-sea CO$_2$ flux changes during MHWs we apply the Taylor decomposition to all air-sea flux components on global scale as well as for all regions. Note that the analysis of regions and globally, which do not show a significant response of the air-sea CO$_2$ flux during MHWs, helps to understand compensating processes and assessing the origin of the uncertainty.

At the global scale, all components of the air-sea CO$_2$ flux (gas transfer velocity, solubility, oceanic and atmospheric pCO$_2$; Equation (2)) collectively contribute to the reduced uptake of CO$_2$ by the ocean during MHWs (Figure 2a). Oceanic pCO$_2,o$ experiences a slight increase during MHWs, leading to an average reduction of air-sea CO$_2$ flux by $-0.012$ mol C m$^{-2}$ yr$^{-1}$. However, there is considerable variability across data products, ranging from $-0.052$ mol C m$^{-2}$ yr$^{-1}$ to positive contributions of 0.051 mol C...
Figure 1. a) Observation-based air-sea CO$_2$ flux anomalies during MHWs averaged over the 1990-2019 period and across all observation-based products. Data is only shown for regions where all six observation-based pCO$_2$ products have data. The grey dashed lines indicate the regions shown in panel b). b) Climatological mean air-sea CO$_2$ flux, mean air-sea CO$_2$ flux during MHWs and mean air-sea CO$_2$ flux anomalies during MHWs for the years 1990-2019. The bars represent the averages across all observation-based products. The black error lines represent the min-max spread across the 30 observation-based data products. The purple error lines represent the min-max spread originating from the six observation-based pCO$_2$ products using the average wind product.
Figure 2. Global and regional drivers of air-sea CO$_2$ flux anomalies during MHWs over the 1990-2019 period across all observation-based products. The blue bars represent the average contribution of each flux term to the air-sea CO$_2$ flux anomalies during MHWs with grey error bars representing the min-max spread across the 30 observation-based data products. The grey bar is the sum of all the contribution terms. For comparison, the horizontal black line is the averaged observation-based product air-sea CO$_2$ flux anomalies during MHWs, and the black error lines represent the min-max spread across the 30 observation-based data products. A positive contribution indicates anomalous uptake, while a negative contribution suggests anomalous outgassing.

$\text{m}^{-2} \text{yr}^{-1}$. Decreased wind speed, and consequently gas transfer velocity, during MHWs results in a negative contribution of -0.015 (-0.025 to -0.004) mol C m$^{-2}$ yr$^{-1}$ to the air-sea CO$_2$ flux. Moreover, the global decrease in solubility due to warmer sea surface temperatures as well as lower atmospheric pCO$_2$ during MHWs, also contribute negatively, with values of -0.010 (-0.013 to -0.008) mol C m$^{-2}$ yr$^{-1}$ and -0.015 (-0.016 to -0.015) mol C m$^{-2}$ yr$^{-1}$, respectively.

When analyzing the different regions individually (Figure 2b-i; Supplementary Figure S1), oceanic pCO$_2$,o changes emerge as the primary driver of air-sea CO$_2$ flux anomalies during MHWs in most regions. Notably, regions such as the North Pacific (Figure 2b), the equatorial Pacific (Figure 2f) and the Southern Ocean (Figure 2i) experience anomalously lower oceanic pCO$_2$,o (i.e., a positive pCO$_2$,o contribution), leading to in-
creased air-sea \( \text{CO}_2 \) fluxes during MHWs. Conversely, the low-mid latitudes in both hemi-

sphere (Figure 2d,h) experience higher oceanic \( \text{pCO}_{2,0} \) (i.e., a negative \( \text{pCO}_{2,0} \) contri-

bution) and therefore lower air-sea \( \text{CO}_2 \) fluxes during MHWs.

The secondary driver of air-sea \( \text{CO}_2 \) flux anomalies varies across regions. In the equa-
torial Pacific (Figure 2f), anomalous \( \text{CO}_2 \) uptake is also substantially driven by weaker

gas transfer velocities during MHWs (i.e. weaker winds). In the North Pacific (Figure 2b), reduced solubility and weaker gas transfer velocities somewhat offset the stronger

uptake. In the North Atlantic (Figure 2c), the anomalous outgassing is caused by a com-
bination of weaker gas transfer velocities and lower solubility, which reduce the region’s

ability to uptake \( \text{CO}_2 \) and outweigh the decrease in \( \text{pCO}_{2,0} \) observed during MHWs. In

the equatorial Indian (Figure 2e) and Atlantic Ocean (Figure 2g), the very small \( \text{CO}_2 \)

flux anomalies during MHWs are a result of small and counterbalancing contributions

of changes in oceanic \( \text{pCO}_{2,0} \) and the gas transfer velocities. The atmospheric \( \text{pCO}_{2,\text{atm}} \)

changes play a negligible role in all regions.

By breaking down the oceanic \( \text{pCO}_{2,0} \) anomalies during MHWs (Equation (3)), we can

attribute the flux response to a balance between thermal (temperature) and non-thermal
dissolved inorganic carbon (DIC) effects on oceanic \( \text{pCO}_{2,0} \) (Figure 3), along with changes

in alkalinity and salinity. In all ocean regions, the thermal effect - resulting from elevated

sea surface temperatures during MHWs - positively contributes to oceanic \( \text{pCO}_{2,0} \) anom-

alies. Globally, this effect increases oceanic \( \text{pCO}_{2,0} \) by 15.34 (15.24 to 15.39) \( \mu \text{atm} \). This

is due to the decrease in \( \text{CO}_2 \) solubility in seawater and due to an increase in \( \text{CO}_2 \) con-
centration from a shift in chemical equilibrium between carbonate species with rising tem-

peratures, both leading to anomalously higher oceanic \( \text{pCO}_{2,0} \). Simultaneously, lower

DIC concentrations during MHWs result in anomalously lower oceanic \( \text{pCO}_{2,0} \) of -18.12

(-19.11 to -16.16) \( \mu \text{atm} \). Changes in alkalinity contribute to a small increase in oceanic

\( \text{pCO}_{2,0} \) and salinity changes are negligible at the global scale.

While globally, the thermal and DIC effects on oceanic \( \text{pCO}_{2,0} \) nearly balance each other

out (Figure 3a), the dominance of either effect varies by region (Figure 3b-i; Supplemen-
tary Figure S2). In the equatorial Pacific (Figure 3f) and high latitude regions like the

North Pacific (Figure 3b), North Atlantic (Figure 3c), and Southern Ocean (Figure 3i),
the decrease in oceanic \( \text{pCO}_{2,0} \) anomalies driven by DIC outweighs the increase caused

by thermal effects. This DIC-driven effect is particularly notable in the equatorial Pa-
cific, where it counteracts both thermal and alkalinity-driven \( \text{pCO}_{2,0} \) increases during

MHWs, resulting in lower than usual \( \text{pCO}_{2,0} \) (-8.43 (-12.40 to 0.25) \( \mu \text{atm} \)) and reduced

outgassing fluxes. In contrast, in low to mid latitude regions (Figure 3d,h), the thermal-

drive increase in oceanic \( \text{pCO}_{2,0} \) typically dominates the flux response during MHWs.

