Reply to reviewer for “Exceptional 2023 marine heatwave reshapes North Atlantic coccolithophore blooms”

REV#2

The manuscript «Exceptional 2023 marine heat wave reshapes North Atlantic coccolithophore blooms» assesses the impact of the 2023 big North Atlantic marine heatwave on blooms of a key coccolithophore species in terms of bloom intensity, extent, and phenology in both the Celtic Sea and the Barents Sea. The study finds a decline in bloom intensity and extent in the Celtic Sea, while the Barents Sea experiences record-breaking bloom expansion, which, according to the authors, is likely due to ongoing Atlantification and sea ice retreat. The authors discuss the implications for the carbon cycle and marine food webs, emphasizing the importance of continued monitoring in the context of current climate change.

I found the study to be scientifically relevant as it addresses the response of fundamental marine organisms to extreme climate events. Especially, as coccolithophore plays a role on carbon sequestration and on climate regulation through the production of DMS. However, I found this article to be chiefly descriptive, and to not contribute any new data or new methods. I think it is reviewing and commenting concepts that are not all provided by their results. It does not directly examined the mechanisms underlying the observed bloom changes, but rather relies on other studies. The study frequently references broad concepts such as Atlantification, ecological niches, or acidification yet lacking of specific information (nor even concise definitions) or supporting analyses. These terms are (look like) used as buzzwords without being their effects quantified, and with insufficient evidence nor support by the article results. I also believe the paper is not written for non-specialists, as the referencing is quite incomplete and some key concepts are not explained at all.

Though I think the use of satellite data is justified and the variables selected are appropriately used, some methodological definitions such as how bloom extent and leading/trailing edges are defined and calculated, or what is the thermal range for E. huxleyi blooms, are missing.

Finally, I think that authors overstates the role attributed to the coccolithophore species in the carbon cycle. Authors suggest a major contribution to the biological carbon pump, but not providing sufficient evidence for that.

All in all, I think that the structure of this paper need to be revised in order to provide justification for the observed changes in the coccolithophore blooms, and including analyses of their potential drivers as, by now, it is unclear which novelties are specifically provided by their own results.

We would like to thank the reviewer for their comments on our article, for the time they spent reviewing it in detail, and for their help in improving it. The reviewer raised important issues, which we have addressed by adding new figures and analyses to the revised version. We believe that these changes will address his/her concerns. Due to the extent of the work involved, some comments are not addressed point by point, as we decided to revise most sections. In particular, we have added references on the ecological niches of G. huxleyi and proposed an analysis of PAR and polar front trends during the satellite era. This has allowed us to demonstrate the key role of extreme heat events in intensifying blooms.

Specific comments (I just provided few comments as I think the manuscript needs a thorough revision)

Lines 16 and 21: Here, which conditions are specifically referred to.

Sentence modified :

"During boreal spring and summer, large parts of the North Atlantic Ocean are transformed into shades of color, indicating the occurrence of phytoplankton blooms."

Lines 35 to 40: It is not clear if author claim that coccolithophore are affected by or can resist acidification and warming.

Sentence changed to "the inhibitory effects of ocean acidification may limit coccolithophore calcification in the Arctic, despite the region's rapid warming (Schlüter et al., 2014, Smith et al., 2017)."

Line 43 and 52 (where it is redundantly written): Are authors claiming that long-term warming and internal variability the drivers of MHWs?

MHWs are primarily driven by oceanic and atmospheric processes that are part of internal variability (synoptic conditions leading to increased solar radiation, below-average cloud cover, reduced winds, and turbulent mixing), as demonstrated in the review article by Holbrook et al. 2020. In addition to these processes, extreme events are amplified by long-term warming, which affects both the baseline and stratification, as shown in recent studies (Guinaldo et al. 2025, England et al 2023, Gyuleva et al. 2025).

However, in the revised version we removed this sentence.

Line 47: What "hazards arising from different sources.."?

Sentence changed to : "These consequences are exacerbated by a combination of biogeochemical or atmospheric known as compound events (Zscheischler et al., 2018; Burger et al., 2022; Le Grix et al., 2022)"

Line 55: In June, but for how long?

