https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

Exceptional 2023 marine heat wave reshapes North Atlantic coccolithophore blooms

Thibault Guinaldo[1] and Griet Neukermans[2,3]

[1]Centre National de Recherches Météorologiques, Université de Toulouse, Météo-France, CNRS, Lannion, France
[2]Ghent University, Biology Department, MarSens Research Group, Krijgslaan 281 – S8, 9000 Ghent, Belgium
[3]Flanders Marine Institute, InnovOcean Campus, 8400 Ostend, Belgium

Correspondence: Thibault Guinaldo (thibault.guinaldo@meteo.fr)

Abstract. The North Atlantic Ocean is undergoing rapid transformation driven by long-term warming and the increasing frequency of extreme marine heatwaves. In 2023, surface temperatures across the basin reached record highs, raising concerns about the resilience of phytoplankton ecosystems. This study examines the response of Emiliania huxleyi, a key calcifying phytoplankton species, using satellite-derived ocean colour data. The 2023 marine heatwave significantly disrupted bloom intensity and phenology, revealing contrasting trends between two bloom regions. While bloom intensity and extent declined in the Celtic Sea, conditions in the Barents Sea became increasingly favorable for growth. These shifts reflect the immediate impacts of the heatwave superimposed on long-term environmental changes, influenced by processes such as Atlantification, sea-ice retreat, and vertical stratification. The resulting changes have critical implications for carbon cycling and trophic interactions, underscoring the need for sustained, high-resolution monitoring to track both extreme events and persistent trends in phytoplankton dynamics. As high-latitude regions emerge as potential refuges, their long-term stability is highly uncertain under continued warming, ocean acidification, and ecosystem restructuring. A deeper understanding of these dynamics is essential for predicting future carbon cycle feedbacks and for managing ocean ecosystem services in a rapidly changing climate.

1 Introduction

Under specific oceanic and radiative conditions, large parts of the North Atlantic Ocean are transformed into shades of color, signaling the occurrence of phytoplankton blooms. Among these, the coccolithophore *Emiliania huxleyi* forms extensive blooms, typically in summer months, that play a crucial role in oceanic biogeochemical cycles (Shutler et al., 2010). During the decline phase of these blooms, the overproduction and detachment of its calcite plates (coccoliths) color the surface waters a distinctive milky-turquoise, detectable by ocean color satellites (Tyrrell et al., 1999; Smyth et al., 2002). In these conditions, coccoliths can contribute up to 90% of the total particulate backscattering coefficient, b_{bp}, a major determinant of ocean color reflectance (Balch and Mitchell, 2023).

As a photosynthetic organism, *E. huxleyi* contributes an estimated 1-10% of global primary production, underscoring its importance in the context of anthropogenic-driven ocean warming and acidification. *E. huxleyi* is also an important contributor to the oceanic stock and downward flux of particulate inorganic carbon (PIC), and a key player in the oceanic carbon cycle, influencing both the organic carbon pump and the carbonate counter pump mechanisms (Neukermans et al., 2023). Finally, coccolithophores play a significant role in the production of the volatile sulfur-containing compound dimethylsulfide (DMS, Malin et al., 1993), that can promote the formation of marine clouds with important implications for climate regulation (Fiddes et al., 2018; Mahmood et al., 2019).

Due to their resilience in low nutrient conditions, coccolithophore dynamics are expected to be driven by ocean warming and stratification, as evidenced by their poleward shift in response to rising sea surface temperatures (SSTs) (Meyer and Riebesell, 2015; D'Amario et al., 2020). This shift, associated with an increased occurrence in the North Atlantic (Rivero-Calle et al., 2015) is leading to regional changes in carbon export and ocean alkalinity (Hutchins and Tagliabue, 2024). While bio-advection and atlantification of water masses contribute significantly to this poleward migration (Oziel et al., 2020), the inhibitory effects of ocean acidification may limit coccolithophore calcification in the Arctic, despite the region's rapid warming (Smith et al., 2017). However, the resilience and adaptive capacity of coccolithophores suggest that they may be able to persist and even flourish under changing environmental conditions (Schlüter et al., 2014).

Over the past 40 years, oceans have absorbed approximately 91% of excess anthropogenic heat (Von Schuckmann et al., 2020), leading to significant increases in ocean heat content and raising concerns about an accelerated warming (Li et al., 2023; Minière et al., 2023). Globally, SSTs have risen by an average of 0.97°C (confidence interval: [0.77°C - 1.09°C]) between 1850-1900 and 2014-2023 (Forster et al., 2024). This long-term warming trend, combined with internal variability, results in anomalously high SSTs known as marine heatwaves (MHW, Hobday et al., 2016; Oliver et al., 2021). These events have become more frequent and intense, with the North Atlantic emerging as a hotspot, particularly at high latitudes (Oliver et al., 2018). Despite a surface signature, these extremes can extend vertically and increase environmental pressure on marine ecosystems altering trophic functions, thus leading to economic impacts (Smith et al., 2021, 2023). These consequences are exacerbated by a combination of hazards arising from different sources known as compound events (Zscheischler et al., 2018; Burger et al., 2022; Le Grix et al., 2022). These conditions can cause an irreversible state for marine communities in a short to medium-term period even in the context of overshooting (Santana-Falcón et al., 2023).
The North Atlantic ocean has experienced some of the most pronounced ocean heat content increases (Cheng et al., 2022). In recent years, the superposition of this underlying warming trend with extreme internal variability has led to unprecedented marine heat extremes, particularly affecting the North West European Shelf (Fig. 1a, Guinaldo et al., 2023; Simon et al., 2023). In 2023, a record-breaking MHW developed resulting in SST anomalies exceeding 5°C across broad areas of the shelf in June (Berthou et al., 2024). In fact, the entire North Atlantic has reached record-level SSTs explained by anomalies in the air-sea fluxes enhanced by anthropogenically driven stratification of the upper ocean (Guinaldo et al., 2025). Knowledge about the global causes and consequences of MHWs have increased significantly in recent years (Sen Gupta et al., 2020; Capotondi

et al., 2024) with several studies documenting impacts of MHWs on phytoplankton blooms using remotely sensed chlorophyll-a observations (Cheung and Frölicher, 2020; Arteaga and Rousseaux, 2023; Cyr et al., 2024). This study aims at providing a comprehensive assessment of the impacts of the 2023 North Atlantic exceptional MHW on coccolithophore blooms, a less-studied but ubiquitous taxon in this region using the long-term ocean colour satellite data record (1998-2023) as a baseline.

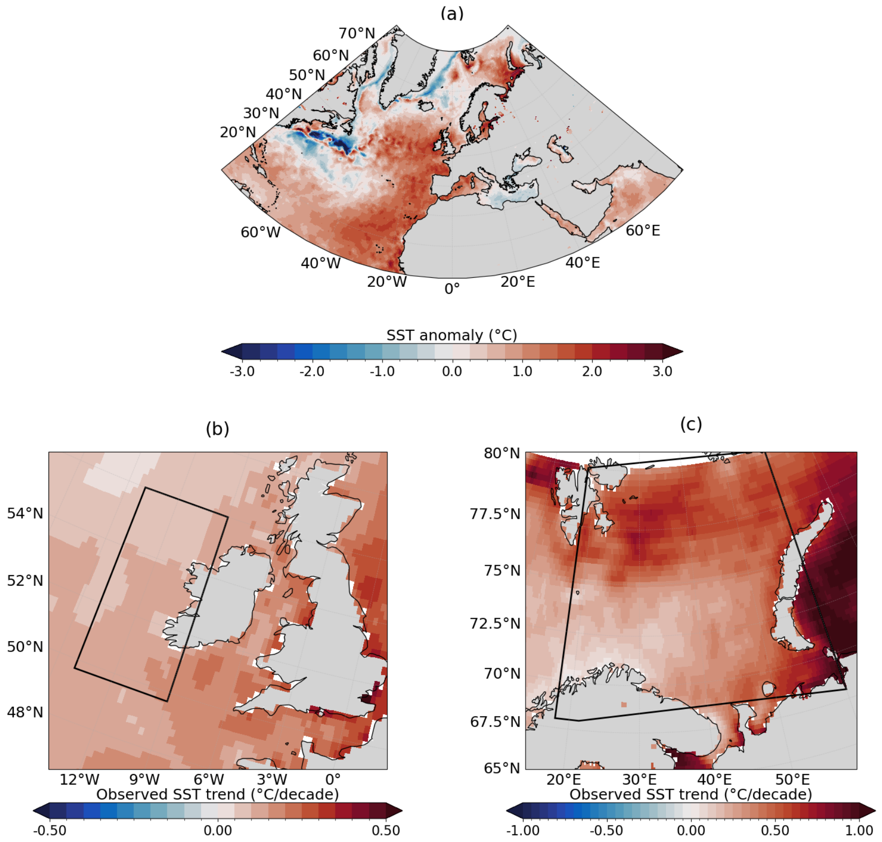

Figure 1. Maps of SST anomalies for May-June 2023 in the North Atlantic and SSTs trends over the study sites. (a) May-June averaged SSTs anomalies compared to the corresponding 1991-2020 period. Observed SST linear trend expressed in Celsius degrees by decade, computed from OSTIA over the period 1958-2023 for (b) the Celtic Sea and (c) the Barents Sea. Black boxes indicated the study sites chosen.