Changes in alkalinity play a moderate role in the equatorial Pacific (Figure 3f) and equa-
torial Atlantic (Figure 3g). However, in all other regions, both alkalinity and salinity changes
play a negligible role.

It is important to note that a potential limitation of the Taylor decomposition is the as-
sumption of linearity as we know that the functions governing air-sea \( \text{CO}_2 \) flux are non-
linear. To check whether this limitation has an impact on our attribution of the drivers
we compare the sum of the Taylor decomposition terms with the calculated flux and driver
anomalies. In particular for the air-sea \( \text{CO}_2 \) flux changes (grey bar versus horizontal black
lines in Figures 2 and 3), there are slight discrepancies: the Taylor decomposition tends
to overestimate the flux anomalies in the North Atlantic (Figure 2b), equatorial Pacific
(Figure 2f) and low-mid latitudes (Figure 2d,h), while underestimating anomalies in the
North Pacific (Figure 2b). Thus, this limitation may alter our quantitative assessment
of the drivers, but we maintain confidence in the robustness of the qualitative findings
of the drivers.
Figure 3. Global and regional drivers of oceanic pCO$_2$ anomalies during MHWs over the 1990-2019 period across all observation-based products. The results are shown for regions where all six observation-based pCO$_2$ products have data. The blue bars represent the average contribution of each pCO$_2$ term to the total pCO$_2$ anomalies during MHWs with grey error bars representing the min-max spread across the 30 observation-based data products. The grey bar is the sum of all the contribution terms. For comparison, the horizontal black line is the averaged observation-based product oceanic pCO$_2$ anomalies during MHWs, and the black error lines represent the min-max spread across the 30 observation-based data products. A positive total contribution indicates an increase in oceanic pCO$_2$. 
3.3 Importance of MHW-induced CO\textsubscript{2} flux anomalies within its natural variability

Next, we examine the importance of CO\textsubscript{2} flux anomalies induced by MHWs in the broader context of natural variations in air-sea CO\textsubscript{2} exchange. Our aim is to determine whether strong CO\textsubscript{2} flux anomalies are primarily attributable to MHWs or if these events play a minor role in explaining the substantial variations in air-sea CO\textsubscript{2} fluxes.

Across much of the global ocean, particularly in the low-to-mid latitudes, Southern Ocean and Atlantic Ocean, the mean air-sea CO\textsubscript{2} flux anomalies during MHWs do not surpass the 80\% or 20\% percentile of average background flux variations (Figure 4). This suggests that MHWs do not distinctly induce strong anomalies in air-sea CO\textsubscript{2} fluxes in these regions. However, areas experiencing very strong positive or negative flux anomalies during MHWs relative to the natural variations in air-sea CO\textsubscript{2} fluxes are the equatorial Pacific, Northeast Pacific, and eastern Indian Ocean (regions depicted in Figure 4).

The pronounced CO\textsubscript{2} flux response during MHWs is particularly strong in the central equatorial Pacific, where mean CO\textsubscript{2} flux anomalies exceed the 80th percentile of the CO\textsubscript{2} flux distribution. These periods of extreme anomalous CO\textsubscript{2} uptake often coincide with
El Niño events in these regions (Oliver et al., 2019; Holbrook et al., 2019; Le Grix et al., 2021). For example, the strongest El Niño events in 2015/2016 and of 1997/98 align with the most extreme anomalous oceanic CO$_2$ uptake observed in the past 30 years in this region. Similarly, in the eastern North Pacific, we observe very strong anomalous outgassing occurring during MHWs, falling below the 20th percentile of the regional distribution. These strong outgassing events also often coincide with El Niño events.

In the eastern Indian Ocean, MHWs induce strong anomalous CO$_2$ outgassing (below the 20th percentile). For example, the MHWs in 2010/11 and 2015/16 off the northwest coast of Australia triggered extreme anomalous outgassing. In the northern North Pacific, substantial anomalous CO$_2$ uptake occurs during several MHW events in the earlier part of the time period, but the spread across data products is large.

4 Discussion and conclusions

We show that the global oceanic uptake of CO$_2$ is only slightly reduced during MHWs. However, regionally, MHWs can have a substantial impact on air-sea CO$_2$ fluxes. We find the flux responses to be mainly driven by changes in the partial pressure of CO$_2$ in the ocean, which are a net result of two competing mechanisms during MHWs: a thermal effect and a non-thermal DIC effect. In regions where decreases in oceanic pCO$_2$,o reduce CO$_2$ outgassing (e.g., equatorial Pacific) or increase CO$_2$ uptake (North Pacific and Southern Ocean), the primary driver is a reduction in DIC. In contrast, in regions (e.g., mid-latitudes) where increases in oceanic pCO$_2$,o diminish the air-sea CO$_2$ uptake, temperature rises are the main driving factor for changes in oceanic pCO$_2$,o. Furthermore, while air-sea CO$_2$ flux anomalies triggered by MHWs can stand out as extreme anomalies in some regions such as in parts of the tropics and the Northeastern Pacific, MHW events are not necessarily important drivers for strong air-sea CO$_2$ flux anomalies in many other regions.

Our results align with Mignot et al. (2022) in the equatorial Pacific, where DIC outweighs the temperature effect on oceanic pCO$_2$,o, resulting in a comparable reduction in outgassing (-31% in our study vs. 40% in Mignot et al. (2022)). The agreement is not surprising given that the analysis here is based on similar (though more) CO$_2$,o products as used in Mignot et al. (2022)). Additionally, the additional constraint of focusing on ‘persistent’ MHWs in Mignot et al. (2022) is not needed in this region, since long-lasting El Niño driven MHW are prevalent there (Holbrook et al., 2019). Our results suggest that Mignot et al. (2022)’s findings regarding anomalous outgassing in the mid-latitude North Pacific during MHWs, attributed to warmer temperatures, can be extrapolated to low-to-mid latitude CO$_2$ uptake regions in both hemispheres. This flux response resembles seasonal flux variations in these regions, where during summertime, the thermally driven increase in oceanic pCO$_2$,o is slightly counteracted by the decrease in oceanic pCO$_2$,o due to increased stratification which brings less DIC to the surface, but ultimately the thermal effect prevails (Fay & McKinley, 2017; Takahashi et al., 2002). In the high latitudes, MHWs induce different responses, with regions such as the Southern Ocean and North Pacific experiencing enhanced carbon uptake, while others like the North Atlantic show attenuated uptake. Nevertheless, findings of this study suggest that in high latitudes, the pCO$_2$,o response during MHWs is primarily driven by the non-thermal DIC effect. Furthermore, this DIC-driven pCO$_2$,o response controls the flux response in the Southern Ocean and the North Pacific, consistent with Duke et al. (2023).

