Unusual coccolithophore blooms in Scottish waters

Richard Renshaw[1], Eileen Bresnan[2], Susan Kay[1,3], Robert McEwan[4], Peter I. Miller[3], and Paul Tett[5]

[1]Met Office, FitzRoy Road, Exeter EX1 3PB, UK
[2]Marine Scotland Marine Laboratory, 375 Victoria Rd, Aberdeen AB11 9DB, UK
[3]Plymouth Marine Laboratory, Prospect Place, Plymouth PL1 3DH, UK
[4]Cefas, Barrack Rd, Weymouth DT4 8UB, UK
[5]Scottish Association for Marine Science, Oban, Argyll PA37 1QA, UK

Correspondence: Richard Renshaw (richard.renshaw@metoffice.gov.uk)

Abstract. Two unusual blooms were observed in Scottish waters during summer ~~2021. One was~~ 2021: one in the Clyde Sea and the other by the east coast of the Shetland Islands. Both had the appearance of coccolithophore blooms. Transmission electron microscopy of a sample from the Clyde Sea confirmed the presence there of the coccolithophore *Emiliania huxleyi*. We examine the conditions that led to these unusual blooms. In situ data are scarce and so we draw inference from satellite data and reanalysis. For Shetland, the bloom can be seen to originate further north on the edge of the continental shelf. It is advected south and then west towards the Shetland coast by surface currents~~exceptionally from the east~~. For the Clyde Sea region, April 2021 was ~~on average the coldest weather~~ the coldest April of the last 30 years (National Climate Information Centre). We hypothesize that ~~the cold~~ this cold weather restricted the usual spring bloom of diatoms. A restricted spring bloom would mean higher than usual concentrations of nutrients in the summer. It might also mean reduced numbers of ~~predators~~grazers. These factors would provide ideal conditions for coccolithophores to flourish as temperatures and sunlight increase.

Short summary

There were two unusual blooms in Scottish waters in summer 2021. Both turned the sea a turquoise colour visible from space, typical of coccolithophore blooms. We use reanalysis and satellite data to examine the environment that led to these blooms. We suggest unusual weather was ~~responsible~~ a contributory factor in both cases.

1 Introduction

~~Summer 2021 saw milky, turquoise coloured waters caused by algal blooms in two locations off Scotland, in the Clyde Sea on the west coast, and also to the east of the Shetland Islands (Fig. 2). These blooms were visually striking and so unusual that they were reported in the news (?). Transmission electron microscope analysis of a water sample from the Clyde (Fig. 2(d)) confirmed the algae to be a morphotype of coccolithophore, *Emiliania huxleyi* (morphotype B). Blooms of this organism are common in spring and early summer in the North Atlantic, and occur in some years in the northern North Sea and the western English Channel. However, coccolithophore blooms which discolour water to this extent are uncommon on the west coast of Scotland, and this is thought to be the first such bloom in the Clyde Sea since 1983.~~

Coccolithophores belong to a diverse group of phytoplankters (class Prymnesiophyceae) that is widespread in the oceans. The ecological group that includes *Emiliana* is particularly abundant in upwelling and temperate sub-polar regions (**?**). Most coccolithophores are not themselves harmful or toxic but they are of ecological importance, particularly for carbon cycling and sequestration (**?**). They typically produce an exoskeleton consisting of several calcium carbonate plates called coccoliths (**?**). These coccoliths are not opaque (phytoplankton require light for photosynthesis) but they scatter and polarise light. Coccolith shedding occurs during the later stages of the bloom life cycle when the cells are threatened for example by pathogen pressure (**?**). During this stage, the coccoliths are shed and accumulate in the surrounding water. The visual effect is to turn the sea a milky turquoise colour, visible to the human eye and in satellite imagery.

The function of the coccoliths is unclear. They are believed to be protective, either against grazing, against viral or bacterial attack, or as a refractor of light that acts as a sunshade in excessively bright conditions (**?**). **?** show that coccoliths initially provide some protection from viral attack but once shed can mediate such attacks. **?** suggests that coccolith production may have evolved originally as an efficient mechanism for intracellular Ca^{2+} detoxification at a time of elevated seawater Ca^{2+} concentrations (e.g. during the Cretaceous and Jurassic periods).

~~The conditions that gave rise to these blooms may be indicators of change that will also be relevant to harmful algal blooms , and~~ Summer 2021 saw milky, turquoise coloured waters caused by algal blooms in two locations off Scotland, in the Clyde Sea on the west coast, and also to ~~the marine ecosystem more generally.~~ the east of the Shetland Islands (Fig. 1). These blooms were visually striking and so unusual that they were reported in the news (e.g. **?**). Transmission electron microscope analysis of a water sample from the Clyde (Fig. 1(d)) confirmed the algae to be a morphotype of coccolithophore, *Emiliania huxleyi* (morphotype B). Blooms of this organism are common in spring and early summer in the North Atlantic, and occur in some years in the northern North Sea and the western English Channel. However, 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. In this paper we use observations and reanalysis data to look for unusual environmental conditions in 2021 that might have allowed these blooms to thrive~~in Scottish waters~~.