2 Results

2.1 Environmental conditions

Figure 2 illustrates the temporal evolution of SST and MLD in the Celtic Sea (CS) and Barents Sea (BS) during 2023. Both basins experienced record-breaking MHWs starting in spring. The annual mean SST anomaly was +0.67°C in the CS, peaking in June, and +0.92°C in the BS, peaking in August. Daily SST anomalies reached a maximum value of 17.5°C (anomaly: +3.9°C) in CS and 8.8°C (anomaly: +3.3°C) in BS. These MHWs were exceptional in intensity and duration, persisting for 82 days in the CS and 120 days in the BS. This record-breaking year in the northeastern Atlantic aligns with a global context of extreme heat events occurrence in spring 2023 (Guinaldo et al., 2025)on top of the ongoing warming trend in these basins (Fig. 1b-c).

The mixed-layer depth (MLD) in both basins followed a seasonal cycle, with deeper mixing in winter and shallower MLD in summer, modulated by atmospheric conditions (Fig. 2, de Boyer Montégut et al., 2004). The seasonal MLD pattern reflects the variability of mid- and high-latitude climate driven primarily by the North Atlantic Oscillation (NAO) in winter, which enhances westerly winds and cyclonic conditions (Hurrell et al., 2003). Enhanced vertical mixing and advection during this period lead to deeper MLD. Even at the northern edge of the North Atlantic, BS climate variability is influenced by the NAO which enhances heat transport (Sandø et al., 2010). Conversely, during summer, the climate variability is reduced, with increased likelihood of high-pressure blocking systems. These atmospheric conditions, characterized by low wind and high incoming solar radiation, promote upper-layer ocean warming, stratification, and MHW development (Holbrook et al., 2020). In high-latitude regions, additional stratification is driven by sea-ice melting and freshening of the surface waters (Oziel et al., 2017).

In the CS, oceanic conditions remained favorable for coccolithophores until mid-June, coinciding with the peak of June MHWs. From mid-June to mid-July, SSTs exceeded the upper thermal range of *E.huxleyi* (O'Brien, 2015) while the second half of summer was marked by destratification associated with the return of westerly winds. A second MHW occurred in September, linked to a high-pressure blocking system and the return of favorable conditions for blooms ended with the deepening of the MLD. In contrast, the BS exhibited a less variable pattern, with favorable conditions persisting from mid-July to early October, primarily driven by the stratification dynamic.

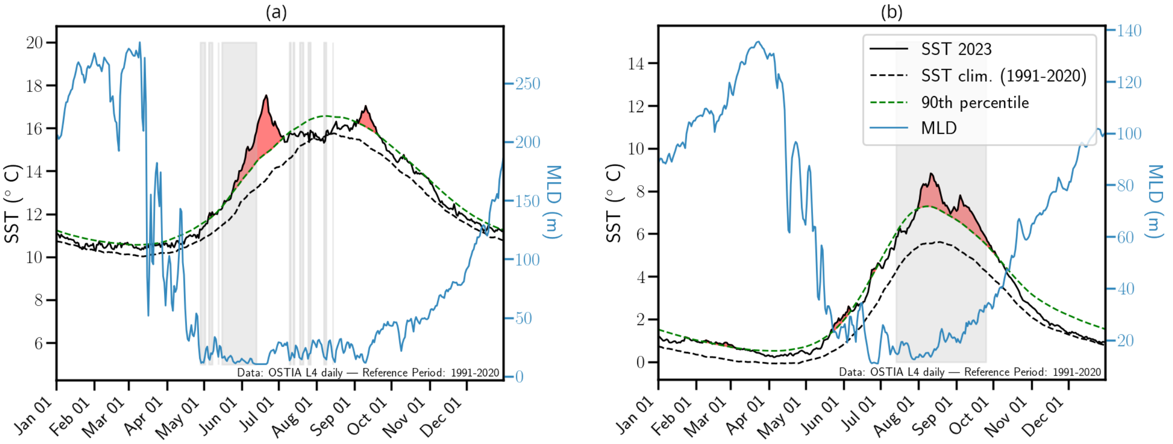

Figure 2. Daily spatially averaged SST and MLD variables for 2023. Spatially averaged sea surface temperature (SST; black solid line) and mixed-layer depth (MLD; blue solid line) anomalies for 2023 in (a) the Celtic Sea and (b) the Barents Sea. The black dashed line represents the climatological SST averaged over each basin for the period 1991–2020, while the green dashed line marks the 90th percentile threshold for marine heatwaves (MHWs), as defined by Hobday et al. (2016). Red shading indicates periods of MHWs, while grey shading highlights conditions conducive to *E. huxleyi* blooms based on SST and MLD thresholds.

2.2 Bloom dynamics and characteristics

The PIC dynamics reflected these environmental conditions. In the CS, the bloom followed a typical seasonal trajectory, with a climatological rise from April to early June, peaking at 0.30 mmol.m^{-3} (climatology: 0.43 mmol.m^{-3}, Fig. 3a), followed by a decline over the summer. An unusual second bloom occurred in August-September, correlated with the SST anomalies, reaching 0.38 mmol.m^{-3} (climatological Q75: 0.23 mmol.m^{-3}). While similar fall blooms have been observed historically (1997-2022 September maximum: 0.61 mmol.m^{-3}, Fig 3a & A1), the 2023 bloom was well above the climatological norm.

In contrast, the BS exhibited an unprecedented summer bloom. While following the climatological seasonal cycle, this bloom was remarkable in its intensity (6.25 mmol.m^{-3} compare to the climatological mean of 1.15 mmol.m^{-3}, Fig. 3b) and duration, surpassing levels of the previous record set in 2022 (6.15 mmol.m^{-3}). This bloom dynamic correlated with the environmental conditions, including MHWs in June and prolonged stratification throughout the summer. The primary limiting factor for blooms in the BS is the photosynthetically active radiation (PAR), which drives bloom onset and decline.

In the CS, the mean summer bloom extent in 2023 reached a record-breaking 46,460 km^2 (Fig. 3c), representing a 30% increase from the previous record in 2007 and an 85% increase from the 1998-2021 mean. However, the maximum bloom extent (126,163 km^2) was comparable to the 1998–2010 mean (126,345 km^2), potentially reflecting the multi-annual North Atlantic variability. The increase in mean bloom extent may be attributed to a prolonged bloom period with smaller blooms unevenly distributed across the CS (Fig. A2).

In the BS, bloom extent exhibited a remarkable rise over the past two years, setting new records in both mean (164,188 km^2,