Our study indicates a comparatively small impact of MHWs on air-sea CO$_2$ variability, contrasting with the substantial impact of land heat waves on regional carbon fluxes (Reichstein et al., 2013; Frank et al., 2015). Terrestrial heat waves (and droughts), such as the European events in 2003, 2010 and 2018, significantly reduced regional vegetation productivity due to various factors like soil moisture deficits, heat stress, and increased fire activity, leading to a net CO$_2$ uptake reduction (Ciais et al., 2005), though the regional...
drivers and responses may be complex (Bastos et al., 2020). Our study shows that MHWs in certain ocean regions can induce extreme CO$_2$ flux changes (e.g., Western Australia 2011 MHW; Arias-Ortiz et al. (2018)), but these events are more exceptional than common.

Furthermore, we show that observation-based products generally agree with each other regarding the direction of air-sea CO$_2$ flux anomalies during MHWs in the low-mid latitudes and the equatorial Pacific. However, discrepancies arise in higher latitudes, notably the North Pacific and Southern Ocean, possibly due to limited observational data in these regions. The lack of comprehensive data underscores the need for improved observation-based datasets and sustained data collection (Dong et al., 2024). Such data will enable us to enhance our understanding of how air-sea CO$_2$ fluxes respond to climate extremes, particularly in crucial carbon sink areas. Moreover, future research shall explore the influence of seasons and background states on the air-sea CO$_2$-flux response to MHWs, as the dominant effect (thermal versus non-thermal) on oceanic pCO$_2$,$_o$ may depend on the season (Burger & Frölicher, 2023) and the background state — the latter highly relevant under future climate change.

Open Research Section

The observational-based air-sea CO$_2$ flux data products are available under https://zenodo.org/records/5482547, the NOAA OISSTv2.1 data under https://www.ncei.noaa.gov/products/optimum-interpolation-sst, the Hadley Centre EN4.2.2 salinity data under https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-2.html, and the phosphate and silicate World Atlas 2018 data under https://www.ncei.noaa.gov/access/world-ocean-atlas-2018/. The analysis scripts used in this study will be available under a Zenodo repository link.

Acknowledgments

This work has received funding from the Swiss National Science Foundation (PP00P2_198897) and was supported by AtlantECO (project number: 862923) as well as TipESM and ClimTIP, which are both funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. We also thank the CSCS Swiss National Supercomputing Centre for computing resources.

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Observed regional impacts of marine heatwaves on air-sea CO$_2$ exchange

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Key Points:

- Marine heatwaves substantially affect local air-sea CO$_2$ fluxes via oceanic pCO$_2$ changes, but their global impacts remains minor.
- During MHWs, tropics decrease outgassing from lower DIC, while mid latitudes weaken uptake due to thermally induced rise in oceanic pCO$_2$.
- MHW events can trigger extreme CO$_2$ flux anomalies, notably in the eastern equatorial Pacific, Indian Ocean and Northeast Pacific.
**Abstract**

Marine heatwaves (MHWs) have devastating effects on ecosystems and impact regional air-sea CO$_2$ exchange. Yet a global assessment of these regional impacts of MHWs on the air-sea CO$_2$ exchange is missing. Here, we analyze thirty global observation-based air-sea CO$_2$ flux datasets from 1990 to 2019. We observe minimal reduction in global oceanic CO$_2$ uptake during MHWs. Regional variations are evident with the equatorial Pacific experiencing a 31% (spread across datasets: 3–49%) reduction in carbon release, suggesting that MHWs are the dominant drivers of strong air-sea CO$_2$ flux anomalies in this region. In low-to-mid latitudes, MHWs cause a 29% (19–37%) decrease in air-sea CO$_2$ uptake. Reduced dissolved inorganic carbon in the tropics weakens outgassing, while high ocean temperatures diminish uptake in the low-to-mid latitudes. In the North Pacific and Southern Ocean, enhanced carbon uptake occurs during MHWs, but uncertainties in pCO$_2$ datasets limit a comprehensive assessment in these regions.

**Plain language summary**

Periods of unusually warm sea surface temperatures have recently been shown to impact the exchange of carbon dioxide between the surface ocean and overlying atmosphere. We find that extremely warm sea surface temperatures (marine heatwaves) have a small impact on the ocean’s overall ability to take up carbon dioxide from the atmosphere, but depending on the region the local exchange of carbon dioxide between the ocean and atmosphere can be substantially impacted. In tropical regions, the ocean’s usual release of carbon dioxide to the atmosphere is reduced during marine heatwaves due to lower dissolved inorganic carbon in the surface ocean. In low to mid latitude regions, the ocean’s uptake of carbon from the atmosphere is reduced during marine heatwaves due to the effect of warmer temperatures. A clear consensus on the impact of marine heatwaves in the North Pacific and Southern Ocean does not emerge due to data limitations. While heatwaves in the ocean can cause substantial changes in air-sea carbon dioxide exchange in some tropical areas and the Northeast Pacific, they are not the main reason for large monthly changes in globally integrated air-sea carbon dioxide exchange.

**1 Introduction**

Human-induced carbon dioxide (CO$_2$) emissions are the primary driver of climate change (IPCC, 2021), with the ocean playing a crucial role in mitigating global warming by taking up about a quarter of these emissions (Friedlingstein et al., 2023). An accurate quantification and understanding of the variability of air-sea CO$_2$ fluxes is essential for predicting future climate trends (Joos et al., 1999) and assessing the ocean ecosystem response (Gattuso et al., 2015).

In recent decades, prolonged periods of anomalously warm sea surface temperatures, known as marine heatwaves (MHWs; Pearce and Feng (2013); Hobday et al. (2016)), have occurred across all ocean basins (Frölicher & Laufkötter, 2018; Oliver et al., 2021), posing substantial risks to marine species, ecosystems and ecosystem services (Collins et al., 2019; Cheung & Frölicher, 2020; Hughes et al., 2017; Smale et al., 2019; Cheung et al., 2021). With global ocean warming, MHWs are becoming more frequent, intense, and prolonged (Oliver et al., 2018; Frölicher et al., 2018). Individual MHWs are generated by a combination of local oceanic and atmospheric processes including air-sea heat flux, horizontal and vertical temperature advection, and vertical mixing (Vogt et al., 2022; Bian et al., 2023), and are often associated with large-scale climate phenomena such as the El Niño Southern Oscillation (Oliver et al., 2021; Holbrook et al., 2019).