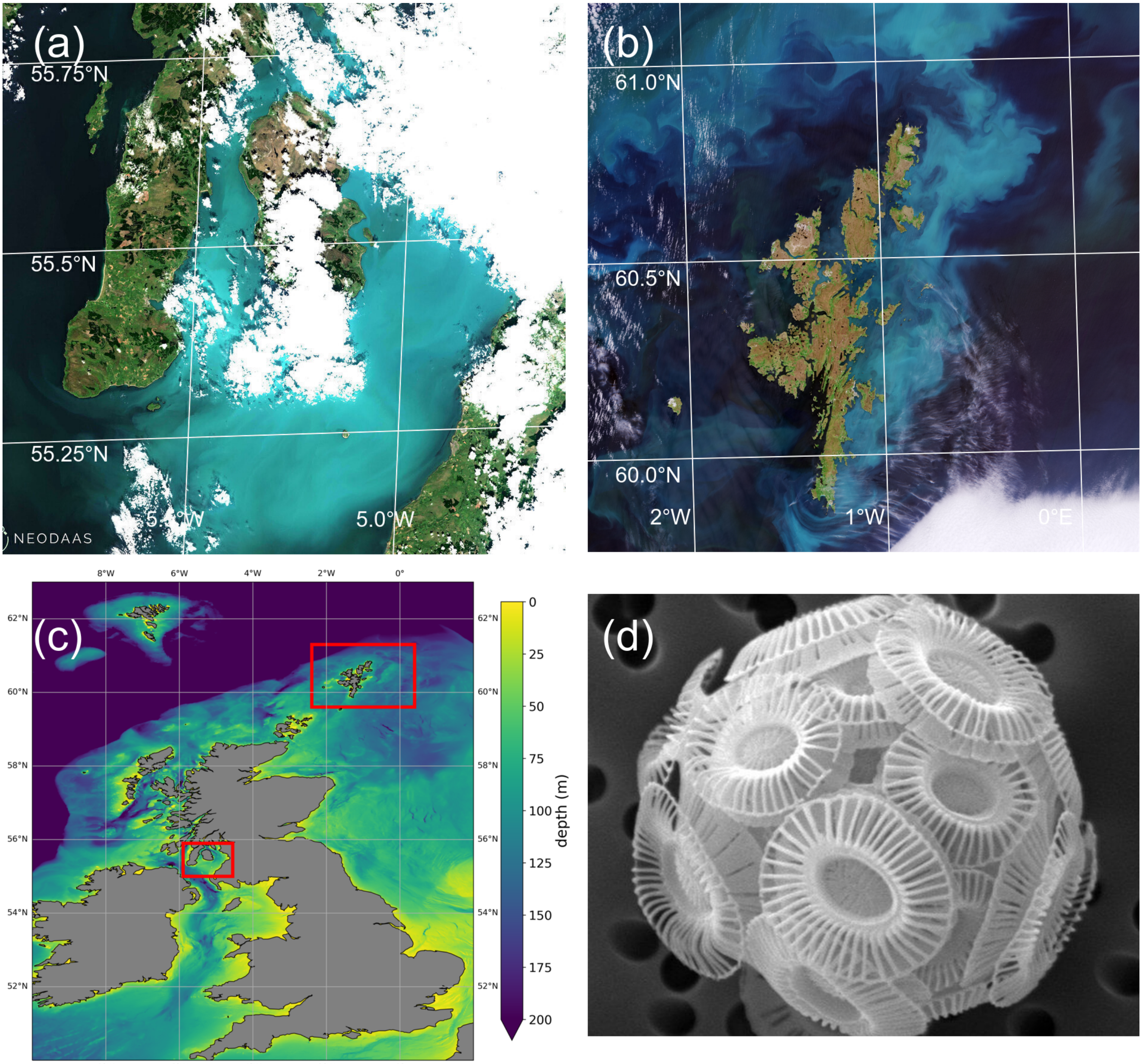

Figure 1. (a) Sentinel-2 MSI image of Clyde Sea on 21 June 2021 11:35 UTC, True Colour with enhanced contrast. Processed by NEODAAS, using ACOLITE atmospheric correction. (b) Sentinel-2 MSI image of Shetland Islands on 1 July 2021, processed by ESA https://www.esa.int/ESA_Multimedia/Images/2021/11/Shetland_Islands (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)

2 ~~North West Shelf reanalysisThe NWS reanalysis~~ Data

2.1 Ocean Colour

Ocean Colour (OC) instruments measure water-leaving radiation at various wavelengths in the visible and near infrared spectrum. Satellite measurements of Ocean Colour are used here in two forms. One is imagery. The enhanced colour maps from Sentinel-3 OLCI and Sentinel-2 MSI in Fig. 2 provide visual indications of algal blooms. The other is observation products, point estimates of near-surface chlorophyll concentration derived from multiple sensors. The CMEMS product used here (product ref~~1 &~~ 2) ~~is a coupled physical and biogeochemical reanalysis for 1993 onwards~~ estimates chlorophyll concentration for several distinct phytoplankton functional types, including diatoms and nanophytoplankton. The nanophytoplankton category includes *E. huxleyi*.

Several factors make chlorophyll estimation difficult for coastal waters. **?** 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. The presence of large numbers of coccoliths would also have a strong impact on backscattered radiation (**?**). The estimation process does mask for cloud, sun glint, and coccoliths (**?**). This masking means there are few OC chlorophyll estimates available for the Clyde during the period of the Clyde bloom (12 June to 7 July 2021). We use the OC product in Fig. 5 not as a measure of absolute value but to show the timing of growth and also how values in 2021 compare to other years.

2.2 North West Shelf reanalysis

The NWS reanalysis (product ref 1) is based on the physical ocean model NEMO (**?**) at 7km horizontal resolution, 51 vertical levels, ~~for~~ with tides represented, over a domain that encompasses the North-West European Shelf (**?**). ~~It uses the physical ocean model NEMO (?) with tides and the biogeochemical model ERSEM (?). The atmospheric forcing is given by~~ Atmospheric forcing is from the ERA5 atmospheric reanalysis (**?**). ~~The river discharge~~ River discharge volumes for years 2018 onwards ~~is~~ come from a daily climatology.

~~ERSEM simultaneously describes pelagic and benthic ecosystems in terms of phytoplankton, bacteria, zooplankton, zoobenthos and the biogeochemical cycling of carbon, nitrogen, phosphorus and silicon. ERSEM uses a functional group approach to describe the ecosystem, whereby biota are grouped together according to their trophic level (subdivided according to first size, then trophic role and finally feeding method). Four functional groups of phytoplankton are included, three of zooplankton and one of bacteria. The four Plankton Functional Types (PFTs) are:~~

- ~~P1: diatoms, 20-200 μm with an affinity for silica~~
- ~~P2: nanophytoplankton, 2-20 μm~~
- ~~P3: picophytoplankton, 0.2-2 μm~~
- ~~P4: flagellates, 20-200 μm without silica requirements~~

The ~~P2 class allows for calcification and so includes coccolithophores. The~~ reanalysis uses NEMOVAR (**?**) to assimilate observations of physical variables (satellite SST, in situ temperature and salinity profiles (**?**)). ~~From September 1997 onwards it also assimilates observations of chlorophyll-a partitioned between the 4 PFTs, estimated from ocean colour satellite data (**?**).~~

~~In data assimilation, the model is adjusted towards the observations. Both observations and model are prone to errors and so the reanalysis does not aim to fit the observations exactly. How closely it fits depends on the statistical errors specified for observations and~~ Here we use the reanalysis for ~~model values. The observationshere are estimates of chlorophyll-a from the OLCI instrument. The estimation process masks for various factors which could corrupt the estimates, including cloud, sun glint, and coccoliths (**?**). This means there are few data available for the Clyde during the period of the bloom (12 June to 7 July) and that those data should be treated with caution~~sea surface temperature and also for near-surface currents in the region of the European Slope Current. Reanalysis SST is strongly constrained by high-quality satellite observations. Variations in surface currents are driven predominantly by surface winds (**?**), provided here by ERA5. The Slope Current itself is forced also by meridional density gradient and steep bathymetry (**?**). Validation of the reanalysis shows that it does produce a realistic Slope Current (**?**).