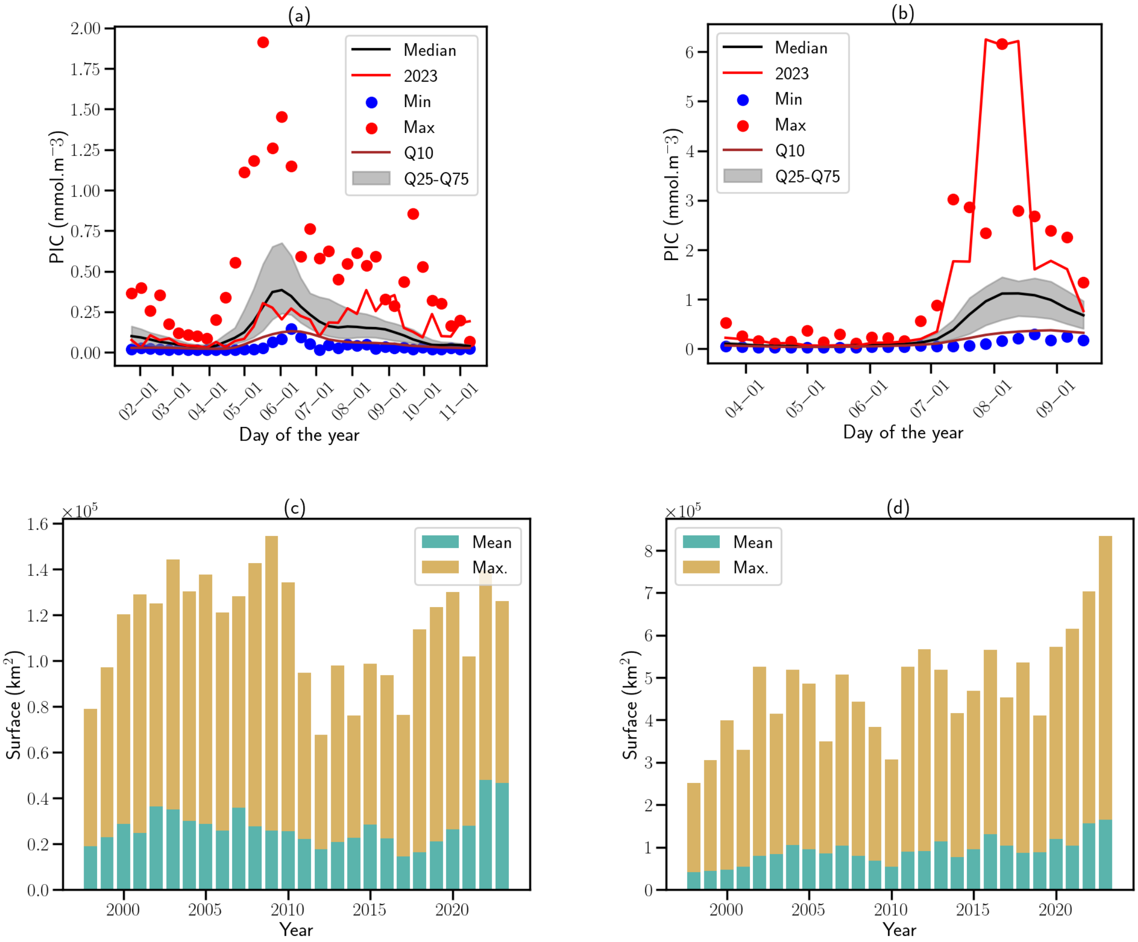

Figure 3. Coccolithophore bloom phenology and extent in the Celtic and Barents Seas over the satellite record (1998-2023). Seasonality in satellite-derived PIC concentration in 2023 (red line) compared to the 1998-2020 climatology (black line) in the (a) Celtic Sea and (b) the Barents Sea. Blue (resp. red) dots indicate minimum (resp. maximum) PIC concentration in the 1997-2022 climatology. Grey shading represents the 25-75 interquantile range . Brown lines represents the $10th$ percentile. Corresponding maximal (yellow bars) and mean (green bars) bloom spatial extent in the (c) CS and (d) BS.

Fig. 3d) and maximum (833,561 km^2) values for 2023. The latter extent represents an 18% increase from the previous record set in 2022 (703,174 km^2). Spatially, this reflects a significant intrusion of the coccolithophores into the BS (Fig. A3), covering 59% of the basin linked to increased atlantification with favorable bloom conditions. Long-term trends indicate a consistent rise in bloom extent, with positive trends of 3,137 km^2 of the mean spatial extent and 12,346 km^2 of the maximum spatial

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

110 extent over the past 25 years, as estimated by LOESS regression (p_value<0.01).

2.3 Trends in coccolithophore bloom phenology over the satellite era (1998-2023)

Basin-averaged analyses may hindered spatial feature such as the repartition and the evolution of blooms across each basin. As shown on Figure A2, the summer maximum PIC concentration showed no detectable trend in the CS. However, in the BS (Fig. A3), a strong northeastward shift in summer maximum concentrations was observed, aligning with the shifting position of the polar front and thus the atlantification of the water masses. Interannual variability in the position of the polar front is accompanied by shifts in PIC maxima, likely driven by bio-advection processes transporting particulate material along the front (Oziel et al., 2020). Years 2004, 2010, and 2023 exhibited larger areas of elevated PIC (Fig. A3). This underscores the compound effect of the Atlantification and ocean warming on the shift of optimal conditions and the enhancement of such a situation under extreme MHWs events like in 2023.

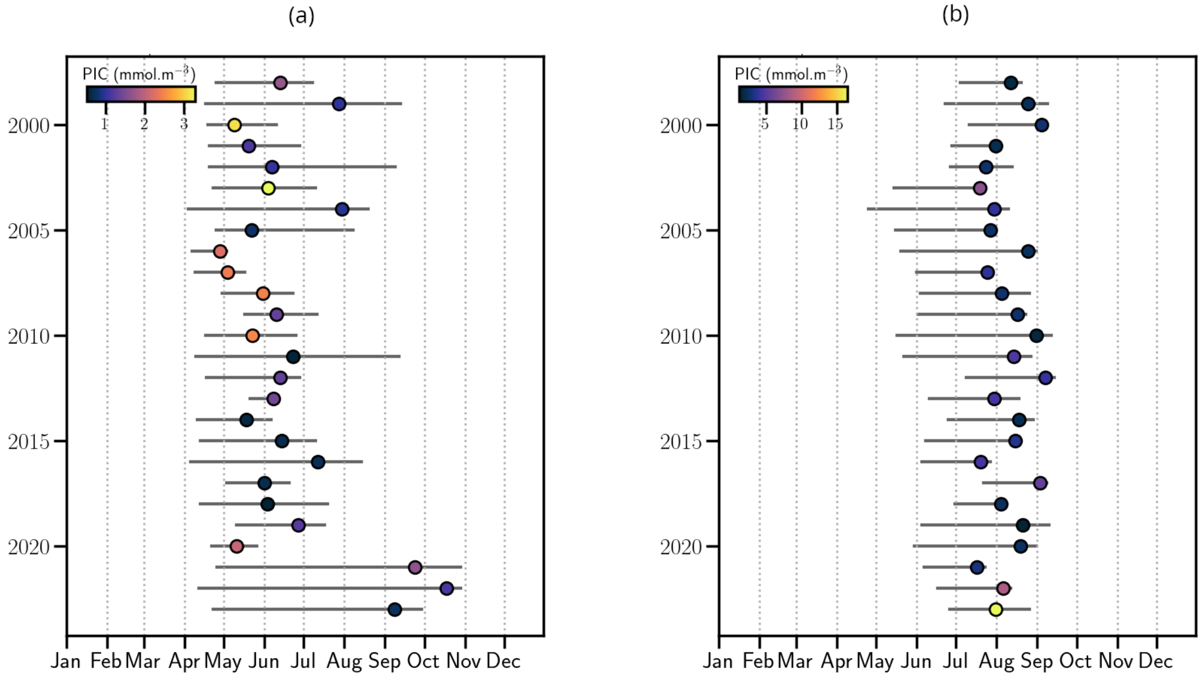

Figure 4. Phenology of coccolithophore blooms in the North-eastern Atlantic ocean (1998–2023). Start and end dates of blooms with maximum PIC, colored by peak PIC concentration (mmol.m^{-3}) in the (a) CS and (b) the BS.

The phenology of coccolithophore blooms in the CS over the 25-year period exhibited marked interannual variability in bloom peak timing, duration, and intensity (see Fig. 4a and Section A1). The average bloom duration was 90 days, ranging from 21 to 200 days for the weakest blooms. The mean bloom start date occurred in mid-April while the blooms generally ended by mid-July. A significant shift in bloom duration was observed during the last three years (2021–2023), a remarkable 130% increase in duration relative to the 1998-2020 mean. This trend underscores recent anomalies in seasonal dynamics which is linked with recurrent warm conditions in summer and autumn thus shifting the optimal thermal conditions. The bloom intensity, as measured by the maximum PIC value, averaged 1.4 mmol.m^{-3} [0.5–3.3] over the study period. Notably, the mean intensity declined by 20% during the last three years compared to the 1998-2020 period. Despite these interannual variations, this recent decline seems to confirm a negative trend in bloom intensity over the 25-year period (-0.03 mmol.m^{-3} per year), although this trend is not statistically significant (p_value = 0.07)(Fig. A4a).

In the BS, coccolithophore bloom phenology differed notably to the one in the Celtic Sea. The mean bloom duration was shorter, averaging 70 days [35–118], with no detectable temporal shift in bloom timing across the 1998-2023 period. The mean start date was consistently around mid-June, while the mean end date occurred mid-August, reflecting a shorter seasonal window for bloom development. The lack of temporal shifts in bloom timing is evident in Figure 4b, which shows consistent bloom periods across years.

Bloom intensity in the BS was significantly higher than in the CS, with a mean maximum PIC value of 3.9 mmol.m^{-3} [1.2–16]. Recent years (2021–2023) demonstrated a notable increase in bloom intensity, culminating in a record daily value of 16.5 mmol.m^{-3} in 2023, nearly double the previous daily record of 8.6 mmmol.m^{-3} in 2022. The mean intensity for the last three years was 12.5 mmol.m^{-3}, compared to 3.2 mmol.m^{-3} for the preceding years. This sharp increase resulted in a significant positive trend in bloom intensity (0.17 mmol.m^{-3} per year, $p < 0.05$) over the 1998-2023 period (Fig. A4b).

Further analysis suggests a link between the observed rise in bloom intensity and environmental conditions influenced by Arctic warming ((Fig. A5). Previous studies have shown that reduced sea ice extent and longer ice-free seasons in the Arctic enhance water column stratification, increase light availability, and facilitate the accumulation of nutrients, creating favorable conditions for coccolithophore growth (Ardyna et al., 2014; Oziel et al., 2016). These processes likely contributed to the unprecedented bloom intensities observed in recent years.

The contrasting phenological responses in the CS and BS highlight the influence of regional environmental drivers on coccolithophore bloom dynamics. While the CS exhibited a recent extension of bloom duration and a decline in intensity deviating from typical multi-annual variability, the BS showed stability in bloom timing but an unprecedented increase in bloom intensity. Here, the bloom period remains limited by PAR availability, preventing further lengthening despite significant SST warming trends (Fig. 2c).

