Unusual coccolithophore blooms in Scottish waters

Replies to Reviewers' Comments

Many thanks to all three reviewers for their useful and constructive comments and suggestions.

Please note that this stage of the review process for State of the Planet requires us to reply to comments without providing an updated manuscript. Here we outline our proposals for major revisions, and then respond to each comment in turn. We have combined responses to all three reviewers in one document, as many of the comments touch on similar issues. A revised set of figures is also provided below, save for Figure 3 which is unchanged.

Reviewer comments are in black. Replies from authors are in blue. Please see the end of this document for any references cited.

Proposals for revision

1. We make clearer in the paper that in the absence of *in situ* data, our conclusions are only hypotheses, guesses as to what happened.

2. We compared conditions for 2021 and 1983, the previous year that we believe a highly visible coccolithophore bloom was seen in the Clyde. This didn't lead to any clear conclusions and it complicated the paper. We proposing removing this comparison.

3. Questions were raised about the reliability of the biogeochemical reanalysis for the Clyde Sea. The reanalysis relies on climatological estimates of river outflow, providing nutrients and fresh water. The weather in the Clyde region for 2021 was unusually dry in April and unusually wet in May, and so river outflow will have been very different from climatology. We agree that it is difficult to draw reliable conclusions from the biogeochemical reanalysis for the Clyde. We believe this complicates the paper and propose now not using it.

We still use the physical reanalysis, for SST and for surface currents. Reanalysis SST is strongly constrained by high-quality satellite observations. Variations in surface currents are driven predominantly by surface winds (Röhrs et al. 2023), provided here by ERA5. The slope current itself is forced also by meridional density gradient and steep bathymetry (Marsh et al., 2017). Validation of the reanalysis shows that it does produce a realistic slope current (Renshaw et al., 2021).

4. The reviewers questioned whether ocean colour estimates of chlorophyll are useful in coastal waters. Bowers et al. (2000) find that Dissolved Organic Matter from freshwater is usually the largest optically active constituent in the Clyde. Ocean colour algorithms are designed to minimise errors due to suspended sediment and DOM. We use the product in Figure 4 not as a measure of absolute value but to show the timing of growth and also how values in 2021, particularly April, compare to other years. The OC product includes an estimate of uncertainty (RMSE) following Brewin et al., 2017. For the Clyde Sea in April 2021, estimated values of RMSE for diatoms are around 0.5 mg/m3. An updated Figure 4 is below, using daily means from the CMEMS 1km OC product averaged over the Clyde Sea region https://data.marine.copernicus.eu/product/OCEANCOLOUR_ATL_BGC_L3_MY_009_113/description For the OC satellite imagery (Figures 1 & 2), the strikingly bright patches are characteristic of the presence of coccoliths. We agree that any estimates of chlorophyll concentration will be unreliable in these bright patches.

5. For the Clyde bloom, we will change the wording to make clear that we are not presenting a conclusion, but are instead suggesting a possible storyline:

   a) Cold April temperatures restricted diatom growth.

   b) In May temperatures returned to normal.

   c) In May there was likely an abundance of nutrients, due to lack of an April bloom, to storm mixing bringing up deeper water, and from river runoff due to greater than usual rainfall that month.

   d) Possibly the low diatom growth might also have led to low numbers of predatory microzooplankton.

   e) (c) and (d) would provide favourable conditions for E. huxleyi to grow in May and early June, producing coccoliths in mid June at the end of their life cycle.

   We have some evidence, direct or indirect, for (a), (b) and (c). (d) is speculative.

   For (e), chlorophyll-a estimates from ocean colour data (Figure 4 below) show growth of the nanophytoplankton functional type in May, but falling after storms around the 10th and 20th of the month. This PFT would include E. huxleyi. We need to be cautious in interpreting this data in the Clyde Sea during a month of storms and rain. The fall could be an error in the ocean colour estimates due to contamination by increased turbidity and DOM in the water. It could also be due to vertical mixing taking plankton away from the visible near-surface layers. We can be confident though that there are substantial numbers of coccoliths in the water in June.

6. For the Shetland bloom, the reviewers asked for clearer evidence of how 2021 differed from previous years. We have tried to answer this in two ways.
    a) We looked at ocean colour imagery for years 2017-2020, and at a catalogue (Kondrik et al., 2016) of coccolithophore blooms assessed from ocean colour imagery for years 1998-2016. Blooms were present most years but none so close inshore on the eastern coast of Shetland as in 2021. In 2020 (Figure 2d) there was a bloom approximately 20km offshore. Some other years were similarly close, but none showed the signature bright patch of coccoliths within the bays and inlets of east Shetland.
    b) Using the same particle tracking code as in the original paper, we placed an initial set of particles along the slope current (the top left plot in Figure 5 below). We then advected these forward in time from April 3rd to July 3rd for each year 1993 to 2021, using currents from the reanalysis. For 2021, it can be seen that the red particles (the easternmost particles from April 3rd) end up close to Shetland on July 3rd. In most years the slope current advects the red (easternmost) particles off the eastern edge of the plot region. 2021 was unusual, although not unique, in that easterly winds during the Spring drove currents that pushed those red particles westward for part of that time. 2012, 2016 and 2019 similarly experienced easterly winds in Spring or early Summer. Other years also see particles advected down the eastern side of the Shetlands, originating from further west on the slope current. For instance 2020, where a bloom was observed close offshore. 2021 was also unusual in that a few days of easterlies in late June and early July pushed the bloom close inshore. This wasn't seen in 2020.