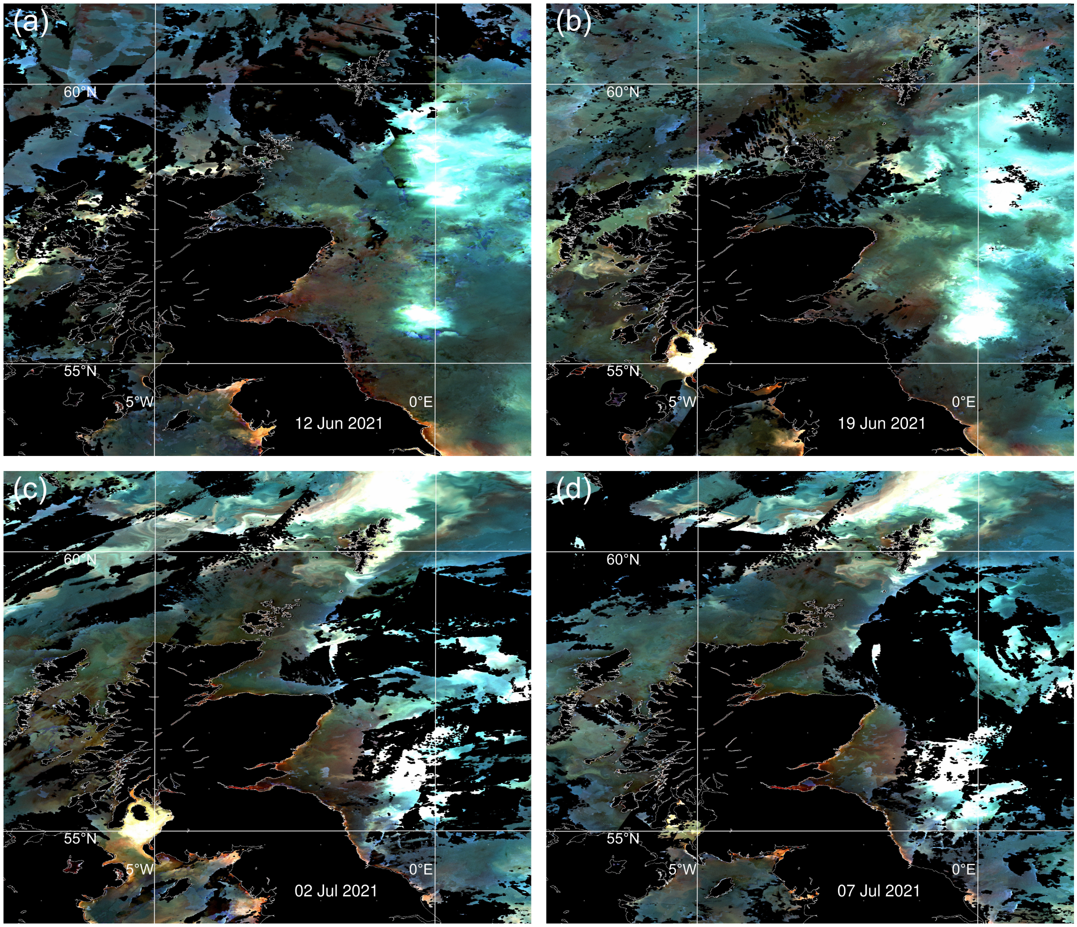

Figure 2. Enhanced ocean colour satellite imagery (provided by PML, product ref 5) from Sentinel-3 OCLI and Sentinel-2 MSI instruments for dates 12th and 19th June 2021, 2nd and 7th July 2021. The brightest pixels are indicative of high numbers of coccoliths. Land and cloud are coloured black.

3 Shetland bloom

Figure~~2~~ 1 shows a bloom on the eastern side of Shetland. There is no information on the species present but the ~~satellite imagery has a distinctive appearance associated with coccolithophores. The feature is visible in satellite imagery over the period 26 June to 15 July 2021. Blooms in the North Sea and as far north as Shetland~~ brightness and turquoise colour of the bloom suggests coccolithophores. Coccolithophore blooms in the North Sea are not unusual. ~~Satellite imagery (not shown) reveals extensive blooms~~ An unusual feature of the 2021 bloom was that it came so close inshore. Examination of imagery for years 2017 to ~~the east of Shetlandin June 2019 and June 2020. Typically, coccolithophore blooms~~ 2020 provided by PML (product ref 5) and of a dataset of coccolithophore blooms for 1998 to 2016 in **?** finds no other examples where blooms intrude among the islands and bays on the eastern side of Shetland.

? show that often blooms develop further south and east in the North Sea ~~develop to the south of Shetland~~ in spring or early summer and are advected by ~~the overall~~ an anti-clockwise circulation ~~in the North Sea. They are often visible on satellite imagery in June and July (**?**). To the northof Shetland, the continental shelf break is marked by the~~ sometimes reaching as far north as Shetland. Sometimes a bloom originates to the north, along the northern edge of the continental shelf, and is advected southwards. Bathymetry in Figure 1(c) shows the location of this shelf edge. The European Slope Current ~~, an intense eastward-flowing jet~~ flows eastward along this edge bringing North Atlantic water into the Norwegian Sea. Some of this water flows south ~~around the western and eastern sides of Shetland . To trace the origin of the bloom,~~ past Shetland into the North Sea. Imagery for July 2021 (Fig. 2(c) & (d)) seems to show the bloom is of the latter kind, originating along the northern edge of the shelf.

To confirm the bloom's origins, and to understand why 2021 was unusual, we used the *OceanParcels* software package (**?**) ~~was used to advect particles backwards in time from the date and region of the bloom. The advection was driven~~ to simulate the trajectory of virtual particles in the ocean. Particles were initially positioned at 1 m depth along the Slope Current (Fig. 3). These locations were chosen based on where the speed of the current (from a reanalysis mean climatology for 1993 to 2021) exceeded $0.2\,\mathrm{m\,s^{-1}}$. *OceanParcels* modelled 3D movement of the particles, advected by daily mean currents from the NWS reanalysis (product ref 1) ~~. Figure 3(c)shows virtual particles positioned at approximately the location of the Shetland bloom on~~ and using a 3 ~~July 2021. In Fig. 3(b) and Fig. 3(a) those particles are advected backwards to 18 June and 2 June respectively. These appear to confirm it is the Slope Current that brought the bloom to the east of Shetland. This is consistent with the satellite imagery in Fig. 3, where a much larger bloom is seen upstream to the north-east of Shetland.~~ hour timestep. This was done separately for each year 1998–2022, starting with particles in initial positions on 3 April and running forward 3 months to predict positions on 3 July (Fig. 3).

~~An unusual feature of the 2021 bloom was that it came so close inshore~~In some years nearly all the particles move off beyond the edge of the plots (1999, 2002, 2003, 2009, 2022). In most years all the red particles (those initially at the eastern end of the Slope Current) disappear in this way. In 2021 it is these red particles that end up close to the eastern side of Shetland on 3 July. ~~Examination of imagery for years~~ 2021 was unusual, although not unique, in that easterly winds during spring drove surface currents that pushed particles westward for part of that time. Figure 4 shows 10 m winds (from ERA5) and surface currents (from NWS reanalysis) for May 2021 and for a May climatology. To the east and north of Shetland, climatological winds are westerly and the surface current is westerly or northerly. For May 2021, winds are north-easterly. These winds induce easterly surface currents (Ekman transport effect).

2012, 2016 and 2019 also experienced easterly winds in spring or early summer (based on ERA5 reanalysis) and similarly show large numbers of red particles still within the plot region on 3 July. Other years see large numbers of other coloured particles come close inshore, in particular 2007, 2017~~to~~ , 2020. In the satellite imagery (2017–2020) and Kondrik catalogue (1998–2016), none of these years show coccolithophore blooms that reach into the bays and inlets of eastern Shetland. Imagery for 2020 ~~provided by PML and of a dataset of coccolithophore blooms for 1998 to 2016 in **?** finds no other examples where blooms intrude among the islands and bays~~ (not shown) comes the closest with a bloom 10–20 km distant from the coast. The 2020 particle tracking has orange particles in this region, originating from further west on the shelf edge.

We conclude that in some years blooms around Shetland form in water coming from the shelf edge. We cannot conclude that bloom development is always linked to specific locations and timings of source water along the shelf edge.

To understand how the bloom appeared so close inshore, we examined the daily particle trajectories for 2021 (not shown). Particles move south down the eastern side of Shetland during the second half of June. In late June and early July there is a brief period of easterly winds and the particles are driven in towards the coast. Brief easterlies aren't unusual but these coincided with coccolithophore-laden water near to the coast. We suggest that coincidences of timing and weather in 2021 created the unusual phenonemon of a visible coccolithophore bloom on the eastern side of Shetland . May Shetland coast.