Mention of 16 days added :

“In 2023, a record-breaking marine heatwave developed, resulting in SST anomalies exceeding +5°C across broad areas of the shelf for 16 days in June”

Lines 99 and 103: If these are the main drivers of the coccolithophore blooms duration and extension, then what are (quantification) the role of MHWs?

In the revised version, we have modified the phrasing and shown that the evolution of the polar front alone cannot explain the intense blooms of 2023 (see Fig A7 and A8) and that record high summer SST are highly correlated to the bloom extent (Table A1) in addition to PAR intensity (Fig 2c-d).

However, quantification is limited in an observation-based analysis and must take into account modeling/attribution studies that are beyond the scope of this study.

Lines 118 to 120: I think this is a vague sentence without referenced.

This section has been modified and we added further analysis.

Instead of :

“However, in BS 115 (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 120 situation under extreme MHWs events like in 2023.”

we propose :

“In contrast, the BS exhibited a northeastward shift in summer maximum concentrations (Fig.A6 & A8). While the western BS shows limited front variability and no consistent trend, the eastern BS is characterized by high interannual variability and a long-term northward shift of 300 km for the northernmost position of the bloom and a shift of 155 km for the latitudinal mean position of the bloom. Even though both the latitudinal mean front position have regressed since 2016, another level close to the record high was reached in 2023 (Fig.A7b), exhibiting a spike in the northward maximal expansion in 2022 and 2023 (Fig.A6). This spatial reorganization of plankton distribution in the Barents Sea has been associated with ’Atlantification’, which in turn enhances blooms of temperate phytoplankton such as G. huxleyi through bio-advection (Oziel et al., 2017). However, this phenomenon does not fully explain the exceptional bloom observed in 2023 even if the interannual variability in the position of the polar front is accompanied by shifts in PIC maxima (e.g. 2004, 2010; Fig.A6 & A7 & A9)."

Line 178: Then, why 2023 is different to other years?

Sentence modified by :

"The changes observed in 2023 and reaching exceptional level are an extreme signature of multi-annual variability superimposed on long-term trends."

Line 195 to 215: This paragraph seems to discuss other studies but not including properly the results of the present manuscript.

As proposed by Rev#2, we have completely revised this section by moving some paragraphs and writing new ones. Instead of discussing other studies, the aim is to highlight the main limitations and gaps in this study and the additional analyses needed to achieve a comprehensive understanding of the impacts of MHWs on coccolithophores

"Coccolithophores, like other calcifying organisms, are sensitive to ocean acidification, potentially reducing their ability to produce coccoliths. Polar regions, subject to increased ocean acidification (Gattuso and Hansson, 2011), may become less favorable for these organisms in the long-term (Terhaar et al., 2020). Additionally, the evolution of water column stratification plays a key role in promoting blooms with a clear signal in the North Atlantic which in fine may alter the regional carbon cycle. These dynamics, including the vertical variation of the summertime mixed-layer depth (Sallée et al., 2006), may reduce both light and nutrient availability, and also have implications for carbon export, a critical function of calcifying species. Knowing the impact of these blooms on the regional ocean carbon cycle, there is a clear interest in knowing the future evolution and implication as these weakening of the ocean carbon sink may compound with decline related to MHW events (Müller et al., 2025).

The changes observed in 2023 are an extreme signature of multi-annual variability superimposed on long-term trends. There is a need to disentangle the contributions of internal climate system variability, such as decadal variability, from the impacts of anthropogenic climate change. This will increase our capacity to assess extreme but plausible events such as the record SSTs in 2023-2024 (Terhaar et al., 2025) and anticipate their consequences. 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 have predominantly focused on terrestrial and atmospheric systems. Similar services for oceans, incorporating biogeochemical components, could be created. This effort could be developed by considering a combination of multi-scale observation networks capable of providing the initial conditions, and enhanced modelling frameworks that capture subsurface dynamics and multi stressor interactions to anticipate future changes and inform adaptive strategies for marine ecosystems (Gregg and Casey, 2007; Nissen et al., 2018; Krumhardt et al., 2019)."