Recent research has highlighted the significance of MHWs in influencing regional oceanic pCO$_2$ and air-sea CO$_2$ fluxes (Arias-Ortiz et al., 2018; Mignot et al., 2022; Duke et al., 2023; Edwing et al., 2024). For example, Mignot et al. (2022) identified reduced oceanic
CO₂ release in the equatorial Pacific and decreased oceanic CO₂ uptake around 40°N in the North Pacific. Duke et al. (2023) examined the North Pacific subpolar gyre, revealing substantial anomalous oceanic uptake of CO₂ during recent MHWs due to limited wintertime entrainment and therefore lower oceanic pCO₂. Additionally, Arias-Ortiz et al. (2018) suggested significant carbon release from seagrass carbon stocks to the atmosphere following the Western Australia 2011 MHW. Despite these insights, a comprehensive global assessment of MHWs impacts on air-sea CO₂ fluxes and their driving mechanisms is lacking. Moreover, understanding how CO₂ flux anomalies during MHWs compare to overall flux variability remains limited, hindering a comprehensive evaluation of the importance of MHWs for air-sea CO₂ flux variability.

In this study, we explore the impacts of MHW events on air-sea CO₂ exchange. Using an ensemble of observation-based pCO₂ and wind products spanning from 1990 to 2019, we initially assess the global and regional impacts of MHW events on air-sea CO₂ fluxes. Subsequently, we identify the underlying mechanisms driving flux anomalies during MHWs. Finally, we contextualize these anomalies within the broader spectrum of natural CO₂ flux variability to assess their relative significance in total regional CO₂ flux variability.

2 Methods

2.1 Observation-based data

To identify MHWs, we use the global observation-based daily-mean sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration (NOAA; Daily Optimum Interpolation Sea Surface Temperature OISST dataset v2.1, Huang et al., 2021). This comprehensive dataset combines in situ ship and buoy sea surface temperature observations with satellite-derived measurements from the Advanced Very High-Resolution Radiometer. Through interpolation, data gaps are filled to create a spatially and temporally complete representation of sea surface temperature. To ensure consistency with the CO₂ flux and oceanic pCO₂ data, the daily mean SST data is regridded from 0.25° × 0.25° to 1° × 1° and averaged from daily to monthly-mean values, spanning the period 1982 to 2021.

For the assessment of CO₂ flux anomalies during MHWs, we rely on CO₂ flux estimates derived from the SeaFlux version 2021.04 ensemble data product (Fay et al., 2021). This dataset integrates six global observation-based pCO₂ products, all based on the Surface Ocean Carbon Dioxide Atlas (SOCAT) pCO₂ dataset (Bakker et al., 2016), alongside five global wind reanalyses (Supporting Information Tables S1 and S2). Combined, we obtain 30 distinct air-sea CO₂ flux datasets at monthly intervals, covering the period 1990 to 2019 on a 1° × 1° grid. We only analyze CO₂ flux data in regions where data from all six observation-based pCO₂ products are available.

To analyze the drivers of CO₂ flux anomalies during MHWs, we use the LIARv2 alkalinity regression algorithm (Carter et al., 2018). This algorithm utilizes salinity data from the Hadley Centre (EN4.2.2; Good et al., 2013) in conjunction with sea surface temperature data to compute total alkalinity on a 1° × 1° grid. Dissolved Inorganic Carbon (DIC) is then calculated with CO2SYS (Humphreys et al., 2022) using the estimated total alkalinity, pCO₂ from the six different SeaFlux pCO₂ data products, temperature, salinity, and monthly mean climatologies of phosphate and silicate from the World Atlas 2018 (WOA18; Boyer et al., 2018; Garcia et al., 2019).

2.2 MHW definition and air-sea CO₂ flux anomalies

A MHW is identified when the local linearly detrended monthly-mean SST surpasses the local seasonally-varying 90th percentile of SST. The seasonally varying 90th percentile is calculated for each calendar month separately and is based on linearly detrended monthly-
mean SST data spanning from 1982 to 2021. The threshold is set to capture extreme temperature anomalies while ensuring a sufficiently large sample size of MHW months for robust statistical analyses. In contrast to the prevailing approach in MHW studies (Hobday et al., 2016; Le Grix et al., 2021), we define MHWs here on monthly anomalies rather than daily anomalies to be consistent with temporal resolution of the CO₂ flux products.

We calculate the monthly mean air-sea CO₂ flux anomalies during MHWs by initially linearly detrending the air-sea CO₂ flux over the period 1990 to 2019. Subsequently, the anomalies during MHWs are derived as deviations from the climatological seasonal cycle of monthly-mean CO₂ fluxes during MHWs.

We divide the global ocean into eight study regions (Figure 1a, and Supporting Information Table S3) given the diverse characteristics of air-sea CO₂ flux, such as strong or weak CO₂ sink or source regions. To assess whether the product-ensemble-mean air-sea CO₂ flux during MHWs significantly differs from the mean CO₂ flux, we conduct a standard two-sample t-test globally and for each study region, using the 5% significance level (Wilks, 2019).

2.3 Decomposition of air-sea CO₂ flux anomalies into drivers

To determine the driving mechanisms behind the air-sea CO₂ flux anomalies during MHWs, we conduct a first-order Taylor series decomposition of the air-sea flux components. This analysis allows us to quantitatively determine the contribution of the solubility, gas transfer velocity, oceanic pCO₂, and atmospheric pCO₂ to the overall air-sea CO₂ flux anomaly during MHWs.

SeaFlux computes the net air-sea CO₂ flux \( F_{\text{air-sea}} \) via the adapted bulk formula established by Wanninkhof (1992):

\[
F_{\text{air-sea}} = k_w \cdot \text{sol} \cdot (p_{\text{CO}_2,a} - p_{\text{CO}_2,o}),
\]

where \( k_w \) is the gas transfer velocity (in units m s\(^{-1}\)), \( \text{sol} \) is the solubility of CO₂ in seawater (mol m\(^{-3}\)µatm\(^{-1}\)), \( p_{\text{CO}_2,a} \) represents the partial pressure of atmospheric CO₂ in the marine boundary layer (µatm), and \( p_{\text{CO}_2,o} \) is the partial pressure of surface ocean CO₂ (µatm). Note that the bulk formula is adapted to omit sea ice regions as not all data products encompass these regions.