Having looked at particle trajectories and bloom locations for other years, we fail to find an obvious pattern. For instance, red (eastern) particles sometimes do and sometimes don't end up in locations that correspond to observed coccolithophore blooms. We find that for particle tracking, based on reanalysis currents that are driven by ERA5 winds, brings particles close inshore for July 2021. We suggest it is serendipitous that the surface winds and the timing and location of coccolithophores in Spring/Summer 2021 coincided to produce the outcome as seen from satellites.

Revised Figures

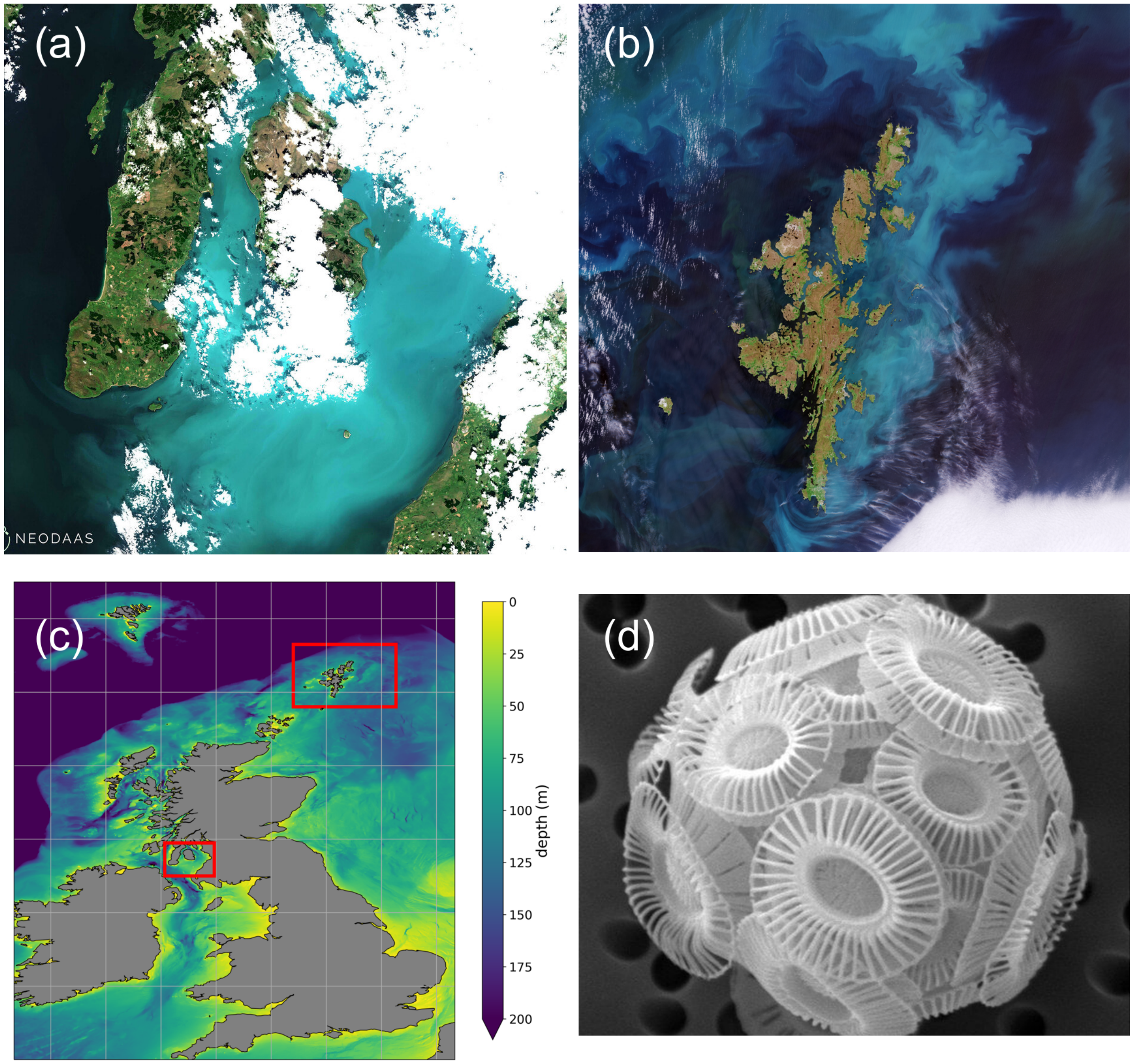

Figure 1. (a) Sentinel-2 MSI image of Clyde Sea on 21 June 2021 11:35 UTC, True Colour with enhanced contrast. Processed by NEODAAS, using ACOLITE atmospheric correction. (b) Sentinel-2 MSI image of Shetland Islands on 1 July 2021, processed by ESA https://www.esa.int/ESA_Multimedia/Images/2021/11/Shetland_Islands (c) Bathymetry map with locations of (a) and (b) marked in red. Shelf edge is visible as transition from light blue (less than 200 m depth) to dark blue (deep water). (d) Scanning electron micrograph of sample from

the Clyde, June 2021, identified as E. huxleyi Morphotype B. Credit: Eileen Bresnan (Marine Laboratory, Aberdeen)