3 Discussions and Conclusions

The year 2023 was marked by extreme surface ocean temperatures extending across the North Atlantic over a prolonged period. The establishment of these temperatures was locally modulated by climate variability, leading to the onset of historic marine heatwaves (Guinaldo et al., 2025). In particular, the Northeast Atlantic experienced oceanic extremes that were both historically intense and prolonged (Berthou et al., 2024). Using ocean-colour dedicated satellite sensors, this study demonstrated that these extremes impacted coccolithophore dynamics and enhanced consequences of the long-term warming trend. Specifically, a shift was observed in the optimal bloom development zones during spring-summer, with a degradation of thermal conditions in trailing regions (Celtic Sea) and an improvement in leading regions (Barents Sea) raising concerns about a possible contraction of the blooms optimal areas. However, the improved conditions at high latitudes depend on other factors, notably the Atlantification dynamics in the Barents Sea, which drive the bio-advection of coccolithophores. Furthermore, this evolution is influenced by sea ice coverage and uncertainties coming from the internal variability (Swart et al., 2015), which, despite its decline, still significantly impacts the surface area of the Barents Sea.

Even if some shifts are underway, our results on phenology align with previous findings in terms of timing of the onset and bloom duration (Hopkins et al., 2015) and of increasing intensity (Rivero-Calle et al., 2015). These shifts need further confirmation, particularly with additional data from diverse regions in the middle of the favorable region but undergoing similar MHWs (e.g. North Sea).

Nevertheless, several limitations must be acknowledged. First, our estimates may be lower due to the spatial averaging inherent in satellite observations and due to the cloud cover at high latitudes; future studies should explore the use of more precise spatial masking techniques to address this or rely on potentially improved retrieval of PIC from hyperspectral ocean-colour sensors such as PACE (Werdell et al., 2019). The lack of vertical observational data, due to limited in situ measurements, constrains our ability to capture the vertical distribution and intensity of these blooms. This limitation may be overcome by applying statistical relationship extrapolating surface observations vertically (Balch et al., 2018).

This change of ecological niches is not unique to 2023 but reflects multi-annual variability superimposed on long-term trends. Over the past two to three years, a notable shift in bloom phenology has emerged, with trailing edge blooms occurring later in the year, particularly in autumn, a period traditionally considered less favourable for such events (return of the westerly winds associated with a southward shift of the storm-track). In contrast, bloom dynamics at the leading edge show high inter-annual variability with less influence on the timing, largely due to the limiting influence of PAR at these latitudes. However, rising temperatures in the Barents Sea, which is warming faster than other basins (Rantanen et al., 2022), have led to blooms of exceptionally high intensity. These observations underscore the critical need to disentangle the contributions of internal climate system variability, such as decadal variability, from the impacts of anthropogenic climate change and our capacity to assess extreme but plausible events such as the record SSTs in 2023-2024 (Terhaar et al., 2025). Advancing our understanding of these processes requires leveraging recent advances in attribution science (Stott et al., 2016; Ribes et al., 2020; Faranda et al., 2024), which predominantly focused on terrestrial and atmospheric systems and create similar services for oceans, incorporating bio-

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

geochemical components. This effort must be supported by the development of integrated, multi-scale observation networks capable of providing the initial conditions needed to better understand processes, anticipate future changes, and inform adaptive strategies for marine ecosystems. Such a perspective will also need to address inter-species competition, especially as changes in MLD and stratification create new subsurface conditions that could alter both predator-prey dynamics and grazing pressures (Arteaga et al., 2020).

This study reaffirms the poleward expansion of temperate phytoplankton communities and highlights the emergence of new ecological hotspots in high-latitude regions (Hutchins and Tagliabue, 2024) and the dynamic of the calcifying communities intrusion in the Barents Sea (Neukermans et al., 2018). These shifts, while globally evident, impact regional biogeochemical cycles and food web dynamics. In addition, ecosystem responses to these changes in species distributions may be contrasted by local adaptation plans and policies (Smale et al., 2019; Smith et al., 2023). Predatory species, in particular, may face challenges in tracking these changing patterns, potentially disturbing trophic interactions and ecosystem functioning (Cyr et al., 2024) even if this redistribution may be vertically uneven (Santana-Falcón and Séférian, 2022; Fredston et al., 2023).
Nevertheless, several local and regional physical constraints could modulate these broader trends. Coccolithophores, like other calcifying organisms, are sensitive to ocean acidification, which may reduce their ability to produce coccoliths. Polar regions, subject to increased ocean acidification, may become less favorable for these organisms in the long term *in fine* altering the regional carbon cycle. Additionally, the evolution of water column stratification plays a key role. In trailing regions like the Celtic Sea, increased stratification driven by thermodynamic factors is evident, whereas the Barents Sea exhibits a contrasting trend toward destratification, a process that is counter-intuitive with the warming and freshening of these waters (Oziel et al., 2017). These dynamics, including the vertical evolution of the summertime mixed-layer depth, which may reduce both light and nutrient availability (Sallée et al., 2021), also have profound implications for carbon sequestration, a critical function of calcifying species. The observed changes in bloom duration and intensity are of particular concern: the Celtic Sea's reduced intensity coupled with prolonged blooms period could signal shifts in nutrient availability, light conditions, or grazing pressures, while the Barents Sea's historical increases in bloom intensity may reflect enhanced nutrient inputs, favorable light conditions, and prolonged ice-free seasons driven by Arctic warming. Understanding the long-term consequences of these changes under different emission scenarios is particularly urgent, given the identification of the Barents Sea and its diminishing sea ice as a tipping point in the Earth system (Wunderling et al., 2024).

These results underscore the importance of continuous monitoring and multi-scale modeling to capture the complex interplay of physical, chemical, and biological factors driving phytoplankton species composition and phenology. Further research integrating high-resolution satellite data and in situ observations is critical to predict the ecological and biogeochemical impacts of these phenological shifts under future climate scenarios. In summary, this work highlights the need for a nuanced perspective on the future of phytoplankton communities in a rapidly changing ocean. While high-latitude regions may offer temporary refuge for coccolithophores, the combined impacts of acidification, stratification changes, and ecosystem restructuring underscore the complexity of these responses. Long-term, interdisciplinary studies will be crucial to projecting the trajectory of these ecosystems and ensuring sustainable management of the services they provide under shifting environmental baselines.

Code and data availability. OSTIA SST data are publicly available for download from the UK Met Office dedicated website: https://ghrsst-pp.metoffice.gov.uk/ostia-website/index.html. Ocean color data are publicly available for download from the ACRI-ST website : https://hermes.acri.fr. Mixed layer depth data are publicly available on the CMEMS website : https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description. Code are available on the dedicated Zenodo deposit :

Appendix A: Appendix

A1 Data and Methods

A1.1 Study sites

The 2023 MHW in the North Atlantic, unprecedented in its extent and intensity, provides a unique opportunity to study the resilience and adaptation of phytoplankton, including *E.huxleyi*, to extreme temperatures. In the North Atlantic, *E. huxleyi* typically blooms annually in regions situated between the continental shelf of Western Europe (Bay of Biscay) and an Arctic shelf Sea (Barents Sea), respectively representing the trailing and leading edges of the bloom distribution (Winter et al., 2014; Neukermans et al., 2018). To assess the impact of the 2023 MHW on *E. huxleyi* blooms, we focused on two regions situated at the northern and southern limits : To assess the impact of the 2023 MHW on *E. huxleyi*, we sampled two regions within its North Atlantic distribution:

- Celtic Sea [14°E - 9°E / 49.7°N - 56°N]: A region at the trailing edge, where blooms occur annually and historical marine heatwaves have resulted in temperature anomalies of up to +5°C in June 2023 (Berthou et al., 2024).
- Barents Sea [18°W - 60°W / 68°N - 80°N]: A region at the leading edge, experiencing rapid warming and sea-ice loss due to Arctic amplification and "atlantification" of its water (Oziel et al., 2020; He et al., 2024).

Within these study sites, a bathymetry mask has been applied to limit turbid waters caused by resuspended bottom sediments and input from rivers, which create false-positive PIC signals. The bathymetric limits are respectively -150 m and -100 m for the Celtic Sea and the Barents Sea and derived from the ETOPO global relief model at 60 arc-second resolution (MacFerrin et al., 2024).

A1.2 Satellite data

To assess ocean color anomalies, we used both the daily and the weekly-merged L3 multi-sensor PIC product, derived from MERIS, MODIS, SeaWIFS, VIIRS, and OLCI, providing a 1/24° spatial resolution for 1997-2024 from the GlobColour project (https://hermes.acri.fr/). NASA's standard PIC algorithm (Balch et al., 2005; Gordon and Du, 2001) was used, based on remote

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

sensing reflectance in either two or three bands in the visible and the near-infrared domain (Balch and Mitchell, 2023). Ocean colour Observations are limited by the presence of clouds (predominant at high latitudes) which motivate the choice of using weekly-merged rather than daily products for the climatological comparison. To construct a reliable climatology, we employed a 20-year archive (1998-2018), following the approach of Cael et al. (2023) who demonstrated that climate change indicators can be derived from ocean color data within a shorter time period than the 30-year WMO recommendation. Daily (resp. weekly) anomalies were calculated by comparing daily (resp. weekly) PIC data to the corresponding constructed seasonal climatology

For SSTs, we used, as a reference climatology, the ESA-CCI level 4 Climate Data Record version 3 (CDR, Embury et al., 2024), which offers a daily and globally consistent record at 0.05° spatial resolution. The daily climatology over the 1991-2020 period is computed with a 5-day moving average. To derive the daily anomalies we compared the daily CDR data to the Operational Sea surface Temperature and sea Ice Analysis (OSTIA) L4 analysis data (Donlon et al., 2012). The SST product is released on a daily basis in a regular latitude-longitude grid with a 0.05° spatial resolution. In the Barents Sea, increased bloom frequency and intensity are driven by bio-advection and atlantification (Oziel et al., 2020) A proxy for atlantification is the polar front, which separates Atlantic and Arctic waters. We computed the Barents Sea polar front position using a local variance filter applied to March-April OSTIA SSTs with a window size of 7x7 pixels (Neukermans et al., 2018). We, first, computed the monthly average from the daily OSTIA archive. Polar Front Waters were, then, defined as SSTs between the 16^{th} and 84^{th} percentiles (Oziel et al., 2016). The evolution of the polar front since 1998 is shown in Fig. A3.