The first order Taylor series decomposition of the air-sea CO₂ flux anomalies during MHWs (referred to hereafter as \( \Delta F_{\text{air-sea}} \)) is as follows:

\[
\Delta F_{\text{air-sea}} \approx \frac{\partial F_{\text{air-sea}}}{\partial k_w} \cdot \Delta k_w + \frac{\partial F_{\text{air-sea}}}{\partial \text{sol}} \cdot \Delta \text{sol} + \frac{\partial F_{\text{air-sea}}}{\partial p_{\text{CO}_2,o}} \cdot \Delta p_{\text{CO}_2,o} + \frac{\partial F_{\text{air-sea}}}{\partial p_{\text{CO}_2,a}} \cdot \Delta p_{\text{CO}_2,a},
\]

The right hand side of equation (2) represents the contributions of the gas transfer velocity, solubility, and oceanic and atmospheric partial pressure of CO₂. The delta values represent the mean anomalies of the variables during MHWs and the partial derivatives are calculated with the temporal mean values.

The oceanic pCO₂ anomalies are further decomposed as:

\[
\Delta p_{\text{CO}_2,o} \approx \frac{\partial p_{\text{CO}_2,o}}{\partial \text{DIC}} \cdot \Delta \text{DIC} + \frac{\partial p_{\text{CO}_2,o}}{\partial \text{ALK}} \cdot \Delta \text{ALK} + \frac{\partial p_{\text{CO}_2,o}}{\partial T} \cdot \Delta T + \frac{\partial p_{\text{CO}_2,o}}{\partial S} \cdot \Delta S
\]
where oceanic $pCO_{2,o}$ is a function of sea surface dissolved inorganic carbon (DIC), alkalinity (ALK), temperature (T), and salinity (S). The 'mocsy 2.0' Fortran 95 routine (Orr & Epitalon, 2015) is used to calculate the partial derivatives, evaluated at temporal mean values for S, T, DIC, ALK, phosphate, and silicate.

3 Results

3.1 Global and regional response of air-sea $CO_2$ fluxes during MHWs

Globally, we observe a small reduction in the oceanic uptake of $CO_2$ by an average of -0.04 mol C/m$^2$/yr during MHWs, with values ranging from 0.01 (anomalous uptake) to -0.11 mol (anomalous release) C/m$^2$/yr depending on the dataset used (Figure 1b). This reduction corresponds to approximately 8% (3 to 19%) of the net global oceanic uptake of $CO_2$ during the time period from 1990 to 2019. In most regions, the $CO_2$ flux - whether into or out of the ocean in the climatological mean - is diminished during MHWs. Consequently, the air-sea $CO_2$ flux anomaly pattern during MHWs is reversed from the climatological mean $CO_2$ flux pattern (Figure 1a).

Although the global $CO_2$ flux response during MHWs is minor, we observe substantial $CO_2$ flux responses on the regional scale. The $CO_2$ uptake in the North Atlantic and the low-mid latitude regions in both the northern and southern hemispheres is reduced by an average of -0.10 mol C/m$^2$/yr (-0.24 to -0.00), -0.17 mol C/m$^2$/yr (-0.22 to -0.11), and -0.12 mol C/m$^2$/yr (-0.18 to -0.04), respectively. In the equatorial Pacific, $CO_2$ outgassing is reduced by an average of 0.30 (0.03 to 0.48) mol C/m$^2$/yr. However, this general pattern of reduced air-sea $CO_2$ fluxes does not apply to the North Pacific and the Southern Ocean. In these regions, $CO_2$ uptake is even stronger during MHWs (North Pacific: 0.14 (-0.12 to 0.30); Southern Ocean: 0.09 (-0.05 to 0.22) mol C/m$^2$/yr). In the equatorial Atlantic and the equatorial Indian Ocean, MHW events have minimal to no effect on the air-sea $CO_2$ fluxes.

The spread in the air-sea $CO_2$ flux anomalies during MHWs across all observation-based products is considerable (Figure 1b). The primary contributors to this spread are the $pCO_2$ datasets, as indicated by the contrast between the purple and black ranges in Figure 1b. Minimal variation is observed between $CO_2$ flux anomalies calculated with the average $pCO_2$ product and different wind products (not shown), further underscoring the role of $pCO_2$ reconstructions as the primary source of uncertainty. As a result, significant $CO_2$ flux anomalies during MHW are only detectable in four of the eight study regions: the equatorial Pacific, the low-to-mid latitudes in both hemispheres, and the Southern Ocean. While statistical significant changes are observed in the Southern Ocean, a comprehensive assessment is hindered by the absence of the $pCO_2$ data, particularly during austral winter (Landschützer et al., 2016; Gray et al., 2018).

3.2 Drivers of air-sea $CO_2$ flux changes during MHWs

To detect the drivers of air-sea $CO_2$ flux changes during MHWs we apply the Taylor decomposition to all air-sea flux components on global scale as well as for all regions. Note that the analysis of regions and globally, which do not show a significant response of the air-sea $CO_2$ flux during MHWs, helps to understand compensating processes and assessing the origin of the uncertainty.

At the global scale, all components of the air-sea $CO_2$ flux (gas transfer velocity, solubility, oceanic and atmospheric $pCO_2$: Equation (2)) collectively contribute to the reduced uptake of $CO_2$ by the ocean during MHWs (Figure 2a). Oceanic $pCO_{2,o}$ experiences a slight increase during MHWs, leading to an average reduction of air-sea $CO_2$ flux by -0.012 mol C m$^{-2}$ yr$^{-1}$. However, there is considerable variability across data products, ranging from -0.052 mol C m$^{-2}$ yr$^{-1}$ to positive contributions of 0.051 mol C
Figure 1. a) Observation-based air-sea CO$_2$ flux anomalies during MHWs averaged over the 1990-2019 period and across all observation-based products. Data is only shown for regions where all six observation-based pCO$_2$ products have data. The grey dashed lines indicate the regions shown in panel b). b) Climatological mean air-sea CO$_2$ flux, mean air-sea CO$_2$ flux during MHWs and mean air-sea CO$_2$ flux anomalies during MHWs for the years 1990-2019. The bars represent the averages across all observation-based products. The black error lines represent the min-max spread across the 30 observation-based data products. The purple error lines represent the min-max spread originating from the six observation-based pCO$_2$ products using the average wind product.
Figure 2. Global and regional drivers of air-sea CO$_2$ flux anomalies during MHWs over the 1990-2019 period across all observation-based products. The blue bars represent the average contribution of each flux term to the air-sea CO$_2$ flux anomalies during MHWs with grey error bars representing the min-max spread across the 30 observation-based data products. The grey bar is the sum of all the contribution terms. For comparison, the horizontal black line is the averaged observation-based product air-sea CO$_2$ flux anomalies during MHWs, and the black error lines represent the min-max spread across the 30 observation-based data products. A positive contribution indicates anomalous uptake, while a negative contribution suggests anomalous outgassing.

m$^{-2}$ yr$^{-1}$. Decreased wind speed, and consequently gas transfer velocity, during MHWs results in a negative contribution of -0.015 (-0.025 to -0.004) mol C m$^{-2}$ yr$^{-1}$ to the air-sea CO$_2$ flux. Moreover, the global decrease in solubility due to warmer sea surface temperatures as well as lower atmospheric pCO$_2$,a during MHWs, also contribute negatively, with values of -0.010 (-0.013 to -0.008) mol C m$^{-2}$ yr$^{-1}$ and -0.015 (-0.016 to -0.015) mol C m$^{-2}$ yr$^{-1}$, respectively.