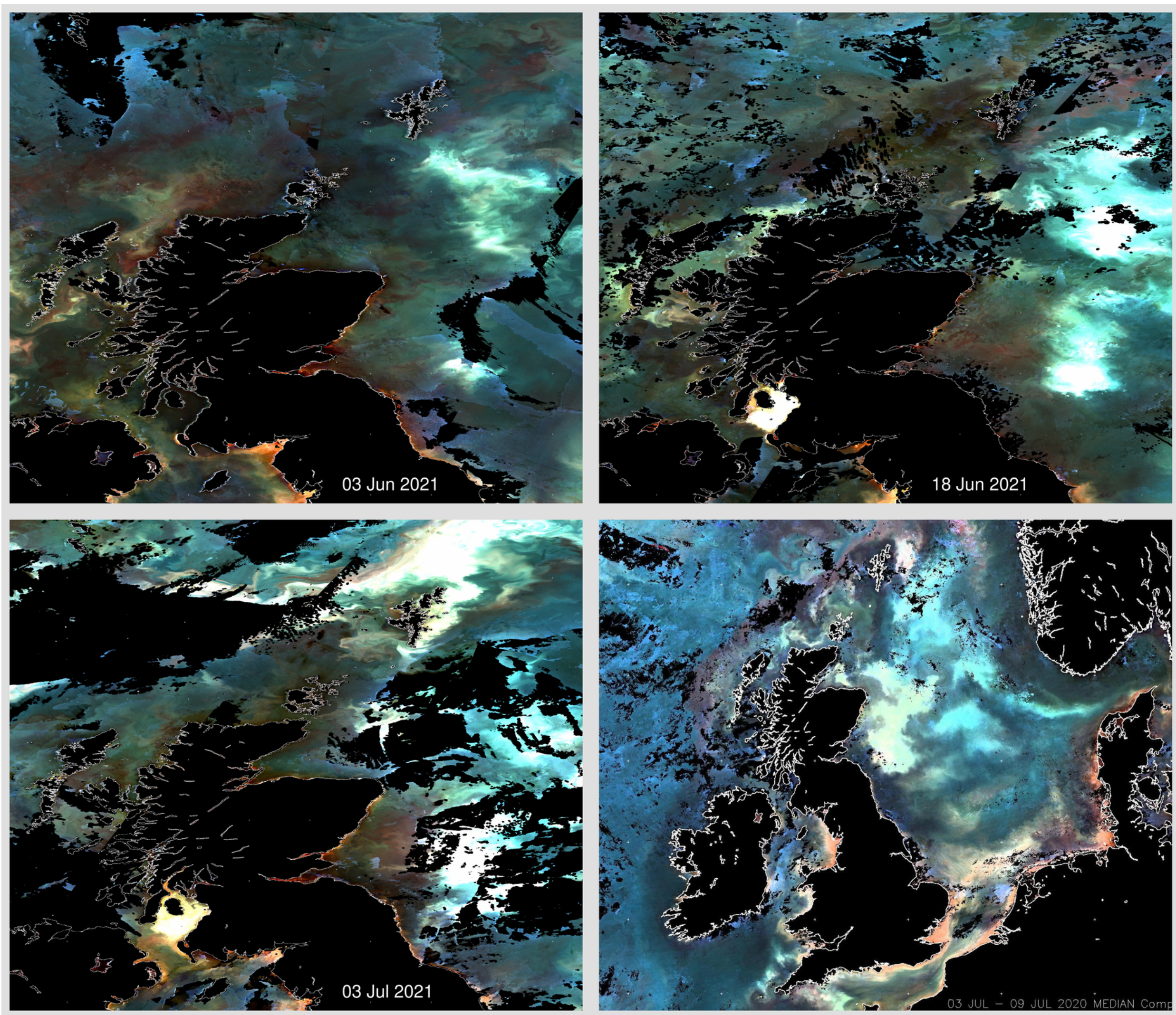

Figure 2. Enhanced ocean colour satellite imagery (provided by PML, product ref 5) from SENTINEL-3 OCLI instrument for: top left 3 June 2021, top right 18 June 2021, bottom left 3 July 2021, and bottom right for 4 July 2020. Regions coloured black are masked as being land areas or obscured by cloud. (apologies, better annotation will be added to the figures)