~~Left-hand side: Enhanced ocean colour satellite imagery (provided by PML, product ref 5) from SENTINEL-3 OCLI instrument for dates 3 June 2021, 18 June 2021, 3 July 2021. The brightest pixels are indicative of high numbers of coccoliths. Right-hand side: simulation for the same dates, using particles advected backward in time from the Clyde (orange, 18 June 2021) and from Shetland (green, 03 July 2021)~~

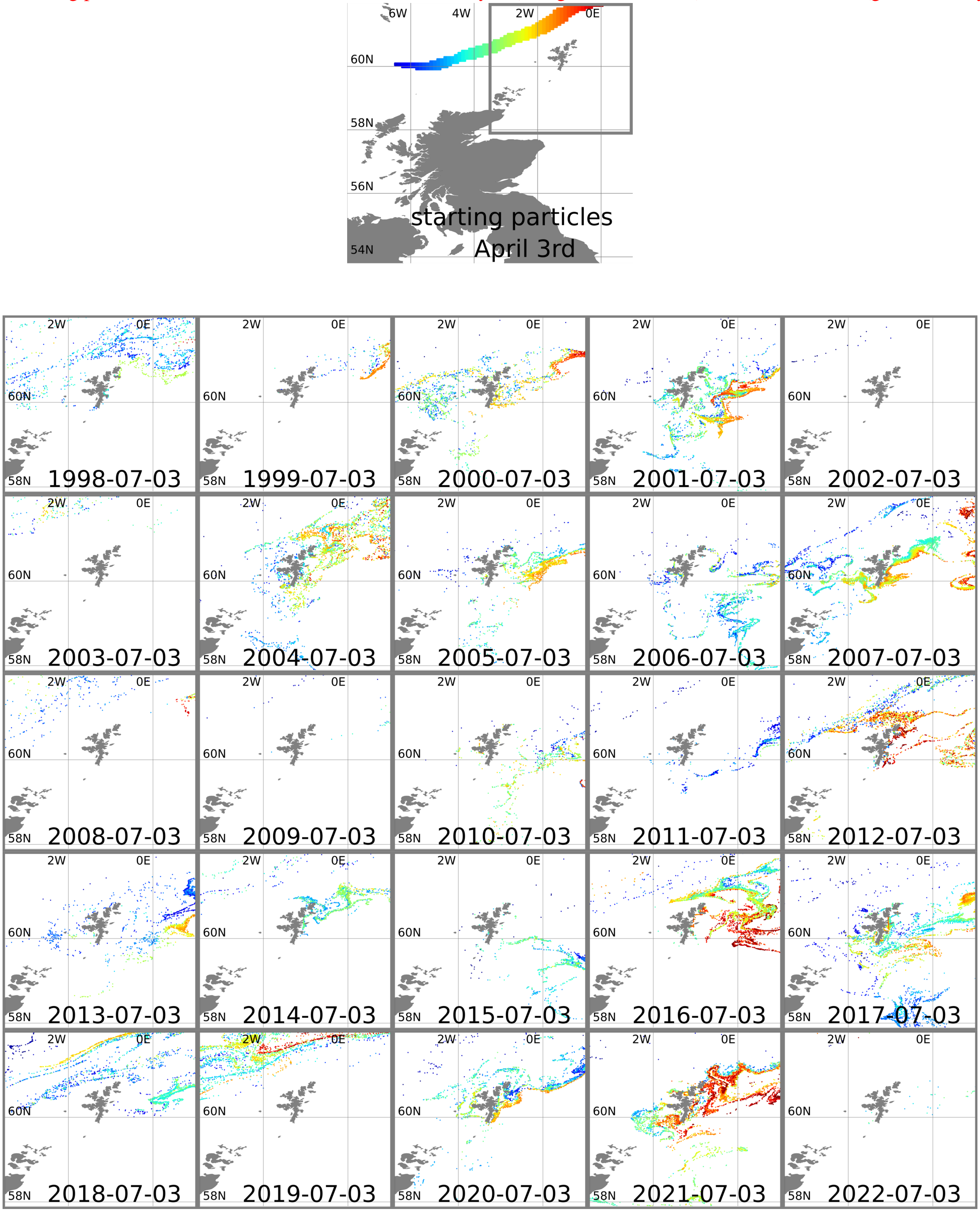

Figure 3. Top plot shows April 3rd starting positions for particles positioned along the Slope Current. The area around Shetland is marked with a grey line. Other plots show particle positions in this area advected forward 3 months, using reanalysis surface currents for each year 1998–2022. Particles are coloured according to longitude of starting position.

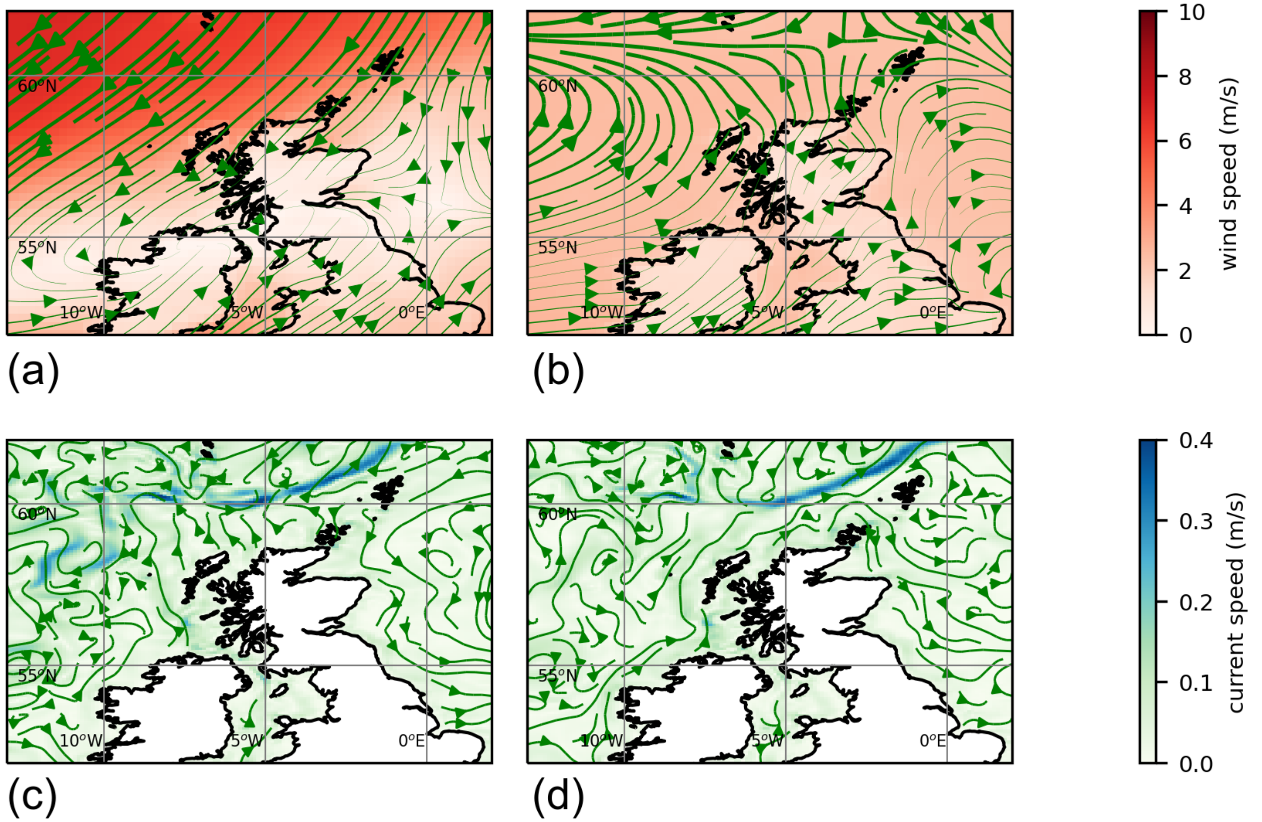

Figure 4. Top: ERA5 monthly mean 10 m winds (product ref 4) for (a) May 2021, (b) 1979–2020 May climatology. Bottom: surface current for May from reanalysis (product ref 1). (c) May 2021, (d) 1983–2020 May climatology.