When analyzing the different regions individually (Figure 2b-i; Supplementary Figure S1), oceanic pCO$_2$,o changes emerge as the primary driver of air-sea CO$_2$ flux anomalies during MHWs in most regions. Notably, regions such as the North Pacific (Figure 2b), the equatorial Pacific (Figure 2f) and the Southern Ocean (Figure 2i) experience anomalously lower oceanic pCO$_2$,o (i.e., a positive pCO$_2$,o contribution), leading to in-
increased air-sea CO$_2$ fluxes during MHWs. Conversely, the low-mid latitudes in both hemi-

spheres (Figure 2d, h) experience higher oceanic pCO$_2$ (i.e., a negative pCO$_2$ contribu-

tion) and therefore lower air-sea CO$_2$ fluxes during MHWs.

The secondary driver of air-sea CO$_2$ flux anomalies varies across regions. In the equa-
torial Pacific (Figure 2f), anomalous CO$_2$ uptake is also substantially driven by weaker

gas transfer velocities during MHWs (i.e. weaker winds). In the North Pacific (Figure

2b), reduced solubility and weaker gas transfer velocities somewhat offset the stronger

uptake. In the North Atlantic (Figure 2c), the anomalous outgassing is caused by a com-
bination of weaker gas transfer velocities and lower solubility, which reduce the region’s

ability to uptake CO$_2$ and outweigh the decrease in pCO$_2$ observed during MHWs. In

the equatorial Indian (Figure 2e) and Atlantic Ocean (Figure 2g), the very small CO$_2$

flux anomalies during MHWs are a result of small and counterbalancing contributions

of changes in oceanic pCO$_2$ and the gas transfer velocities. The atmospheric pCO$_2$,a

changes play a negligible role in all regions.

By breaking down the oceanic pCO$_2$ anomalies during MHWs (Equation (3)), we can

attribute the flux response to a balance between thermal (temperature) and non-thermal
dissolved inorganic carbon (DIC) effects on oceanic pCO$_2$ (Figure 3), along with changes

in alkalinity and salinity. In all ocean regions, the thermal effect - resulting from elevated

sea surface temperatures during MHWs - positively contributes to oceanic pCO$_2$ anom-

alies. Globally, this effect increases oceanic pCO$_2$ by 15.34 (15.24 to 15.39) µatm. This

is due to the decrease in CO$_2$ solubility in seawater and due to an increase in CO$_2$

concentration from a shift in chemical equilibrium between carbonate species with rising tem-

peratures, both leading to anomalously lower oceanic pCO$_2$. Simultaneously, lower

DIC concentrations during MHWs result in anomalously lower oceanic pCO$_2$ of -18.12

(-19.11 to -16.16) µatm. Changes in alkalinity contribute to a small increase in oceanic

pCO$_2$ and salinity changes are negligible at the global scale.

While globally, the thermal and DIC effects on oceanic pCO$_2$ nearly balance each other

out (Figure 3a), the dominance of either effect varies by region (Figure 3b-i; Supplemen-
tary Figure S2). In the equatorial Pacific (Figure 3f) and high latitude regions like the

North Pacific (Figure 3b), North Atlantic (Figure 3c), and Southern Ocean (Figure 3i),

the decrease in oceanic pCO$_2$ anomalies driven by DIC outweighs the increase caused

by thermal effects. This DIC-driven effect is particularly notable in the equatorial Pa-
cific, where it counteracts both thermal and alkalinity-driven pCO$_2$ increases during

MHWs, resulting in lower than usual pCO$_2$ (-8.43 (-12.40 to 0.25) µatm) and reduced

outgassing fluxes. In contrast, in low to mid latitude regions (Figure 3d,h), the thermal-
drive increase in oceanic pCO$_2$ typically dominates the flux response during MHWs.

Changes in alkalinity play a moderate role in the equatorial Pacific (Figure 3f) and equa-
torial Atlantic (Figure 3g). However, in all other regions, both alkalinity and salinity changes

play a negligible role.

It is important to note that a potential limitation of the Taylor decomposition is the as-
sumption of linearity as we know that the functions governing air-sea CO$_2$ flux are non-

linear. To check whether this limitation has an impact on our attribution of the drivers

we compare the sum of the Taylor decomposition terms with the calculated flux and driver

anomalies. In particular for the air-sea CO$_2$ flux changes (grey bar versus horizontal black

lines in Figures 2 and 3), there are slight discrepancies: the Taylor decomposition tends
to overestimate the flux anomalies in the North Atlantic (Figure 2b), equatorial Pacific
(Figure 2f) and low-mid latitudes (Figure 2d, h), while underestimating anomalies in the

North Pacific (Figure 2b). Thus, this limitation may alter our quantitative assessment

of the drivers, but we maintain confidence in the robustness of the qualitative findings

of the drivers.
Figure 3. Global and regional drivers of oceanic pCO\textsubscript{2,0} anomalies during MHWs over the 1990-2019 period across all observation-based products. The results are shown for regions where all six observation-based pCO\textsubscript{2,0} products have data. The blue bars represent the average contribution of each pCO\textsubscript{2,0} term to the total pCO\textsubscript{2,0} anomalies during MHWs with grey error bars representing the min-max spread across the 30 observation-based data products. The grey bar is the sum of all the contribution terms. For comparison, the horizontal black line is the averaged observation-based product oceanic pCO\textsubscript{2,0} anomalies during MHWs, and the black error lines represent the min-max spread across the 30 observation-based data products. A positive total contribution indicates an increase in oceanic pCO\textsubscript{2,0}. 
Figure 4. Global pattern of the percentile associated with the mean air-sea CO\textsubscript{2} flux anomalies averaged over all MHW months, compared to the local empirical distribution of monthly detrended air-sea CO\textsubscript{2} flux anomalies from 1990-2019. For three specific ‘extreme’ regions where the percentile of air-sea CO\textsubscript{2} flux anomalies exceeds 80% or falls below 20% of the average regional distribution, the time series of the mean monthly detrended air-sea CO\textsubscript{2} flux anomalies across all data products, detrended sea surface temperature anomalies (blue lines) and identified MHW events (red shading) are shown. The black shading shows the min-max range across all 30 air-sea CO\textsubscript{2} flux data products.