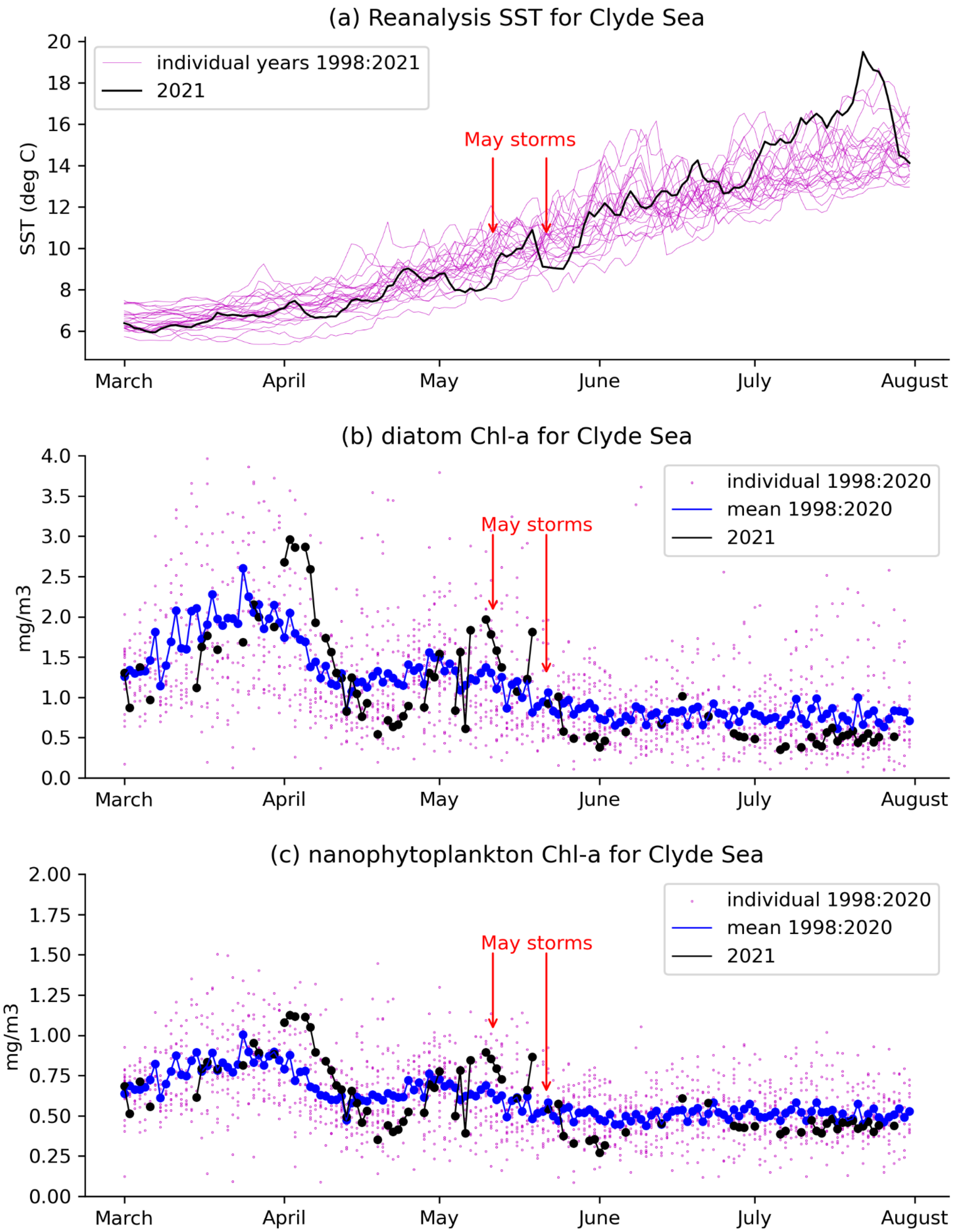

Figure 4. Daily mean values averaged over the Clyde Sea basin, of (a) reanalysis sea surface, and also chlorophyll concentrations (product ref 2) from ocean colour products for (b) diatoms and © nanophytoplankton. For (a), black line is 2021. For (b) and (cd), black dots and line are ocean colour estimates for 2021. Blue is mean estimates for 1998 to 2020. Smaller purple dots are values for individual years, showing the spread.