4 Clyde Sea bloom

Analysis of the 2021 ~~saw anomalously low atmospheric pressure over the UK (?) bringing easterly winds to the north of the UK. These winds brought cold air over the North Sea and Scotland, consistent with cold SST that month (Fig. 4). The winds also drive surface currents which were, unusually, easterly to the east of Shetland in the NWS reanalysis in May 2021 (Fig. 4). We suggest these anomalous currents brought coccolithophore laden water close inshore~~bloom in the Clyde Sea is hampered by a paucity of observations. Weather stations provide data on the atmospheric conditions. Satellite instruments provide estimates of SST and of chlorophyll, with caveats discussed below. We have found no in situ measurements of conditions within the Clyde Sea itself. Biogeochemical reanalysis data is available (?) but its ability to simulate accurately the Clyde Sea is hampered by a lack of data on river discharge. Freshwater and nutrient input from rivers are important variables for the biogeochemistry here.

In this paper we analyse the data that are available, and build from them a plausible storyline. That storyline starts with diatom growth in early Spring.

5 ~~Clyde Sea bloom~~

4.1 The Clyde Sea and the annual cycle of diatoms

The Clyde Sea comprises a large tidal estuary with several islands and fjord-like sea lochs. It is the outlet of the River Clyde and other rivers into the Irish Sea. It has a maximum depth of ~~164m~~164 m, with a sill (the ‘Great Plateau’) of approximately ~~40m~~ 40 m depth where it meets the Irish Sea. Freshwater outflow from rivers and from land drainage tends to maintain stable stratification in the basin (**?**). This together with the sill restricts tidal mixing to mostly near-surface waters. **?** estimate a residence time of 2 months for surface water in the Outer Firth. Nutrient content in the Clyde tends to be higher than adjacent coastal waters (based on measurements of nitrate, in **?**). Tidal currents within the Clyde Sea tend to be weak. Water in the deeper waters below the sill can stagnate, leading to nutrient build-up near the sea bed. **?** show that strong winds can sometimes overcome the vertical stability and mix the water column. This would act to replenish nutrients in the surface layers in the event of an algal bloom.

4.2 ~~Annual cycle of diatoms in the Clyde Sea~~

? sampled the Clyde Sea and its lochs extensively, finding that

> "There is a well-marked spring diatom maximum which starts at the end of March or the beginning of April."

~~They~~ A diatom bloom will consume nutrients (**?**) which will tend to inhibit further phytoplankton growth (**?**). **?** also observed a second, smaller, summer maximum but noted that diatoms near the surface were less healthy than those several metres deeper. Tests with samples left in direct sunlight and in shade showed that summer light levels were injurious for these diatoms.

? assessed extensive and more recent surveys (1976-1978) of the Inner Firth. They found rapid growth in diatoms from late March or early April in each year of the study, dominated by *Skeletonema spp.* and *Thalassiosira nordenskioldii*. They also found ~~*Nitschia*~~ *Nitzschia seriata* (now called *Pseudo-nitzschia ‘seriata* type’) and *Chaetoceros spp.* at those times present in considerable numbers. During these spring blooms total chlorophyll was dominated by diatoms. For 1977 they found evidence that the *Skeletonema* were being grazed by microzooplankton (*Ebria*). **?** also report an intense spring bloom dominated by *Skeletonema* during the monitoring period ~~2005-2013~~2005–2013.

4.1.1 ~~Timing and source of 2021 Clyde bloom~~

~~Figure2~~

4.2 Timing and source of 2021 Clyde coccolithophore bloom

Figure 1 shows the Clyde bloom on 21 June 2021. There are earlier visual reports of bright patches in the sea around the Isle of Arran in the centre of the Clyde Sea on 12 June (**?**). ~~Enhanced colour imagery from SENTINEL-3 OLCI imagery reveals nothing significant for~~ Satellite imagery (Fig. 2(a)) has no bright patch in the Clyde that day but ~~is much~~ the sea around Arran is partly obscured by cloud. Imagery for ~~13-16~~ 13–16 June is almost wholly obscured by cloud, and the first clear satellite image of a bright patch across the whole of the Clyde Sea is from 18 June (Fig. ~~3~~2(b)). This ~~bright~~ patch persists until 5 July and then fades. Figure~~3~~ 2(c) shows that by this time the bloom is apparent even in the northernmost reaches of Loch Fyne. This sea loch flows into the Clyde Sea but is tidal along its ~~65km~~ 65 km length.

~~Figure 3(a) shows virtual particles from the Clyde Sea on 18 June~~ Transmission electron microscopy of a sample from Millport collected at the end of June revealed the bloom to be comprised of liths and cells of *E. huxleyi* - morphotype B (Fig. ~~3(b))advected backwards in time to 2 June. Some of the particles stay within the Clyde Sea. Other particles appear to have originated from further south in the Irish Sea. The satellite image in Fig. 3(a) reveals no plankton features within the Clyde Sea itself on 2 June but several bright patches in the Irish Sea at that time, indicating the presence of significant concentrations of plankton.~~ 1(d)), providing the first confirmation of this species in high abundance at this site. *E. huxleyi* morphotypes A and B have been recorded in the waters around Scotland (**??**). Little is known about the seasonality of *E. huxleyi* morphotypes on the west coast of Scotland. A study at the Marine Scotland Scottish Coastal Observatory (SCObs) monitoring site at Stonehaven on the east coast from 2010–2013 showed a distinct repeated seasonality in the occurrence of different *E. huxleyi* morphotypes (**?**). Morphotype B was commonly recorded in spring with morphotype A occurring from June to August followed by an overcalcified form of morphotype A (type AO) in autumn and winter months. The dominance of *E. huxleyi* morphotype B in the 2021 Clyde bloom differs in timing from the seasonality recorded on the east coast.

Coccolithophores have a haplodiplontic life cycle (**?**). New cells are haploid (one set of chromosomes in the nucleus). These haploid cells develop into diploid cells (two sets of chromosomes in the nucleus). For genus Emiliania, it is only the diploid form that produces coccoliths. **?** explain its "Cheshire Cat" strategy for resisting viral attack. Giant phycodnaviruses (Emiliania huxleyi viruses, EhVs) infect and lyse diploid-phase cells and are heavily implicated in the termination of blooms. The diploid cells transition to haploid cells that are resistant to EhVs, shedding coccoliths as they do. Thus the bloom in the Clyde may have started some time before sufficient coccoliths had accumulated to make it visible.

It is possible that *E. huxleyi* was introduced by tidal mixing into the Clyde from the Irish Sea, or that it was already resident~~in small quantities.~~. Reverse particle tracking (not shown) excludes immediate seeding from blooms at the Malin shelf break as a likely cause. The satellite imagery shows the bloom mostly confined to the Clyde Sea. We conclude that conditions within the Clyde basin in late May or early June were particularly favourable for ~~the bloom to thrivein place~~*E. huxleyi* to thrive. We aim here to understand exactly which aspects were favourable and what brought them about.