3.3 Importance of MHW-induced CO\textsubscript{2} flux anomalies within its natural variability

Next, we examine the importance of CO\textsubscript{2} flux anomalies induced by MHWs in the broader context of natural variations in air-sea CO\textsubscript{2} exchange. Our aim is to determine whether strong CO\textsubscript{2} flux anomalies are primarily attributable to MHWs or if these events play a minor role in explaining the substantial variations in air-sea CO\textsubscript{2} fluxes.

Across much of the global ocean, particularly in the low-to-mid latitudes, Southern Ocean and Atlantic Ocean, the mean air-sea CO\textsubscript{2} flux anomalies during MHWs do not surpass the 80% or 20% percentile of average background flux variations (Figure 4). This suggests that MHWs do not distinctly induce strong anomalies in air-sea CO\textsubscript{2} fluxes in these regions. However, areas experiencing very strong positive or negative flux anomalies during MHWs relative to the natural variations in air-sea CO\textsubscript{2} fluxes are the equatorial Pacific, Northeast Pacific, and eastern Indian Ocean (regions depicted in Figure 4).

The pronounced CO\textsubscript{2} flux response during MHWs is particularly strong in the central equatorial Pacific, where mean CO\textsubscript{2} flux anomalies exceed the 80th percentile of the CO\textsubscript{2} flux distribution. These periods of extreme anomalous CO\textsubscript{2} uptake often coincide with
El Niño events in these regions (Oliver et al., 2019; Holbrook et al., 2019; Le Grix et al., 2021). For example, the strongest El Niño events in 2015/2016 and of 1997/98 align with the most extreme anomalous oceanic CO$_2$ uptake observed in the past 30 years in this region. Similarly, in the eastern North Pacific, we observe very strong anomalous outgassing occurring during MHWs, falling below the 20th percentile of the regional distribution. These strong outgassing events also often coincide with El Niño events.

In the eastern Indian Ocean, MHWs induce strong anomalous CO$_2$ outgassing (below the 20th percentile). For example, the MHWs in 2010/11 and 2015/16 off the northwest coast of Australia triggered extreme anomalous outgassing. In the northern North Pacific, substantial anomalous CO$_2$ uptake occurs during several MHW events in the earlier part of the time period, but the spread across data products is large.

4 Discussion and conclusions

We show that the global oceanic uptake of CO$_2$ is only slightly reduced during MHWs. However, regionally, MHWs can have a substantial impact on air-sea CO$_2$ fluxes. We find the flux responses to be mainly driven by changes in the partial pressure of CO$_2$ in the ocean, which are a net result of two competing mechanisms during MHWs: a thermal effect and a non-thermal DIC effect. In regions where decreases in oceanic pCO$_2$,o reduce CO$_2$ outgassing (e.g., equatorial Pacific) or increase CO$_2$ uptake (North Pacific and Southern Ocean), the primary driver is a reduction in DIC. In contrast, in regions (e.g., mid-latitudes) where increases in oceanic pCO$_2$,o diminish the air-sea CO$_2$ uptake, temperature rises are the main driving factor for changes in oceanic pCO$_2$,o. Furthermore, while air-sea CO$_2$ flux anomalies triggered by MHWs can stand out as extreme anomalies in some regions such as in parts of the tropics and the Northeastern Pacific, MHW events are not necessarily important drivers for strong air-sea CO$_2$ flux anomalies in many other regions.

Our results align with Mignot et al. (2022) in the equatorial Pacific, where DIC outweighs the temperature effect on oceanic pCO$_2$,o, resulting in a comparable reduction in outgassing (-31% in our study vs. 40% in Mignot et al. (2022)). The agreement is not surprising given that the analysis here is based on similar (though more) CO$_2$,o products as used in Mignot et al. (2022)). Additionally, the additional constraint of focusing on ‘persistent’ MHWs in Mignot et al. (2022) is not needed in this region, since long-lasting El Niño driven MHW are prevalent there (Holbrook et al., 2019). Our results suggest that Mignot et al. (2022)’s findings regarding anomalous outgassing in the mid-latitude North Pacific during MHWs, attributed to warmer temperatures, can be extrapolated to low-to-mid latitude CO$_2$ uptake regions in both hemispheres. This flux response resembles seasonal flux variations in these regions, where during summertime, the thermally driven increase in oceanic pCO$_2$,o is slightly counteracted by the decrease in oceanic pCO$_2$,o due to increased stratification which brings less DIC to the surface, but ultimately the thermal effect prevails (Fay & McKinley, 2017; Takahashi et al., 2002). In the high latitudes, MHWs induce different responses, with regions such as the Southern Ocean and North Pacific experiencing enhanced carbon uptake, while others like the North Atlantic show attenuated uptake. Nevertheless, findings of this study suggest that in high latitudes, the pCO$_2$,o response during MHWs is primarily driven by the non-thermal DIC effect. Furthermore, this DIC-driven pCO$_2$,o response controls the flux response in the Southern Ocean and the North Pacific, consistent with Duke et al. (2023).

Our study indicates a comparatively small impact of MHWs on air-sea CO$_2$ variability, contrasting with the substantial impact of land heat waves on regional carbon fluxes (Reichstein et al., 2013; Frank et al., 2015). Terrestrial heat waves (and droughts), such as the European events in 2003, 2010 and 2018, significantly reduced regional vegetation productivity due to various factors like soil moisture deficits, heat stress, and increased fire activity, leading to a net CO$_2$ uptake reduction (Ciais et al., 2005), though the regional
drivers and responses may be complex (Bastos et al., 2020). Our study shows that MHWs
in certain ocean regions can induce extreme CO$_2$ flux changes (e.g., Western Australia
2011 MHW; Arias-Ortiz et al. (2018)), but these events are more exceptional than com-
mon.

Furthermore, we show that observation-based products generally agree with each other
regarding the direction of air-sea CO$_2$ flux anomalies during MHWs in the low-mid lat-
titudes and the equatorial Pacific. However, discrepancies arise in higher latitudes, no-
tably the North Pacific and Southern Ocean, possibly due to limited observational data
in these regions. The lack of comprehensive data underscores the need for improved observation-
based datasets and sustained data collection (Dong et al., 2024). Such data will enable
us to enhance our understanding of how air-sea CO$_2$ fluxes respond to climate extremes,
particularly in crucial carbon sink areas. Moreover, future research shall explore the in-
fuence of seasons and background states on the air-sea CO$_2$-flux response to MHWs, as
the dominant effect (thermal versus non-thermal) on oceanic pCO$_2$ may depend on the
season (Burger & Frölicher, 2023) and the background state — the latter highly relevant
under future climate change.