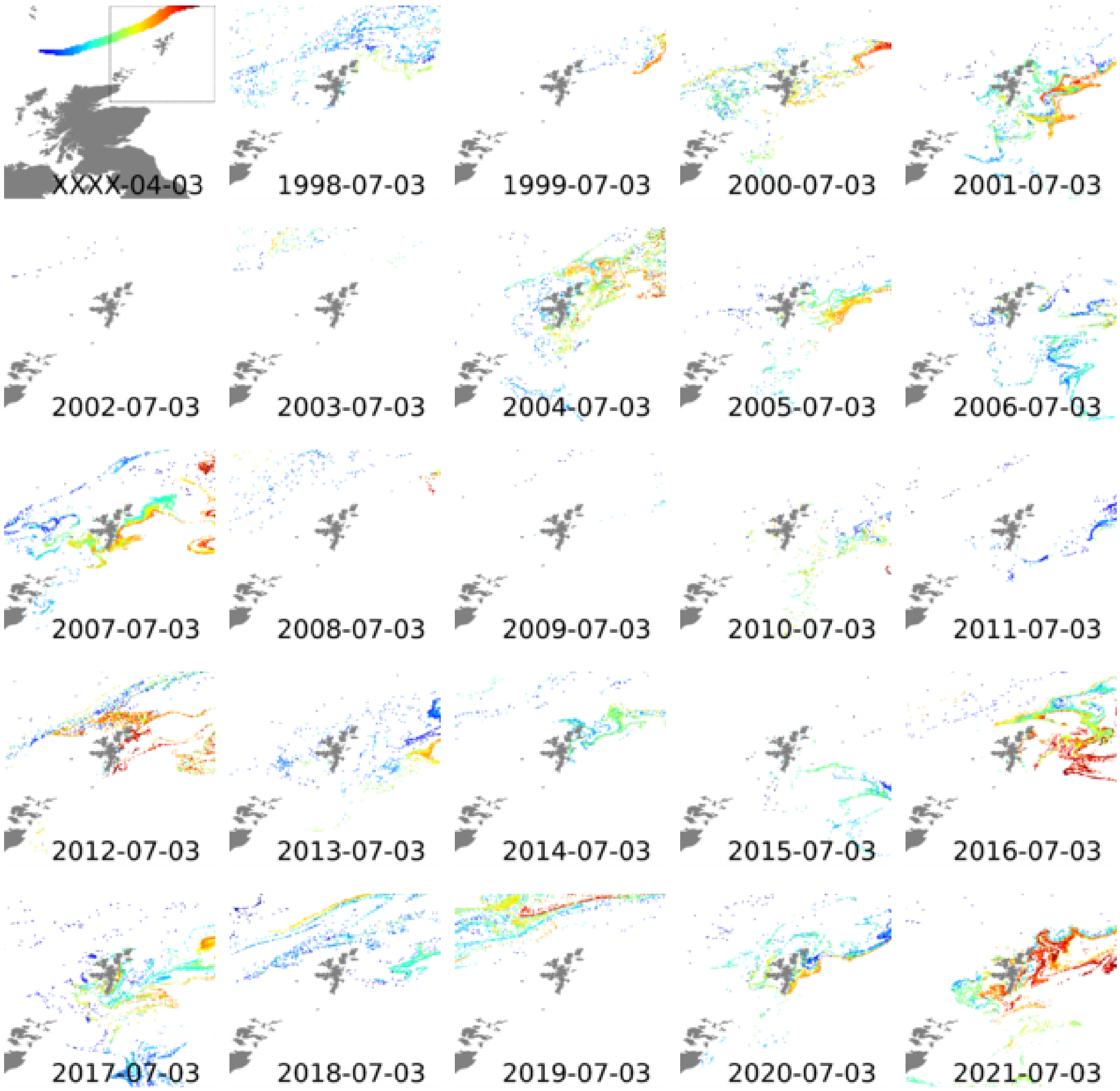

Figure 5. Top left-hand plot is a starting set of particles for April 3rd, positioned along the slope current and coloured according to longitude. Remaining plots are simulations of the positions of those particles 3 months later for individual years, using particle tracking driven by reanalysis currents, plotted for the area around the Shetland and Orkney islands.

Replies to Reviewer 1

General Comments:

The authors have used satellite observations to identify two unusual suspected coccolithophore blooms off the Shetland Islands and in the Clyde Sea. They have presented reanalysis model data and satellite observations to try and attribute the drivers of each bloom. I feel that overall the manuscript lacks detail and I encourage the authors to take more care with the analysis of data, preparation of the figures and formation of the conclusions. I also require further justification the satellite ocean color and chlorophyll data is appropriate to use for this coastal, shallow water study (i.e. does turbidity/ DOM impact the measurements), especially as it outlines in the methods that it ‘masks coccoliths’. I would recommend the manuscript undergoes major revisions.

We hope to have addressed these concerns in the proposals above.

Specific Comments:

I encourage the authors to provide more evidence to allow the reader to ‘see’ how the 2021 summer is different to a ‘normal’ year, particularly in terms of ocean color, SST and currents. I feel more detail is needed when the methodologies are described, including more mention of uncertainties, errors, assumptions and model performance. I appreciate that the authors lack in situ data but I feel they could delve deeper into the data and reanalysis output that they do have. I also would encourage the authors to make their figures more digestible for the reader e.g. including latitude and longitude, marking key events such as the storms and presenting observational data where possible. The reanalysis model also appears to consistently underpredict the chlorophyll concentration and barely shows a seasonal cycle in most years including 2021. I encourage the authors to discuss this and to make it clear what value the reanalysis brings to the paper. I have provided further detailed comments below.

We take these comments on board and hope that the proposals go much of the way to meeting them. We have added Figure 5 to give some idea of the diversity of current trajectories from year to year. We have dropped use of the biogeochemical reanalysis, given the uncertainties around its performance within the Clyde basin. Figure 4 now has observational data, shows means over the basin rather than point values, and includes markers for the May storms. We would be happy to consider further changes.

Technical corrections:

Line 15-35: Personally, I would start with the background on coccolithophores and their importance in the introduction. The first paragraph could be merged with the last paragraph of the introduction.

Yes, will do.

Line 52: ‘and so includes coccolithophores’ amend to ‘which could represent coccolithophores’ as it is a general PFT that doesn’t have specific parameterisations for coccolithophores but is parameterised to produce calcite.