Mixed layer depth (MLD) data were obtained from the daily GLORYS12 Version 1 reanalysis, which provides a daily and global record from 1993 to 2024 at 1/12° spatial resolution (Jean-Michel et al., 2021).

A1.3 Bloom detection and phenology

To assess coccolithophore bloom phenology, we applied the methods of Hopkins et al. (2015) on the L3 daily multi-sensor PIC product. This allows us to estimate bloom start and end dates, maximum concentration, and extent knowing the limitations of such data at high latitudes. This method is based on the analysis of the temporal evolution of the PIC concentration over the study site and the identification of both local minimum before and after the detected peak of the bloom.

The analysis of environmental conditions driving the onset of blooms is based on two essential conditions (a relatively warm and stratified upper-ocean) :

$$MLD < 40 - 50m \text{ and } SST \in [6 - 16°C[\tag{A1}$$

The surface extent computation relies on the number of relevant pixel areas detected with a PIC concentration greater than a region-based threshold. The threshold is computed based on the 1998-2018 climatology and determined as the PIC concentration on the climatological bloom start date, serving as a baseline for identifying significant anomalies. The respective values for

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

CS and BS are 0.06 mmol.m^{-3} and 0.1 mmol.m^{-3}. The study sites are located in mid- and high-latitudes, the surface extent must take into account the surface spherical deformation, defined as follows:

285 $$S = \sum s_i \text{ with } s_i = 110.574 * \text{latitude} * 111.320 * \text{longitude} * \cos(\text{latitude}) \qquad \text{(A2)}$$

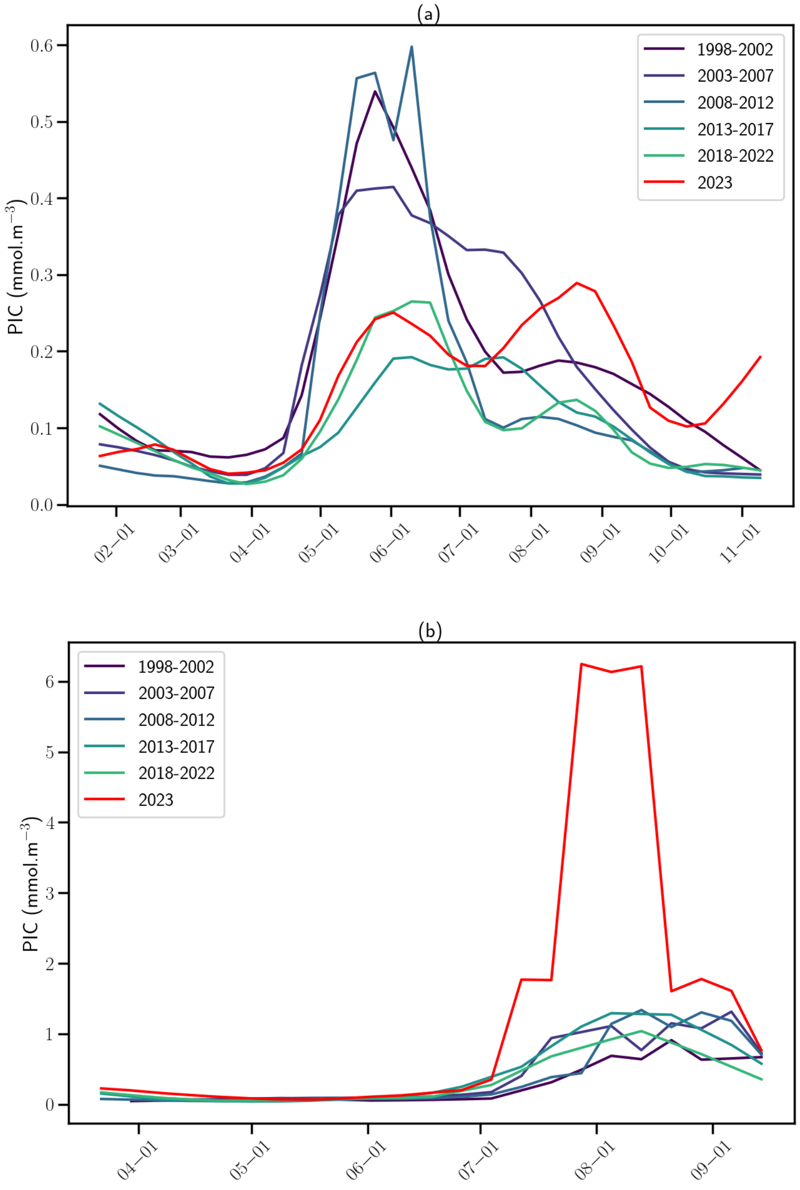

Figure A1. Seasonal evolution of daily PIC concentration in the Celtic Sea and Barents Sea. Daily PIC concentrations (mmol·m^{-3}) averaged over 5-year period and smoothed using a LOWESS regression for (a) Celtic Sea and (b) the Barents Sea. The year 2023 is highlighted in red.

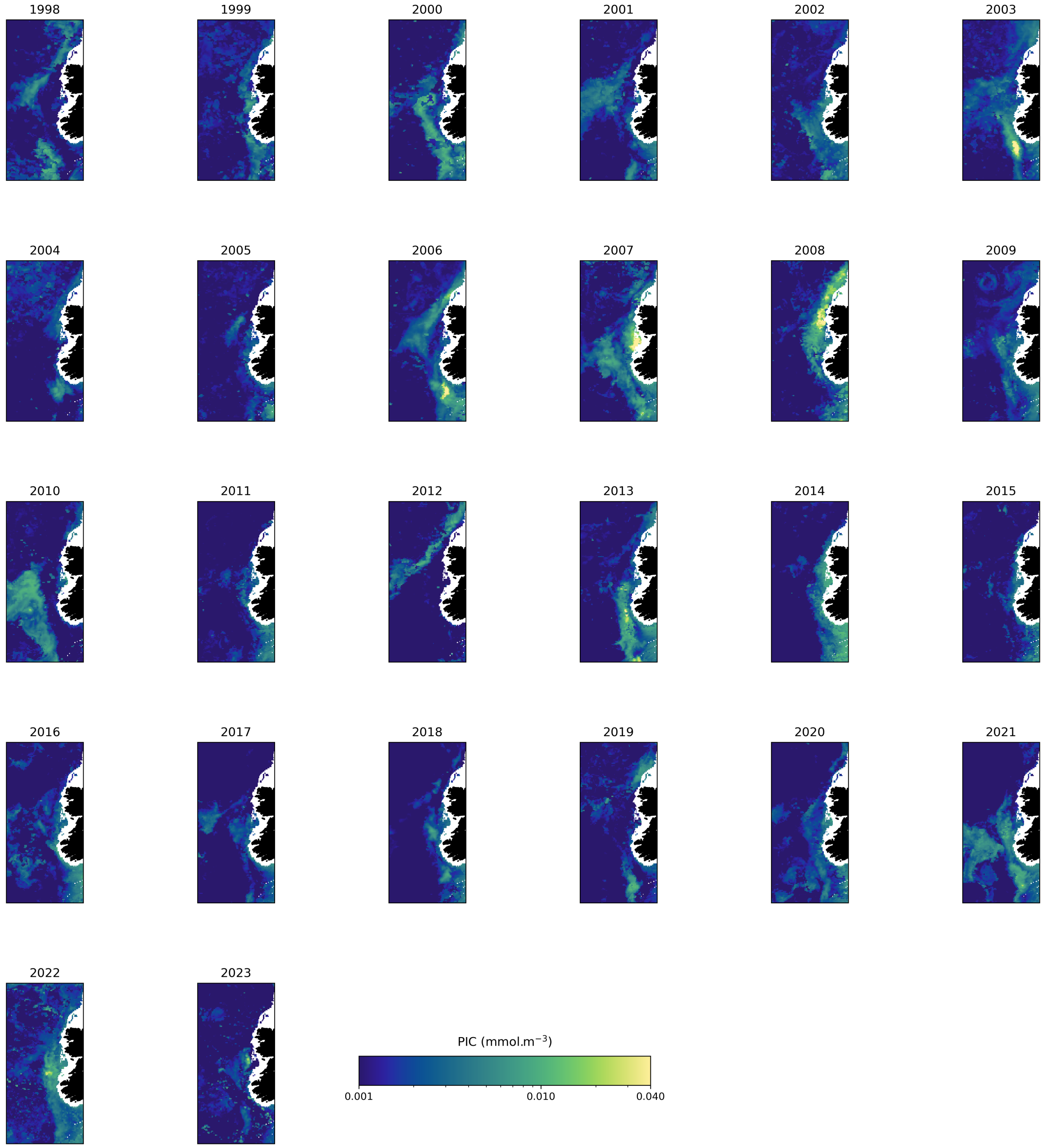

Figure A2. Summer maximum PIC concentration in the Celtic Sea. Annual evolution of the remotely-sensed summer maximun PIC concentration. White areas defined coastal zones where the bathymetry is higher than -150m.