4.2.1 ~~Physical environment in 2021 & 1983~~

~~Figure~~

4.3 Physical environment in 2021

Figure 5(a) shows daily values of Sea Surface Temperature (SST) from the NWS reanalysis ~~for a point central in~~ averaged over the Clyde Sea, for years ~~1998-2021~~1998–2021. June 2021 values are in the middle of the range. Values for April and May are towards the cold end of the range. Statistics from a high-resolution satellite SST product in Table 1 (product ref ~~4~~3) confirm this. Monthly means for April, May and June 2021 are, respectively, at the 10^{th}, 5^{th} and 52^{nd} percentiles for those months over the period ~~1982-2021~~1982–2021.

Table 1(a) includes statistics for 1983, the previous year that such a bloom was seen in has monthly statistics of SST from a satellite SST product (product ref 3) for a point within the Clyde Sea . SST in April, May and June 1983 was colder than average, with values at the 25th, 22nd (55.27° N, 5.11° W, close to the lower right intersection of gridlines in Fig. 1). April and 17th percentiles respectivelyMay 2021 SSTs were unusually cold compared to climatology. June was close to the median. The cold SST for both years can be linked to the weather at the time. (Table 1(b,c,d)shows weather data for these months in). April saw anticyclonic weather, cold, dry and exceptionally sunny (**?**). May 2021 and 1983, averaged for a set of land-based weather stations chosen by the National Climate Information Centre (NCIC)to represent the Clyde catchment area. For 2021, April and May were unusually cold, but June was had anomalously low atmospheric pressure over the UK bringing storms, high rainfall and high winds (**?**). June was drier and warmer than average. April was exceptionally sunny and dry. 1983

There were two severe storms in May 2021, one on 9, 10 and 11 May and 2021 have in common a cold and dry April, a cold, cloudy and wetter than average May , and a dry June. In both years, Maywas a month of storms and high winds (**??**).The two years differ in that 2021 had asunny April and a warm June. In 1983 April had average sunshine and June was colder than averagea stronger one on 20 and 21 May. These appear to coincide with periods when there is a pause in the rate of increase of SST (Fig. 5(a)). This suggests the strong winds are mixing the water column.

4.3.1 Additional data for 2021 from reanalysis and observations

Figure5 shows reanalysis daily values of SST and also of chlorophyll from the

4.4 Ocean Colour estimates of chlorophyll

Figure 5 shows a timeseries of estimates of chlorophyll a from the CMEMS ocean colour product for (product ref 2) for two plankton functional typesP1 (diatoms) and P2 (nanophytoplankton). These are for a point in the central Clyde Sea (55.27 N, 5.11 E, as for Table 1) . Values are shown for 2021 and also for the years 1998-2020. The black line is the 2021 reanalysis, and the green line a 'free run', which is the 2021 reanalysis without assimilation of PFT chlorophyll. The values of the observations are also plotted (product ref 3), as blue dots(2021)and as a blue dashed line for the 1998-2020 daily average.

For P1, the 1998-2020 reanalysis has spring growth starting variously between end of March to mid May, reaching values between 2 , diatoms and 10, with some later peaks much higher. Observed values nanophytoplankton. Mean values for 1998–2020 (blue line) show similar patterns for diatoms and nanophytoplankton: concentrations rising to a peak in late March and a smaller second peak in early May, although with considerable year-to-year variation (purple dots). Estimates for 2021 show limited growth at the end of March and then a decline from are again similar between both functional types. Both have strong peaks in early April, as SST cools. Values increase in May to no more than average (2). The reanalysis has low values from March to mid-May, and the free run even lower. The reanalysis doesn't rise as far as the observations, but does achieve a compromise between the observations and the free run. ERSEM would appear to expect low growth of diatoms given the environmental conditions. The observed values in April are consistent with that. well above the 1998–2020 mean. Values drop rapidly during April, rising again towards the end of that month. Both types also show a fall immediately following the two May storms, around the 10th and 20th.

Table 1. Statistics of monthly means from (a) CMEMS European area level 4 SST analysis at 55.27° N, 5.11° W, and (b,c,d) from weather stations in Clyde catchment area (National Climate Information Centre)

a) Sea surface temperature			
	monthly mean (° C)	anomaly (° C)	percentile ~~monthly mean (C) anomaly (C) percentile~~
April	~~7.93 -0.25 25%~~ 7.53	-0.65	10%
May	~~9.70 -0.31 22%~~ 8.81	-1.20	5%
June	~~11.65 -0.54 17%~~ 12.24	0.05	52%
b) Air temperature			
	monthly mean (° C)	anomaly (° C)	percentile ~~monthly mean (C) anomaly (C) percentile~~
April	~~4.9 -2.0 4%~~ 5.5	-1.4	10%
May	8.4	-1.4	~~7% 8.4 -1.4~~ 10%
June	~~11.6 -0.8 26%~~ 13.4	1.0	83%
c) Sunshine hours			
	total	% of climatology	percentile ~~total % of climatology percentile~~
April	~~134 90% 38%~~ 236	159%	100%
May	~~114 60% 5%~~ 151	80%	19%
June	~~154 98% 59%~~ 174	111%	76%
d) Rainfall			
	total (mm)	% of climatology	percentile ~~total () % of climatology percentile~~
April	~~57 73% 28%~~ 16	20%	5%
May	~~104 124% 69%~~ 96	115%	64%
June	~~73 82% 36%~~ 42	47%	12%

Anomalies and percentiles are relative to yearly climatology: (a) SST is CMEMS reprocessed level 4 satellite product 1982–2020 (product ref 3) (b,c,d) Weather station data are for Clyde catchment area from NCIC for 1980–2021

~~For P2, observations peak at around 1 from mid March to mid April, dip, and then rise to around 0.7 from late April to mid May, appearing to follow the rise in SST. The free run starts with low values, rises sharply in mid May to around 1.0 , and falls again in mid June. The reanalysis starts March with values around 0.2 and stays within ±0.2 of this for the whole period March to July. In most other years, the reanalysis peaks rather higher (0.5 or higher) at some point in April or May , with 3 years reaching 2.0 or more. The reanalysis and free run in 2021 do not track the observations closely. Sharp rises in the free run coincide with two storms that passed over northern UK, one on 9, 10 and 11 May and a stronger one on 20 and 21 May. The first storm also appears to cause a rise in P2 for the reanalysis, and a pause in the rate of increase for SST. This suggests the winds are mixing the water column. The second storm coincides with a dip in SST, again consistent with mixing.~~

4.4.1 ~~Diversity of the Clyde bloom~~

~~Transmission electron microscopy of a sample from Millport collected at the end of June revealed the bloom to be comprised of liths and cells of *E. huxleyi* - morphotype B (Fig 1(d)), providing the first confirmation of this species in high abundance at this site. *E. huxleyi* morphotypes A and B have been recorded in the waters around Scotland (??). Little is known about the seasonality of *E. huxleyi* morphotypes on the west coast of Scotland. A study at the Marine Scotland Scottish Coastal Observatory (SCObs) monitoring site at Stonehaven on the east coast from 2010-2013 showed a distinct repeated seasonality in the occurrence of different *E. huxleyi* morphotypes (?). Morphotype B was commonly recorded in spring with morphotype A occurring from June to August followed by an overcalcified form of morphotype A (type AO)in autumn and winter months. The dominance of *E. huxleyi* morphotype B in~~ As discussed in section 2.1, chlorophyll estimation can be difficult in coastal waters. Vertical mixing and river discharge due to the May storms might increase levels of Dissolved Organic Matter and sediment in the water. Vertical mixing might dilute plankton in the surface layers that are sensed by the ocean colour instruments. The presence of coccoliths and cloud mean that much of the data for June has been masked in the estimation process. The ocean colour product includes an estimate of root mean square error (RMSE) following **?**. For the Clyde Sea, values of RMSE for diatoms and nanophytoplankton in both April and May 2021 ~~Clyde bloom differs in timing from the seasonality recorded on the east coast~~are given as approximately 0.5 $\mathrm{mg\,m^{-3}}$. This is similar in size to the estimates themselves for nanophytoplankton and so we avoid drawing conclusions from Figure 5(c). Estimated concentrations for diatoms are somewhat larger and so we have more confidence in drawing conclusions from the diatom timeseries Figure 5(b).