Yes

Line 54: with the sites being close to the coast and in relatively shallow waters does this disrupt the chlorophyll estimates (e.g. from turbidity/DOM)?

Yes it will. We will discuss this in the paper as in Proposal 4 above.

Line 55: extra bracket

ok

Line 58: add more detail about the OLCI instrument as it’s not clear to the reader

This was a mistake. Actually the OC product we used does not come from OLCI, it’s a multi-sensor product from the Ocean Colour Climate Change Initiative. We will add:

“The observations here are estimates of chlorophyll from multiple ocean colour sensors, which measure water-leaving radiation at various wavelengths in the visible and near infrared spectrum. These observations are combined and processed to give estimates of chlorophyll concentration for four phytoplankton functional types.”

Line 59: If the estimation process masks for coccoliths is it appropriate to use it in this study?

Figure 4 has been updated with the OC product in place of the reanalysis. We will make clear in the text that during the period that coccoliths are clearly visible (12 June to 7 July), estimates of chlorophyll are unreliable.

Line 71: More detail should be provided regarding the parcels simulations. What timestep was used? Were the simulations the same length (i.e. how many days)? What depth were the particles released (or was it surface only?)? Currently, there is no way for this work to be replicated as there are scant details provided.

We will add these details. We propose to replace the original Figure 2 and to show instead a set of forward particle tracks in the new Figure 5, above.

The new tracking releases particles at 1m depth and tracks forwards for 3 months (3 April to 3 July) using 3D currents and a 3 hour timestep.

Figure 1: It would be helpful for the reader to see what a normal ‘June’ looked like for the satellite data to allow for comparison and for the reader to evaluate how ‘unusual’ these blooms are.

We struggled with this as there isn’t really such a thing as a “normal June” in the OC imagery. The Clyde bloom does appear to be unique for 2021. Shetland sees a wide range of positions and timings for bright patches that appear to be coccolithophores. We have included a single image from 2020 in the updated Figure 2, which was similar to 2021 except not so close inshore.

Figure 1: the bathymetry map requires a colourbar

Done

Line 80: is the weather magazine reference meant to have a date in place of b?

Yes

Line 82: we hypothesise?

ok

Line 90: missing a bracket

ok

Figure 2: why is chlorophyll concentration not presented alongside the ocean colour data? Is it because the measurements are not robust in such shallow coastal areas? Also, for Figure 2b there is a plotting error with a black triangle projected from the top right of the figure down to the bottom-mid left. I would find it instructive to see where particles were advected to at a similar time period during a ‘normal’ year otherwise it’s hard to confirm that these current pathways are unusual.

We could provide plots of the OC chlorophyll product if required. As you say, the accuracy is unreliable in coastal areas, and especially in the presence of many coccoliths. We do make some use of the data qualitatively to indicate relative values and timings, in Figure 4 and as discussed in Proposal 4 above.

We don’t see the black triangle in Figure 2b but hope that with the updated Figure 2 this artefact has gone away.

We agree about needing to see how the 2021 pathway was unusual, and hope the new Figure 5 helps answer that.

Section 4.1: First introduce why you have switched to discussing diatoms when the paper is focused on coccolithophore blooms.

Will add text to make that clear.

Section 4.1.2: I'm not clear why this section focuses on 1983 as well. I don't think this has been introduced to the reader yet and very little data, besides the Table, is presented for 1983 so I'm not sure how much it adds to the paper.

We will remove comparison with 1983, as under Proposal 2.

Physical environment section: all of the sentences are quite vague, perhaps some quantitative numbers (i.e temperatures) could be added in line?

Yes, this section needs improving. We will make this much shorter and remove comparisons with 1983. Very likely we will also remove Table 1 and pick out just a few salient numbers to quote in line.

Figure 4: I find it confusing that the observations are blue dots for 2021, the black line is the NWS 2021 mean and then the dashed blue line is the mean of the 1998-2020 observations. I first thought that the blue dashed line was the 2021 reanalysis. Perhaps pick a different color for either the line or the observations or add a legend to make it more digestible.

We hope the new Figure 4 is better.

Figure 4: no graphs have any latitude or longitude axis which makes it hard to pin where 55.27N -5.11 E is. Why has a specific location been chosen rather than an average over the extent of the bloom?

Figure 4 now shows averages over the Clyde Sea basin.

Line 126: 'Table 1(a) includes statistics for 1983, the previous year that such a bloom was seen in the Clyde Sea.' – how was it 'seen'? 1983 precedes satellite chlorophyll and there is no reference provided for the bloom.

We will remove the comparison to 1983. We have looked and found no published or online references to a 1983 bloom nor any other since. We rely on the local knowledge of one of the authors, and will write:

"Such striking occurrences have not been reported from the Clyde Sea for many years. Colleagues of one of the authors (PT) remember sampling turquoise waters and coccolithophores in sea-lochs of the Firth of Clyde, probably in June 1983."