Open Research Section

The observational-based air-sea CO$_2$ flux data products are available under https://zenodo.org/records/5482547,
the NOAA OISSTv2.1 data under https://www.nci.noaa.gov/products/optimum-interpolation-
sst, the Hadley Centre EN4.2.2 salinity data under https://www.metoffice.gov.uk/hadobs/en4/download-
en4-2-2.html, and the phosphate and silicate World Atlas 2018 data under https://www.ncei.noaa.gov/access/world-
ocean-atlas-2018/. The analysis scripts used in this study will be available under a Zen-
do repository link.

Acknowledgments

This work has received funding from the Swiss National Science Foundation (PP00P2_198897)
and was supported by AtlantECO (project number: 862923) as well as TipESM and ClimTIP,
which are both funded by the European Union. Views and opinions expressed are how-
ever those of the author(s) only and do not necessarily reflect those of the European Union
or the European Climate and Environment Executive Agency (CINEA).

Neither the European Union nor the granting authority can be held responsible for them.

We also thank the CSCS Swiss National Supercomputing Centre for computing resources.

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Supporting Information for "Observed regional impacts of marine heatwaves on air-sea CO\textsubscript{2} exchange"

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Table S1: Summary of the six observation-based $p$CO$_2$ products used in SeaFlux.

<table>
<thead>
<tr>
<th>$p$CO$_2$ mapping product</th>
<th>Area coverage (% global ocean)</th>
<th>Surface-ocean $p$CO$_2$ data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMEMS-FFNN</td>
<td>89%</td>
<td>SOCAT v5</td>
<td>Denvil-Sommer et al. (2019) Chau et al. (2022)</td>
</tr>
<tr>
<td>CSIR-ML6</td>
<td>93%</td>
<td>SOCAT v5</td>
<td>Gregor et al. (2019)</td>
</tr>
<tr>
<td>JENA-MLS</td>
<td>100%</td>
<td>SOCAT v1.5</td>
<td>Rödenbeck et al. (2013)</td>
</tr>
<tr>
<td>JMA-MLR</td>
<td>85%</td>
<td>SOCAT v5</td>
<td>Iida et al. (2020)</td>
</tr>
<tr>
<td>MPI-SOMFFN</td>
<td>89%</td>
<td>SOCAT v5</td>
<td>Landschützer et al. (2014)</td>
</tr>
<tr>
<td>NIES-FNN</td>
<td>91%</td>
<td>SOCAT v2</td>
<td>Zeng et al. (2014)</td>
</tr>
</tbody>
</table>

Table S2: Summary of the five observation-based wind products used in combination with the observation-based $p$CO$_2$ products in SeaFlux. Mean wind speed is given for the ice-free ocean for the period 1990 to 2019.

<table>
<thead>
<tr>
<th>Wind product name</th>
<th>Temporal Resolution (hr)</th>
<th>Spatial Resolution (°)</th>
<th>Date range</th>
<th>Mean speed (m s$^{-1}$)</th>
<th>Scaling ($a$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-Calibrated Multi-Platform v2</td>
<td>6</td>
<td>0.25</td>
<td>1988-present</td>
<td>7.7</td>
<td>0.257</td>
<td>Atlas et al. (2011)</td>
</tr>
<tr>
<td>ECMWF Reanalysis 5th Generation</td>
<td>1</td>
<td>0.25</td>
<td>1979-present</td>
<td>7.5</td>
<td>0.271</td>
<td>Hersbach et al. (2020)</td>
</tr>
<tr>
<td>Japanese 55-year Reanalysis</td>
<td>3</td>
<td>0.50</td>
<td>1958-present</td>
<td>7.6</td>
<td>0.260</td>
<td>Kobayashi et al. (2015)</td>
</tr>
<tr>
<td>NCEP-NCAR reanalysis 1</td>
<td>6</td>
<td>2.50</td>
<td>1948-present</td>
<td>7.2</td>
<td>0.287</td>
<td>Kalnay et al. (1996)</td>
</tr>
<tr>
<td>NCEP-NCAR reanalysis 2</td>
<td>6</td>
<td>2.50</td>
<td>1979-present</td>
<td>8.3</td>
<td>0.216</td>
<td>Kanamitsu et al. (2002)</td>
</tr>
</tbody>
</table>
Table S3: Definition of regional latitude–longitude boxes.

<table>
<thead>
<tr>
<th>Region</th>
<th>Longitude range</th>
<th>Latitude range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Pacific</td>
<td>140°E - 130°W</td>
<td>65°N - 40°N</td>
</tr>
<tr>
<td>Northern Atlantic</td>
<td>70°W - 10°E</td>
<td>65°N - 40°N</td>
</tr>
<tr>
<td>Low-Mid Latitude Northern Hemisphere</td>
<td>Full</td>
<td>10°N - 40°N</td>
</tr>
<tr>
<td>Equatorial Indian</td>
<td>40°E - 125°E</td>
<td>10°S - 10°N</td>
</tr>
<tr>
<td>Equatorial Pacific</td>
<td>125°E - 80°W</td>
<td>10°S - 10°N</td>
</tr>
<tr>
<td>Equatorial Atlantic</td>
<td>77°W - 10°E</td>
<td>10°S - 10°N</td>
</tr>
<tr>
<td>Low-Mid Latitude Southern Hemisphere</td>
<td>Full</td>
<td>10°S - 45°S</td>
</tr>
<tr>
<td>Southern Ocean</td>
<td>Full</td>
<td>65°S - 45°S</td>
</tr>
</tbody>
</table>
Figure S1: Global maps of the Taylor decomposition of the air-sea CO$_2$ flux anomalies during MHWs over the 1990-2019 period averaged across all observation-based products. The left hand column shows the SeaFlux anomaly (top), the sum of the flux decomposition contributions (middle), and the difference between the two (bottom). The right hand column shows the contributions of each flux component ($k_w$, solubility, pCO$_2,o$ and pCO$_2,a$) to the air-sea CO$_2$ flux anomaly during MHWs.
Figure S2: Global map of the Tayler decomposition of the pCO$_2,o$ during MHWs averaged over 1990-2019 period averaged across all observation-based products. The left hand column shows SeaFlux dataset air-sea CO$_2$ flux anomalies during MHWs (top), the sum of the pCO$_2,o$ decomposition terms (middle), and the difference between the two (bottom). The right hand column shows the contributions of each pCO$_2,o$ component (alkalinity, dissolved inorganic carbon, salinity, and temperature) to the pCO$_2,o$ anomalies during MHWs.
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May 23, 2024, 12:35pm


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