4.4.1 ~~Possible causes of Clyde bloom~~

4.5 Possible causes of Clyde bloom

? assessed coccolithophore growth and mortality rates based on samples from the Celtic Sea in April 2015. They identified several conditions that favour coccolithophore blooms. These are considered individually below.

a) Warm, stratified waters SST in June 2021 was close to average for that month (Table 1(a)). ~~June 1983 was unusually cold.~~ Vertical profiles of temperature from the reanalysis for 2021 (not shown) are stably stratified but this is typical for June.

Conclusion: ~~not likely to be a contributory factor for~~ June 2021 ~~and even less so for 1983~~ temperatures were not unusual.

b) Sunlight June 2021 was sunnier than average (76$^{\text{th}}$ percentile, Table 1(c)). ~~June 1983 was close to average.~~

Conclusion: Sunshine might have been a contributory factor in 2021.

c) Availability of nutrients We have no direct measurements of nutrients in the Clyde Sea. ~~Reanalysis estimates are of limited use because the reanalysis relies on a climatology for river inputs. Rainfall (and so river flow) in~~ April 2021 ~~and 1983 was much less than climatology (~~was a dry month (5$^{\text{th}}$ percentile, Table 1(d)) ~~, which would tend to limit diatom growth in the spring~~and so river discharge in April would have been low. Rainfall in May was above average~~for both years~~. May was also a stormy month ~~for both years,~~ which may have mixed the water column, bringing nutrients from deep water into the photic zone (**?**). Each of these factors could lead to higher than usual nutrient availability by the end of May. ~~The~~

observations of chlorophyll and the reanalysis both Ocean colour estimates of diatoms suggest lower than usual diatom growth in April and May 2021 increased growth during May (Fig. 5). This would also lead to higher than usual nutrient availability at the end of May. (b)).

Conclusion: Observations show low chlorophyll mass in spring 2021. This can be explained by the cold air and water temperatures in April 2021, also seen in April 1983. could be due to the cold water temperatures and limited nutrient input in April 2021. The wet and stormy conditions in May of both years likely increased nutrient levels in near-surface layers in the Clyde. Both these factors would help produce suitable conditions for a bloom.

d) Scarcity of predatory microzooplankton **?** found that microzooplankton exert strong top-down control on coccolithophore populations, grazing up to 80% of daily production in a bloom of *E. huxleyi*. We might hypothesize that fewer diatoms in April and May led to low numbers of microzooplankton during that time, reducing the grazing pressure on *E. huxleyi* in late May and early June. However, growth rates for microzooplankton can be rapid, sometimes more than 3 doublings per day for tintinnids (**?**).

Conclusion: This could be a contributory factor. We , though we have no evidence for this. The ability of microzooplankton to multiply rapidly suggests at least that other factors were also involved.

Advection of a bloom into the region is another possible cause. We consider this unlikely for two reasons. The Clyde Sea is semi-enclosed with an estimated residence time of 2 months for surface water in the Outer Firth (**?**). This was consistent with reverse tracking (not shown) of a set of virtual particles placed in the Clyde Sea in June and tracked backwards for 60 days to find their source. The majority remained within the Clyde Sea. Also, satellite imagery shows a bloom in the Clyde Sea but not in the adjoining Irish Sea.

5 Discussion

Phytoplankton are of special interest in the waters around Scotland, where aquaculture and fishing are major industries. Through primary production, phytoplankton form the base of a food chain that sustains marine fauna (**?**). Blooms of phytoplankton can be harmful to other marine life and can produce toxins dangerous for human consumers of seafood (**?**). There is thus increasing interest from policy makers to understand the diversity dynamics of phytoplankton communities in Scotland and other parts of the North West European Shelf (NWS) and to understand its influence on industries and diversity status assessments (**??**).

This paper presents hypotheses to explain two unusual blooms. We suggest that the bloom on the eastern side of Shetland originated in Atlantic water brought north of Shetland by the Slope Current, and then . The water's passage eastward was retarded by a period of anomalous easterly winds in May, and it was later steered towards the coast by surface currents which were driven by anomalous Shetland coast by a shorter period of easterly winds. The timing was such that there were abundant coccoliths present when this water was close inshore. The bloom within the Clyde Sea appears to have developed in place. We suggest hypothesize that environmental factors may have combined to create suitable conditions in the Clyde Sea. A cold and dry April could have restricted spring growth of diatoms, leaving nutrients available for a summer bloom of coccolithophores. A wet and stormy May might also have added to the nutrients. ~~Most of these conditions (all but the dry April) were also present in 1983, the last time there was such a bloom.~~

Our ~~suggestions~~ explanations are based on limited evidence (SST and chlorophyll estimates from satellite, modelling by the reanalysis). We do not have in situ measurements from within the blooms to confirm ~~some aspects of~~ our hypotheses.

For both blooms, we propose the weather as a key factor. Other studies also identify the importance of the weather for algal blooms. **?** looked at unusually strong blooms of the biotoxin-producing dinoflagellate *Dinophysis* on the western side of the Shetland Islands in the summers of 2006 and 2013. They found these blooms coincided with periods where the winds, usually more southerly, became westerly. They suggested the westerly winds advected *Dinophysis* populations onshore resulting in an increase in Diarrhetic Shellfish Toxin levels in farmed mussels (*Mytilus edulis*).

There is evidence that the distribution of coccolithophores has expanded polewards in recent decades (**???**), due either to changes in ocean temperature or dissolved inorganic carbon. Growth of E. huxleyi is also known to be impacted by major changes in ocean pH (**?**) but this unlikely to explain recent variability in coccolithophore abundance in Scottish waters.

Changing weather patterns have the potential to influence the occurrence of unusual phytoplankton blooms in coastal waters. These changes have the potential to impact higher trophic levels in the marine ecosystem. A better understanding of the processes and dynamics involved will help in forewarning, preparation and development of adaptation measures for these changes.

This paper has shown how use of satellite data and model reanalysis can help to meet the challenge of assessing major events in UK waters, despite a sparsity of in situ observations. However we could be more confident in our findings if we had more information about environmental conditions. More complete data on river discharge would help in simulating biogeochemical and ecosystem variables in the Clyde and other inshore water bodies. Widespread routine monitoring of nutrient levels and phytoplankton components could help greatly in understanding future blooms.

Data availability. Data used was as listed in Table 2. Nearly all data are publicly available from the websites referenced there.