Line 174: even with low rainfall in April it would surprise me if the level of nutrients would limit diatom growth enough that a population wouldn't pick up in May when nutrients became more available post-mixing events. The P1 diatom observations do also increase again in May (which is hard to tell with the figures on different y-scales) and I suspect the chl concentration was greater than the ~0.5 mg/m3 shown for the P2 observations. There is a lack of substantive evidence in this paragraph to support the claims, which I appreciate is due to a lack of data availability but the authors still need to be careful with the conclusions they reach.

Accepted. We will rewrite to avoid drawing conclusions but to present a plausible storyline (Proposal 5).

Figure 4: The P2 chlorophyll concentration from observations for 2021 is consistently below the mean observations from early April onwards – how does this line up with the ocean color data that is posited to be showing a coccolithophore bloom? It seems from the P2 magenta reanalysis lines that there have been much larger blooms in May previously but these are not mentioned. Did these blooms show up in ocean colour data?

The updated Figure 4c (below) now shows observations from ocean colour data, rather than values from the reanalysis. Values for 12th June onwards should be treated with severe caution due to optical contamination by the coccoliths, visible in the imagery (Figure 2). We know that no previous years have shown this characteristic signature of a coccolithophore bloom in the satellite imagery.

Our storyline (Proposal 5) suggests growth of E. huxleyi during May and early June. Figure 4c (nanophytoplankton concentration) has higher than average values during May, reducing sharply after the two May storms (10th and 20th May). These estimates may be unreliable due to turbidity and presence of DOM. As you suggest below, it may also be that vertical mixing by the storms diluted the numbers of nanophytoplankton in surface layers, at the depths visible to satellites.

We will make sure to explain this in the updated text.

Figure 4: it would be helpful if you could mark the storm timings on the figures. Could the SST observations that fed into the 2021 reanalysis be added to the figure?

Storm timings have been added. We can add observations if required. The reanalysis does fit the SST observations closely (validation in Renshaw et al., 2021) when these are available. Coverage for May and for much of June is patchy due to cloud cover.

Abstract: Having now reviewed the manuscript I am not sure about the cold temperatures restricting the bloom i.e. ‘We hypothesize that the cold restricted the usual spring bloom of diatoms. A restricted spring bloom would mean higher than usual concentrations of nutrients in the summer.’ The authors discuss how storm events and colder SSTs indicate mixing. My understanding is that satellite ocean colour can only ‘see’ the top ~10m or so. Therefore, is it not the dilution of the phytoplankton populations across a deeper mixed layer that has led to low chl concentrations in May?

Thank you, we’re grateful to take that theory on board.
We will also speculate that an unusually sunny April (the sunniest in the Clyde since at least 1982) could have restricted diatom growth. As we say in lines 97-99 of the original text, Marshall and Orr (1927) found that diatoms are damaged by excessive light.

Comments from Reviewer 2

General comments

Article focusing on 2 interesting bloom events that, unfortunately, only brings forward hypotheses regarding the origin of the blooms which could become concrete results if a more thoroughly and deeper analysis of the available data would be performed.

Specific comments

Methodologies are not detailed enough; especially the method of parcels simulations requires more details. Information about why data from 1983 was also included is lacking. Details need to be added to the figures for a better link between text and figures (for example: coordinates are given for the "point in the central Clyde Sea" but no latitude and longitude are on the other maps). The results regarding the conditions leading to those blooms could be turned from hypotheses into results and would hence gain in meaning if models were used to identify the statistically most important drivers associated with these unusually high abundances for example. The discussion should include a part on satellite imagery's weakness in areas close to the coast.

Thank you for your comments. We hope to have addressed many of these in the proposals at the top of this document. We would like to be able to provide statistical analysis but are hampered by the lack of reliable quantitative data, and a limited sample size. Further specific points are answered below.

Technical corrections

Page 3 – Line 52 "The P2 class allows for calcification and so includes coccolithophores" needs further explanation

Yes, our description wasn't clear. Under Proposal 3 we will drop use of the biogeochemical reanalysis and so will remove this section.

– Line 53 *in situ*

We agree but are compelled to follow State of the Planet guidelines, "in situ" not to be in italics!

https://www.state-of-the-planet.net/submission.html#templates

– Line 55 unnecessary bracket

Yes

– Line 60 “there are few data available for the Clyde” : Why? Because of higher cloud coverage than in Shetland?

Yes, that’s correct. We do now provide the ocean colour data in the updated Figure 4 (b & c) above. There are some values (black dots) for June, but intermittent.

Page 5 – Figure 1 caption a) … “image of THE Clyde Sea…”; b) “…of THE Shetland Islands…”; c) Add legend on map for depth and add longitude/latitude, “deep water” not precise enough; d) Add scale bar on image

Please see revised Figure 1, above.

Page 6 – Line 98 several metERS

Again we are constrained by Copernicus guidelines, which insist on “metres”.

– Line 102 *NitZschia seriata*

Yes

– Section 4.1 lacks information about the link between diatoms and coccolithophores, needed to better integrate this section into the overall topic of the paper

Yes, this does need making clearer. We will add text to explain this.

Page 7 – Line 121 Why these 2 years?

We hoped to get insight by comparing 2021 against 1983, which was the previous known occurrence of extensive coccoliths in the Clyde Sea. But no insight was forthcoming and we will remove comparison with 1983 (Proposal 2).