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

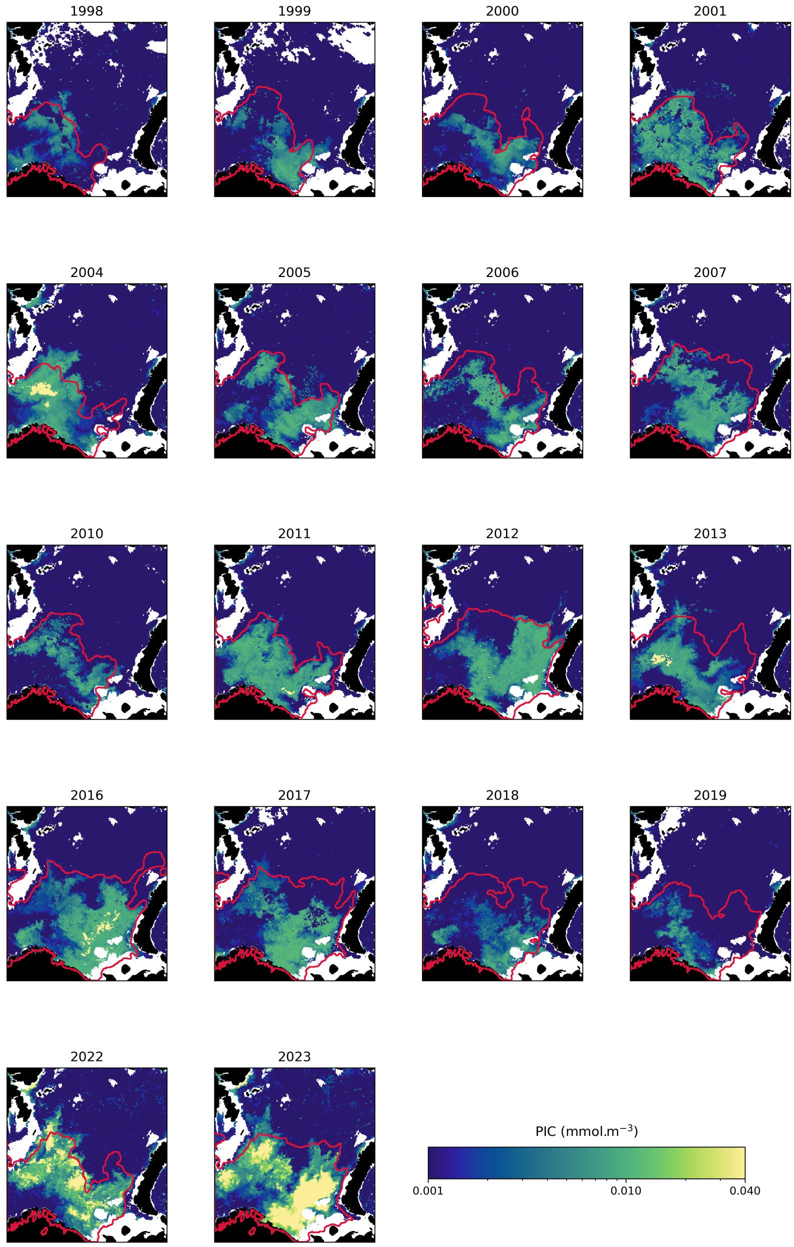

Figure A3. Summer maximum PIC concentration in the Barents Sea. Annual evolution of the remotely-sensed summer maximun PIC concentration and the corresponding polar front in red. The polar front is based on an analysis of the ice-free March-April SSTs. White areas defined coastal zones where the bathymetry is higher than -100m.

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

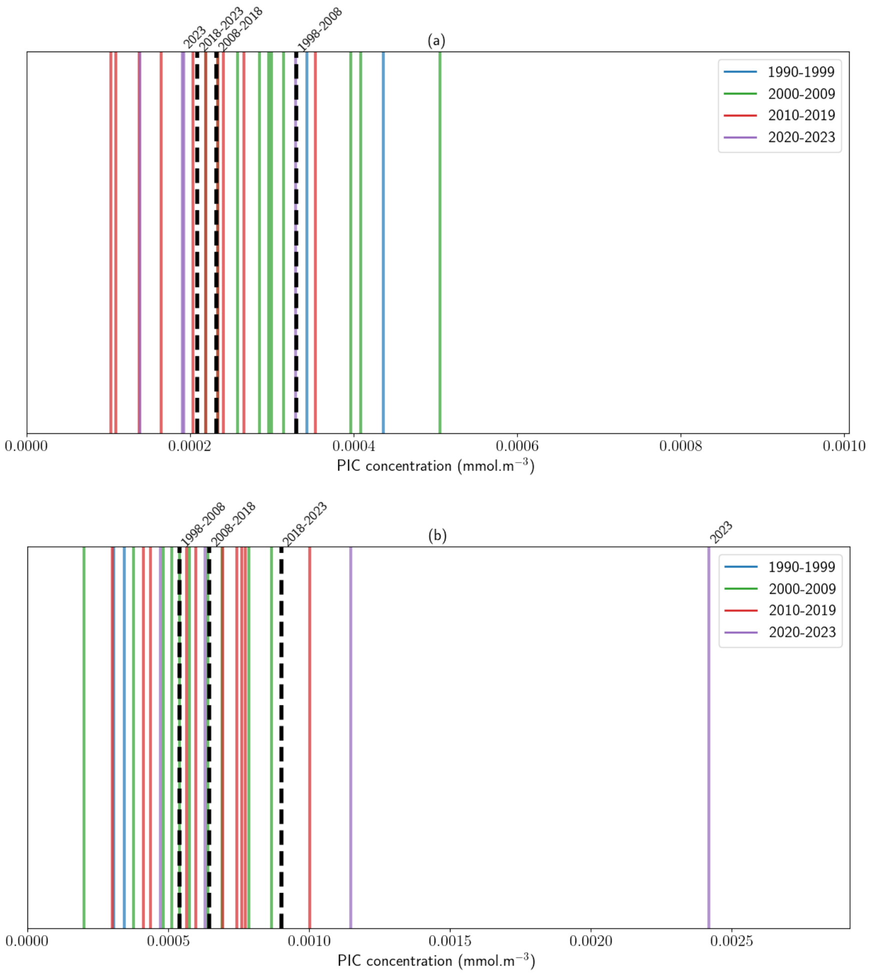

Figure A4. Decadal evolution of summer mean PIC concentration in the Celtic Sea and Barents Sea. Barcode plots of the distribution of yearly summer (June-July-August) mean PIC concentrations (mmol·m^{-3}). Colors refer to the corresponding decade with decadal means indicated by black dashed lines.(a) Celtic sea and (b) Barents Sea.

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

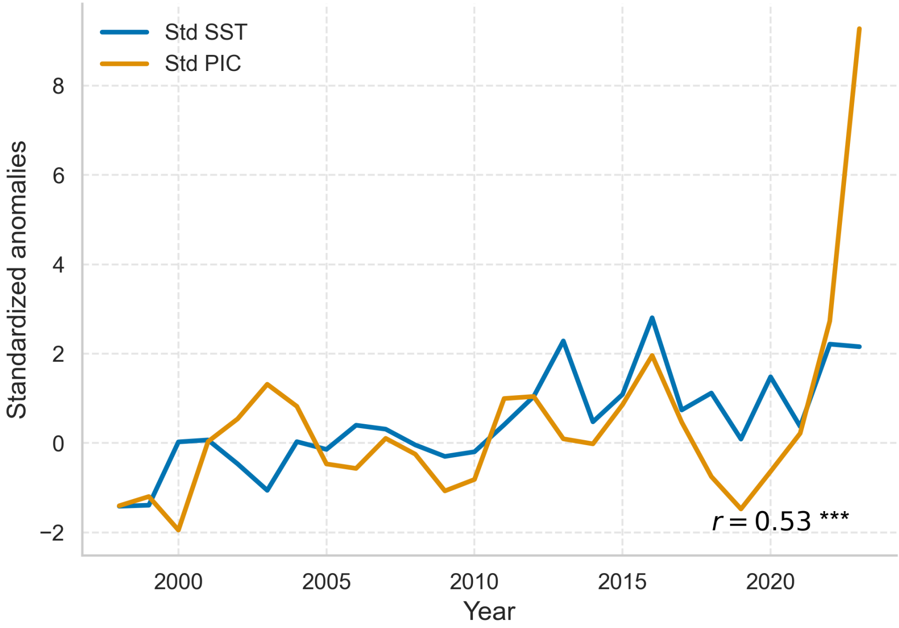

Figure A5. Evolution of the standardized anomalies of summertime (July-August) SSTs and PIC over the Barents Sea. Yearly standardised anomalies of SSTs (blue) and PIC (brown) compared to respectively the 1991-2020 and the 1998-2017 climatological period. Pearson correlation coefficient indicate the strength of correlation between the standardised anomalies and the *** refers to a p_value < 0.01.