Author contributions. R. Renshaw processed the reanalysis data and wrote much of the text. E. Bresnan produced the micrograph of the *E. huxleyi* sample. P. Miller produced the ocean colour images. Every author contributed to discussion and development of the hypotheses presented. Every author also added to and reviewed the text.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We gratefully acknowledge use of the *OceanParcels* code (**?**) in calculating backward trajectories. We also acknowledge use of collated station statistics from the UK National Climate Information Centre, and ERA5 reanalysis data (**?**) downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store. We thank ESA for the satellite image in Fig. ~~2~~1, made available under Creative Commons license BY-SA 3.0 IGO https://creativecommons.org/licenses/by-sa/3.0/igo/ Transmission Electron Analysis of the Millport water sample was performed at the Microscopy Unit, Institute of Medical Sciences, University of Aberdeen.

Tables

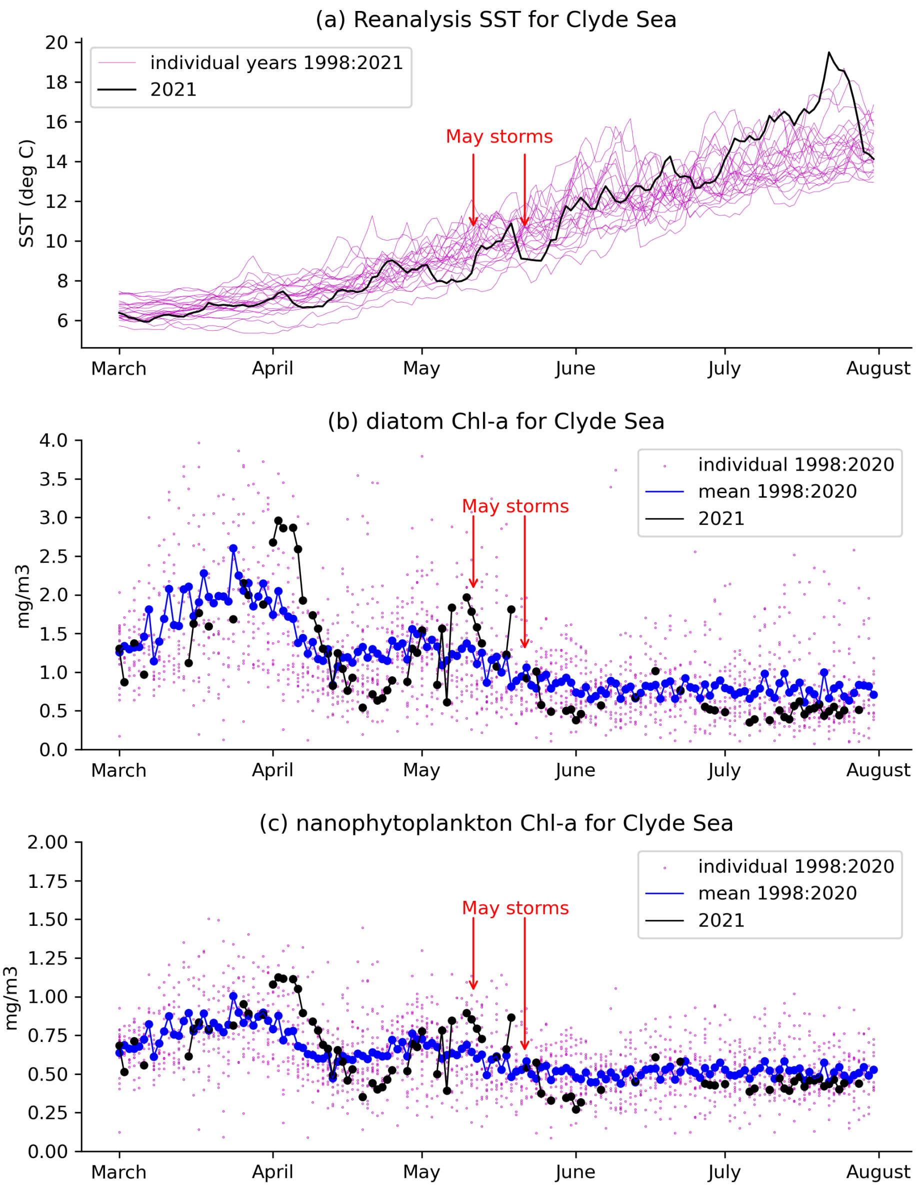

Figure 5. Top: Daily mean values averaged over the Clyde Sea basin, of (a) reanalysis sea surface temperature monthly mean from CMEMS high-resolution L4 data for individual years. 2021 is in black.

Also chlorophyll concentrations (product ref 42) . Left is May 2021 from near real-time product. Right is 1983-2020 climatology for May the Clyde Sea from reprocessed product. Bottom: surface current ocean colour products for May from reanalysis (product ref 1b) diatoms and (c) nanophytoplankton. Left Black dots and line are ocean colour estimates for 2021. Blue is May 2021mean estimates for 1998 to 2020. Smaller purple dots are values for individual years, right is 1983-2020 May climatologyshowing the year-to-year spread.

Daily mean values of (a) sea surface temperature (product ref 1) and chlorophyll concentrations (product ref 2) for (b) P1 diatoms, (c) P2 nanophytoplankton. **Black line** is daily mean values from the NWS reanalysis for 2021. **Magenta lines** are reanalysis values for the same days in the years 1998-2020. **Blue dots** are observations of PFT chlorophyll for 2021 from ocean colour data (product ref 3). **Dashed blue line** is mean values of the observations for the years 1998-2020. **Green line** is 2021 values from a version of the reanalysis not assimilating the PFT chlorophyll observations.

Table 2. CMEMS and non-CMEMS products used in this study.

Ref. No.	Product name & type	Documentation
1	NWSHELF_MULTIYEAR_PHY_004_009	PUM: https://catalogue.marine.copernicus.eu/documents /PUM/CMEMS-NWS-PUM-004-009-011.pdf QUID: https://catalogue.marine.copernicus.eu/documents /QUID/CMEMS-NWS-QUID-004-009.pdf https://doi.org/10.48670/moi-00059
2	NWSHELF_MULTIYEAR_BGC_004OCEANCOLOUR_011 PUM: https://catalogue.marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-009-011.pdf QUID: https://catalogue.marine.copernicus.eu/documents/QUID/CMEMS-NWS-QUID-004-011.pdf 3 OCEANCOLOUR_GLOATL_BGC_L4L3_MY _OBSERVATIONS_009_104 013	PUM: https://catalogue.marine.copernicus.eu/documents /PUM/CMEMS-OC-PUM.pdf QUID: https://catalogue.marine.copernicus.eu/documents /QUID/CMEMS-OC-QUID-009-101to104-116-118CMEMS-OC-QUID-0 https://doi.org/10.48670/moi-00286
4 3	SST_ATL_SST_L4_REP_OBSERVATIONS_010_026	PUM: https://catalogue.marine.copernicus.eu/documents /PUM/CMEMS-SST-PUM-010-026.pdf QUID: https://catalogue.marine.copernicus.eu/documents /QUID/CMEMS-SST-QUID-010-026.pdf https://doi.org/10.48670/moi-00153
4	ERA5 atmospheric reanalysis	? Copernicus Climate Change Service (C3S) Climate Data Store (CDS) https://doi.org/10.24381/cds.adbb2d47
5	Additional satellite ocean colour dataSatellite ocean colour imagery processed by Plymouth Marine Laboratory	E.g. ?