Page 8 – Add longitude/latitude; add simulations of other years for a better understanding that these were unusual advection paths; add in caption that the black shapes on the maps correspond to cloud coverage

Have added explanation of black regions being cloud to Figure 2. Revised Figure 4 now shows means over the Clyde Sea basin, rather than for a specific lat/lon point. New Figure 5 shows simulations for a range of years (1993-2021).

Page 13 – pH is an important factor influencing coccolithophores and changing chemistry in the North Sea should be mentioned as possible cause

Thank you. We have now looked into this as a possible cause.

In a MCCIP report, Humphreys et al. (2020) look at data for Stonehaven in eastern Scotland for 2009-2013. They find a reduction in pH of 0.1 over that period.

Riebesell et al. (2017) report that large CO2 additions caused a decline in growth and calcification rates of E.huxleyi in mesocosm experiments; however, effects were marked only when pH was reduced from 8.14 to 7.2.

We propose adding this to the text:

“Although growth of E. huxleyi is known to be impacted by ocean acidification (Riebesell et al., 2017) it seems unlikely that these effects can explain interannual variability in coccolithophore abundance in the Clyde.”

– Wind direction is mentioned in the discussion but is not discussed in the possible causes section

We will add advection as a possible cause.

Comments from Reviewer 3, D. G. Bowers

General comments

I enjoyed reading this paper. Coccolith blooms are one of the easiest things to identify in ocean colour images of the north-west European shelf in summer and they are a key part of the pump that transfers carbon from the atmosphere to the ocean floor. It is therefore important to study them and understand how they work.

This paper considers two unusual coccolith blooms in the summer of 2021, observed from space, and discusses how they might have been formed. One is to the east of Shetland, the other in the Clyde Sea. I am convinced that these are coccolith blooms but less convinced by the explanations offered (especially for the Clyde bloom). It's a bit tentative.

The main tool that the authors have for seeing what happened at sea level is a reanalysis. I understand that this is a run of a physical-biological model, corrected by reference to the available data. The chlorophyll concentration from this reanalysis for the Clyde Sea and for the group (nanoplankton) that includes coccoliths is shown as the green line in figure 4b. Have I got that right? But that DOES NOT show a bloom in June, right? So the best guess at what is going on at sea level is that there is no bloom, even though the satellites clearly see one. Am I right in thinking that is the nub of the problem? So maybe the point to make is that the reanalysis is not working?

Thank you for the positive comments.
Yes, agreed, the reanalysis biogeochemistry is struggling given inadequate input data (climatological river flow, and assimilating unreliable estimates of chlorophyll from ocean colour data contaminated by coccoliths). Proposal 3 - we have decided to remove use of the BGC reanalysis data, and have updated Figure 4 to use the ocean colour estimates.
We should note that we use the ocean colour data qualitatively, to indicate timings and to compare against other years (Proposal 4). We also note that the data is suspect during June when the Clyde Sea has visible coccoliths.

Maybe that is the take home message from this paper. It looks like you can explain the Shetland bloom by advection of phytoplankton from outside but the Clyde bloom remains a bit of a mystery. No harm in that. In fact it is useful to know that we don't understand things properly.

So, I think my main suggestion if you agree with the above is not to be frightened of saying that these blooms are not properly understood yet. The one in the Clyde Sea is observed to happen but we cannot explain why. There are also a couple of small points:

Thanks. We'd put that slightly differently, to say that for the Clyde we have a plausible, if incomplete and speculative, storyline (Proposal 5).
We're also keen to make the case for more in situ data. Monitoring of nutrient levels and phytoplankton components would let us test this storyline for any future blooms. Data on river

discharge would help enormously in simulating conditions in the Clyde and other inshore water bodies.

Specific comments

line 59 you say that the estimation process masks clouds,sunglint and coccoliths. Isn't it a bit worrying that the tool you are using to observe coccoliths might mask them out?
Yes. We have to distinguish between use of the satellite imagery to spot the bright patches indicative of coccolith plates, and use of the ocean colour algorithms to retrieve estimates of chlorophyll concentration. They are complementary - can do one or the other, not at the same time.

The bathymetry map of figure 2c could do with a key.
Thanks, added in revised Figure 2.

line 88 tidal mixing restricted to mostly near-surface waters. I don't understand that. Aren't the tides here weak? Do you mean wind is mixing near surface waters?

This was from Simpson & Rippeth 1993 https://doi.org/10.1006/ecss.1993.1047
"The buoyancy of this surface water tends to maintain a stable stratification which is not seriously eroded by tidal stirring on account of the generally weak barotropic tidal flows (U < 0.2 ms-1) in the deep water of the basin."
The wider point was that nutrients in the near-surface layer become depleted but can be boosted after storms when wind-driven mixing brings up nutrients from deeper water.
I'll look at making this clearer.

Not sure I understand figure 2 very well. Is it telling us that the Shetland bloom is consistent with the phytoplankton being advected in from elsewhere but the Clyde Sea ons is not?

Yes. The new Figure 5 above hopes to show that 2021 was unusual in that currents brought the phytoplankton close inshore on eastern Shetland (Proposal 6).

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