Author contributions. TG and GN designed the study; TG conducted analysis and wrote the paper with contributions from GN. TG and GN took part in discussions and revisions of the paper.

Competing interests. The contact author has declared that none of the authors has any competing interests.

290 *Acknowledgements.* This work is a contribution to CarbOcean (European Research Council under the European Union's Horizon 2020 research and innovation programme Grant agreement No. 853516) awarded to GN. TG sincerely thanks Jean-Baptiste Sallée for many fruitful discussions on the evolution of current dynamics in the Barents Sea.

References

Ardyna, M., Babin, M., Gosselin, M., Devred, E., Rainville, L., and Tremblay, J.-É.: Recent Arctic Ocean sea ice loss triggers novel fall phytoplankton blooms, Geophysical Research Letters, 41, 6207–6212, 2014.

Arteaga, L. A. and Rousseaux, C. S.: Impact of Pacific Ocean heatwaves on phytoplankton community composition, Communications Biology, 6, 263, 2023.

Arteaga, L. A., Boss, E., Behrenfeld, M. J., Westberry, T. K., and Sarmiento, J. L.: Seasonal modulation of phytoplankton biomass in the Southern Ocean, Nature Communications, 11, 5364, 2020.

Balch, W., Gordon, H. R., Bowler, B., Drapeau, D., and Booth, E.: Calcium carbonate measurements in the surface global ocean based on Moderate-Resolution Imaging Spectroradiometer data, Journal of Geophysical Research: Oceans, 110, 2005.

Balch, W. M. and Mitchell, C.: Remote sensing algorithms for particulate inorganic carbon (PIC) and the global cycle of PIC, Earth-Science Reviews, 239, 104 363, 2023.

Balch, W. M., Bowler, B. C., Drapeau, D. T., Lubelczyk, L. C., and Lyczkowski, E.: Vertical distributions of coccolithophores, PIC, POC, biogenic Silica, and chlorophyll a throughout the global ocean, Global Biogeochemical Cycles, 32, 2–17, 2018.

Berthou, S., Renshaw, R., Smyth, T., Tinker, J., Grist, J. P., Wihsgott, J. U., Jones, S., Inall, M., Nolan, G., Berx, B., et al.: Exceptional atmospheric conditions in June 2023 generated a northwest European marine heatwave which contributed to breaking land temperature records, Communications Earth & Environment, 5, 287, 2024.

Burger, F. A., Terhaar, J., and Frölicher, T. L.: Compound marine heatwaves and ocean acidity extremes, Nature communications, 13, 4722, 2022.

Cael, B., Bisson, K., Boss, E., Dutkiewicz, S., and Henson, S.: Global climate-change trends detected in indicators of ocean ecology, Nature, 619, 551–554, 2023.

Capotondi, A., Rodrigues, R. R., Sen Gupta, A., Benthuysen, J. A., Deser, C., Frölicher, T. L., Lovenduski, N. S., Amaya, D. J., Le Grix, N., Xu, T., et al.: A global overview of marine heatwaves in a changing climate, Communications Earth & Environment, 5, 701, 2024.

Cheng, L., von Schuckmann, K., Abraham, J. P., Trenberth, K. E., Mann, M. E., Zanna, L., England, M. H., Zika, J. D., Fasullo, J. T., Yu, Y., et al.: Past and future ocean warming, Nature Reviews Earth & Environment, 3, 776–794, 2022.

Cheung, W. W. and Frölicher, T. L.: Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific, Scientific reports, 10, 6678, 2020.

Cyr, F., Lewis, K., Bélanger, D., Regular, P., Clay, S., and Devred, E.: Physical controls and ecological implications of the timing of the spring phytoplankton bloom on the Newfoundland and Labrador shelf, Limnology and Oceanography Letters, 9, 191–198, 2024.

de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, Journal of Geophysical Research: Oceans, 109, 2004.

Donlon, C. J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., and Wimmer, W.: The operational sea surface temperature and sea ice analysis (OSTIA) system, Remote Sensing of Environment, 116, 140–158, 2012.

D'Amario, B., Pérez, C., Grelaud, M., Pitta, P., Krasakopoulou, E., and Ziveri, P.: Coccolithophore community response to ocean acidification and warming in the Eastern Mediterranean Sea: results from a mesocosm experiment, Scientific reports, 10, 12 637, 2020.

Embury, O., Merchant, C. J., Good, S. A., Rayner, N. A., Høyer, J. L., Atkinson, C., Block, T., Alerskans, E., Pearson, K. J., Worsfold, M., et al.: Satellite-based time-series of sea-surface temperature since 1980 for climate applications, Scientific Data, 11, 326, 2024.

Faranda, D., Messori, G., Coppola, E., Alberti, T., Vrac, M., Pons, F., Yiou, P., Saint Lu, M., Hisi, A. N., Brockmann, P., et al.: ClimaMeter: contextualizing extreme weather in a changing climate, Weather and Climate Dynamics, 5, 959–983, 2024.

Fiddes, S. L., Woodhouse, M. T., Nicholls, Z., Lane, T. P., and Schofield, R.: Cloud, precipitation and radiation responses to large perturbations in global dimethyl sulfide, Atmospheric Chemistry and Physics, 18, 10 177–10 198, 2018.

Forster, P. M., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D., Gillett, N. P., et al.: Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence, Earth System Science Data, 16, 2625–2658, 2024.

Fredston, A. L., Cheung, W. W., Frölicher, T. L., Kitchel, Z. J., Maureaud, A. A., Thorson, J. T., Auber, A., Mérigot, B., Palacios-Abrantes, J., Palomares, M. L. D., et al.: Marine heatwaves are not a dominant driver of change in demersal fishes, Nature, 621, 324–329, 2023.

Gordon, H. R. and Du, T.: Light scattering by nonspherical particles: application to coccoliths detached from Emiliania huxleyi, Limnology and Oceanography, 46, 1438–1454, 2001.

Guinaldo, T., Voldoire, A., Waldman, R., Saux Picart, S., and Roquet, H.: Response of the sea surface temperature to heatwaves during the France 2022 meteorological summer, Ocean Science, 19, 629–647, 2023.

Guinaldo, T., Cassou, C., Sallée, J.-B., and Liné, A.: Internal variability effects doped by climate change drove the 2023 marine heat extreme in the North Atlantic, Nature Communications : Earth & Environment, 2025.

He, Y., Shu, Q., Wang, Q., Song, Z., Zhang, M., Wang, S., Zhang, L., Bi, H., Pan, R., and Qiao, F.: Arctic Amplification of marine heatwaves under global warming, Nature Communications, 15, 8265, 2024.

Hobday, A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Feng, M., et al.: A hierarchical approach to defining marine heatwaves, Progress in oceanography, 141, 227–238, 2016.

Holbrook, N. J., Sen Gupta, A., Oliver, E. C., Hobday, A. J., Benthuysen, J. A., Scannell, H. A., Smale, D. A., and Wernberg, T.: Keeping pace with marine heatwaves, Nature Reviews Earth & Environment, 1, 482–493, 2020.

Hopkins, J., Henson, S. A., Painter, S. C., Tyrrell, T., and Poulton, A. J.: Phenological characteristics of global coccolithophore blooms, Global Biogeochemical Cycles, 29, 239–253, 2015.

Hurrell, J. W., Kushnir, Y., Ottersen, G., and Visbeck, M.: An overview of the North Atlantic oscillation, Geophysical Monograph-American Geophysical Union, 134, 1–36, 2003.

Hutchins, D. A. and Tagliabue, A.: Feedbacks between phytoplankton and nutrient cycles in a warming ocean, Nature Geoscience, pp. 1–8, 2024.

Jean-Michel, L., Eric, G., Romain, B.-B., Gilles, G., Angélique, M., Marie, D., Clément, B., Mathieu, H., Olivier, L. G., Charly, R., et al.: The Copernicus global 1/12 oceanic and sea ice GLORYS12 reanalysis, Frontiers in Earth Science, 9, 698 876, 2021.

Le Grix, N., Zscheischler, J., Rodgers, K. B., Yamaguchi, R., and Frölicher, T. L.: Hotspots and drivers of compound marine heatwaves and low net primary production extremes, Biogeosciences, 19, 5807–5835, 2022.

Li, Z., England, M. H., and Groeskamp, S.: Recent acceleration in global ocean heat accumulation by mode and intermediate waters, Nature Communications, 14, 6888, 2023.

MacFerrin, M., Amante, C., Carignan, K., Love, M., and Lim, E.: The earth topography 2022 (ETOPO 2022) global dem dataset, Earth System Science Data Discussions, 2024, 1–24, 2024.

Mahmood, R., von Salzen, K., Norman, A.-L., Galí, M., and Levasseur, M.: Sensitivity of Arctic sulfate aerosol and clouds to changes in future surface seawater dimethylsulfide concentrations, Atmospheric Chemistry and Physics, 19, 6419–6435, 2019.

https://doi.org/10.5194/egusphere-2025-1862
Preprint. Discussion started: 6 May 2025

Malin, G., Turner, S., Liss, P., Holligan, P., and Harbour, D.: Dimethylsulphide and dimethylsulphoniopropionate in the Northeast Atlantic during the summer coccolithophore bloom, Deep Sea Research Part I: Oceanographic Research Papers, 40, 1487–1508, 1993.

Meyer, J. and Riebesell, U.: Reviews and Syntheses: Responses of coccolithophores to ocean acidification: a meta-analysis, Biogeosciences, 12, 1671–1682, 2015.

Minière, A., von Schuckmann, K., Sallée, J.-B., and Vogt, L.: Robust acceleration of Earth system heating observed over the past six decades, Scientific Reports, 13, 22 975, 2023.

Neukermans, G., Oziel, L., and Babin, M.: Increased intrusion of warming Atlantic water leads to rapid expansion of temperate phytoplankton in the Arctic, Global Change Biology, 24, 2545–2553, 2018.

Neukermans, G., Bach, L., Butterley, A., Sun, Q., Claustre, H., and Fournier, G.: Quantitative and mechanistic understanding of the open ocean carbonate pump-perspectives for remote sensing and autonomous in situ observation, Earth-Science Reviews, 239, 104 359, 2023.

Oliver, E. C., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., Benthuysen, J. A., Feng, M., Sen Gupta, A., Hobday, A. J., et al.: Longer and more frequent marine heatwaves over the past century, Nature communications, 9, 1–12, 2018.

Oliver, E. C., Benthuysen, J. A., Darmaraki, S., Donat, M. G., Hobday, A. J., Holbrook, N. J., Schlegel, R. W., and Sen Gupta, A.: Marine heatwaves, Annual review of marine science, 13, 313–342, 2021.

Oziel, L., Sirven, J., and Gascard, J.-C.: The Barents Sea frontal zones and water masses variability (1980–2011), Ocean Science, 12, 169–184, 2016.

Oziel, L., Neukermans, G., Ardyna, M., Lancelot, C., Tison, J.-L., Wassmann, P., Sirven, J., Ruiz-Pino, D., and Gascard, J.-C.: Role for A tlantic inflows and sea ice loss on shifting phytoplankton blooms in the B arents S ea, Journal of Geophysical Research: Oceans, 122, 5121–5139, 2017.

Oziel, L., Baudena, A., Ardyna, M., Massicotte, P., Randelhoff, A., Sallée, J.-B., Ingvaldsen, R. B., Devred, E., and Babin, M.: Faster Atlantic currents drive poleward expansion of temperate phytoplankton in the Arctic Ocean, Nature Communications, 11, 1705, 2020.

O'Brien, C. J.: Global-scale distributions of marine haptophyte phytoplankton, Phd thesis, ETH Zurich, available at https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/155234/eth-48069-01.pdf?sequence=1, 2015.

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A.: The Arctic has warmed nearly four times faster than the globe since 1979, Communications earth & environment, 3, 168, 2022.

Ribes, A., Thao, S., and Cattiaux, J.: Describing the relationship between a weather event and climate change: a new statistical approach, Journal of Climate, 33, 6297–6314, 2020.

Rivero-Calle, S., Gnanadesikan, A., Del Castillo, C. E., Balch, W. M., and Guikema, S. D.: Multidecadal increase in North Atlantic coccolithophores and the potential role of rising CO2, Science, 350, 1533–1537, 2015.

Sallée, J.-B., Pellichero, V., Akhoudas, C., Pauthenet, E., Vignes, L., Schmidtko, S., Garabato, A. N., Sutherland, P., and Kuusela, M.: Summertime increases in upper-ocean stratification and mixed-layer depth, Nature, 591, 592–598, 2021.

Sandø, A. B., Nilsen, J. Ø., Gao, Y., and Lohmann, K.: Importance of heat transport and local air-sea heat fluxes for Barents Sea climate variability, Journal of Geophysical Research: Oceans, 115, 2010.

Santana-Falcón, Y. and Séférian, R.: Climate change impacts the vertical structure of marine ecosystem thermal ranges, Nature Climate Change, 12, 935–942, 2022.

Santana-Falcón, Y., Yamamoto, A., Lenton, A., Jones, C. D., Burger, F. A., John, J. G., Tjiputra, J., Schwinger, J., Kawamiya, M., Frölicher, T. L., et al.: Irreversible loss in marine ecosystem habitability after a temperature overshoot, Communications Earth & Environment, 4, 343, 2023.

Schlüter, L., Lohbeck, K. T., Gutowska, M. A., Gröger, J. P., Riebesell, U., and Reusch, T. B.: Adaptation of a globally important coccolithophore to ocean warming and acidification, Nature Climate Change, 4, 1024–1030, 2014.

Sen Gupta, A., Thomsen, M., Benthuysen, J. A., Hobday, A. J., Oliver, E., Alexander, L. V., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., et al.: Drivers and impacts of the most extreme marine heatwave events, Scientific reports, 10, 19 359, 2020.

Shutler, J., Grant, M., Miller, P., Rushton, E., and Anderson, K.: Coccolithophore bloom detection in the north east Atlantic using SeaWiFS: Algorithm description, application and sensitivity analysis, Remote Sensing of Environment, 114, 1008–1016, 2010.

Simon, A., Poppeschi, C., Plecha, S., Charria, G., and Russo, A.: Coastal and regional marine heatwaves and cold spells in the northeastern Atlantic, Ocean Science, 19, 1339–1355, 2023.

Smale, D. A., Wernberg, T., Oliver, E. C., Thomsen, M., Harvey, B. P., Straub, S. C., Burrows, M. T., Alexander, L. V., Benthuysen, J. A., Donat, M. G., et al.: Marine heatwaves threaten global biodiversity and the provision of ecosystem services, Nature Climate Change, 9, 306–312, 2019.

Smith, H. E., Poulton, A. J., Garley, R., Hopkins, J., Lubelczyk, L. C., Drapeau, D. T., Rauschenberg, S., Twining, B. S., Bates, N. R., and Balch, W. M.: The influence of environmental variability on the biogeography of coccolithophores and diatoms in the Great Calcite Belt, Biogeosciences, 14, 4905–4925, 2017.

Smith, K. E., Burrows, M. T., Hobday, A. J., Sen Gupta, A., Moore, P. J., Thomsen, M., Wernberg, T., and Smale, D. A.: Socioeconomic impacts of marine heatwaves: Global issues and opportunities, Science, 374, eabj3593, 2021.

Smith, K. E., Burrows, M. T., Hobday, A. J., King, N. G., Moore, P. J., Sen Gupta, A., Thomsen, M. S., Wernberg, T., and Smale, D. A.: Biological impacts of marine heatwaves, Annual Review of Marine Science, 15, 119–145, 2023.

Smyth, T. J., Moore, G. F., Groom, S. B., Land, P. E., and Tyrrell, T.: Optical modeling and measurements of a coccolithophore bloom, Applied Optics, 41, 7679–7688, 2002.

Stott, P. A., Christidis, N., Otto, F. E., Sun, Y., Vanderlinden, J.-P., van Oldenborgh, G. J., Vautard, R., von Storch, H., Walton, P., Yiou, P., et al.: Attribution of extreme weather and climate-related events, Wiley Interdisciplinary Reviews: Climate Change, 7, 23–41, 2016.

Swart, N. C., Fyfe, J. C., Hawkins, E., Kay, J. E., and Jahn, A.: Influence of internal variability on Arctic sea-ice trends, Nature Climate Change, 5, 86–89, 2015.

Terhaar, J., Burger, F. A., Vogt, L., Frölicher, T. L., and Stocker, T. F.: Record sea surface temperature jump in 2023–2024 unlikely but not unexpected, Nature, pp. 1–5, 2025.

Tyrrell, T., Holligan, P., and Mobley, C.: Optical impacts of oceanic coccolithophore blooms, Journal of Geophysical Research: Oceans, 104, 3223–3241, 1999.

Von Schuckmann, K., Cheng, L., Palmer, M. D., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T., Cuesta-Valero, F. J., Desbruyeres, D., et al.: Heat stored in the earth system: Where does the energy go? The GCOS earth heat inventory team, Earth System Science Data Discussions, 2020, 1–45, 2020.

Werdell, P. J., Behrenfeld, M. J., Bontempi, P. S., Boss, E., Cairns, B., Davis, G. T., Franz, B. A., Gliese, U. B., Gorman, E. T., Hasekamp, O., et al.: The plankton, aerosol, cloud, ocean ecosystem mission: Status, science, advances, Bulletin of the American Meteorological Society, 100, 1775–1794, 2019.

Winter, A., Henderiks, J., Beaufort, L., Rickaby, R. E., and Brown, C. W.: Poleward expansion of the coccolithophore Emiliania huxleyi, Journal of Plankton Research, 36, 316–325, 2014.

Wunderling, N., von der Heydt, A. S., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., Brunetti, M., Couplet, V., Kleinen, T., Lear, C. H., et al.: Climate tipping point interactions and cascades: a review, Earth System Dynamics, 15, 41–74, 2024.

Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., et al.: Future climate risk from compound events, Nature climate change, 8, 469–477, 2018.