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Environmental control of harmful dinoflagellates and diatoms in a fjordic system

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ABSTRACT

Fjordic coastlines provide an ideal protected environment for both finfish and shellfish aquaculture operations. This study reports the results of a cruise to the Scottish Clyde Sea, and associated fjordic sea lochs, that coincided with blooms of the diarrhetic shellfish toxin producing dinoflagellate *Dinophysis acuta* and the diatom genus *Chaetoceros*, that can generate finfish mortalities. Unusually, *D. acuta* reached one order of magnitude higher cell abundance in the water column (2840 cells L^{-1}) than the more common *Dinophysis acuminata* (200 cells L^{-1}) and was linked with elevated shellfish toxicity (maximum $601 \pm 237\,\mu g$ OA eq/kg shellfish flesh) which caused shellfish harvesting closures in the region. Significant correlations between *D. acuta* abundance and that of *Mesodinium rubrum* were also observed across the cruise transect potentially supporting bloom formation of the mixotrophic *D. acuta*. Significant spatial variability in phytoplankton that was related to physical characteristics of the water column was observed, with a temperature-driven frontal region at the mouth of Loch Fyne being important in the development of the *D. acuta*, but not the *Chaetoceros* bloom. The front also provided important protection to the aquaculture located within the loch, with neither of the blooms encroaching within it. Analysis based on a particle-tracking model confirms the importance of the front to cell transport and shows significant inter-annual differences in advection within the region, that are important to the harmful algal bloom risk therein.

1. Introduction

Harmful algal blooms (HABs) are a recurrent problem for marine aquaculture. While some blooms are anthropogenically generated, often related to elevated water column nutrient concentrations (Davidson et al., 2014; Glibert et al., 2005; Gowen et al., 2012), many are natural events that exhibit great spatial and temporal variability.

HABs can be harmful to aquaculture in a number of distinct ways. High biomass blooms are a threat to finfish aquaculture. While some of these blooms may generate toxins or water column deoxygenation, blooms of diatoms can often be harmful to fish by virtue of heavily silicified and barbed setae. These setae can irritate or damage fish gills when concentrations are high enough, sometimes leading to mortality (Davidson et al., 2011).

In temperate waters, human poisoning is typically related to the consumption of shellfish contaminated with algal toxins. Algal toxins are most frequently produced by selected dinoflagellate genera. These organisms can potentially be harmful at relatively low cell concentrations (e.g. <2000 cells L^{-1} for *Alexandrium tamarense* (Lebour) Balech (Davidson and Bresnan, 2009)) when consumed by bivalves that concentrate the toxins in their flesh (Davidson and Bresnan, 2009). Important amongst these is the genus *Dinophysis* (Ehrenberg) that produces potent lipophilic toxins that generate severe gastrointestinal illness in consumers of contaminated shellfish (Reguera et al., 2012). Incidents of *Dinophysis* generated shellfish toxicity (e.g. Whyte et al., 2014)

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have generated significant and indiscriminate negative publicity for the aquaculture industry as a whole.

Understanding the (potentially different) environmental conditions that promote blooms from both of these different harmful genera is therefore important for the sustainable development and management of aquaculture. Given the importance of fjordic regions to aquaculture worldwide (Norway, Chile, New Zealand, Scotland), such understanding is particularly important in these environments (Cembella et al., 2010, 2005). Worldwide, these locations are often relatively remote and free from the anthropogenic nutrient loading that can sometimes generate high biomass HABs in more urban locations. However, even these low anthropogenic impact environments experience temporally and spatially variable naturally occurring HAB events that have the potential to negatively impact both shellfish and finfish aquaculture.

Out of the >200 identified species of the globally occurring genus *Dinophysis*, only 12 of these have been classified as toxin producers (Reguera et al., 2012). These *Dinophysis* species have been associated with the production of okadaic acids (OAs), dinophysistoxins (DTXs [analogues 1–4]) and pectenotoxins (PTX) (Reguera et al., 2012). A low abundance (<100 cells L^{-1}) of *Dinophysis* spp. are present as a background in the regular phytoplankton community but high abundance blooms can occur (Reguera et al., 2012). Blooms are most common in summer and, in Scottish waters, can reach abundances of 10^3 cells L^{-1} (Swan and Davidson, 2012) and 10^4 cells L^{-1} (S. Swan, pers. comm,), although abundances of 10^5 cells L^{-1} have been observed worldwide, probably aggregated by water movements rather than *in-situ* cell growth (Smayda, 2006). Six *Dinophysis* species appear in Scottish waters, the majority of which are toxin producers, the most common being *Dinophysis acuminata* (Claparède & Lachmann) followed by *Dinophysis acuta* (Ehrenberg) (Tett and Edwards, 2002, Swan and Davidson, 2012).

Analysis of plankton data from the Continuous Plankton Recorder has shown spatial and temporal shifts in the distribution of *Dinophysis* in the North Sea over recent decades (Edwards et al., 2006). There has been an observed reduction in the mean annual abundance of *Dinophysis* off the east coast of the United Kingdom, while an increase occurred in west Norwegian coastal waters. Edwards et al. (2006) speculate that the role of increased sea surface temperature (SST) and reduced salinities due to climate change off the Norwegian coast may be important in promoting *Dinophysis* growth. Indeed, there has been an observed reduction in salinity and an increase in water temperatures of Norwegian coastal waters in recent years (Saetre et al., 2003).

Dinophysis blooms are recurrent features in UK waters and have been observed for over 100 years (Davidson et al., 2011). Shellfish toxicity is common and while regulatory monitoring has generally been successful in protecting humans, DSP (Diarrhetic Shellfish Poisoning) incidents do occur. The first reliable record of this was in 1997 when 49 people in London became ill after consuming contaminated shellfish (Scoging and Bahl, 1998). This DSP outbreak represented the first recorded illnesses from UK shellfish in 30 years (Scoging and Bahl, 1998). See Tett and Edwards (2002) for a summary of shellfish toxicity outbreaks in Scotland.

The most recent UK outbreak of DSP happened in 2013 when 70 people were recorded as suffering from symptoms in London. Whyte et al. (2014) argue that this bloom, and another in 2006, was related to a rapid a change in the dominant mean wind direction around the Shetland Islands where the contaminated shellfish were grown. This hypothesis is supported by research carried out into "wind-driven water exchange" onto the southwest Irish shelf and links to recurrent HAB events, including *Dinophysis* blooms (Raine et al., 2010). These *Dinophysis* spp. cells are carried along a wind-initiated coastal jet current off the Irish west coast into Bantry Bay (Farrell et al., 2012; Raine, 2014), on the Irish southwest coast, an area responsible for 80% of mussels and 50% of oysters in total Irish aquaculture (Raine et al., 2010). Once inside the bay the cells are able to proliferate in toxic blooms which close shellfish harvesting sites for months of the year resulting in inconvenience and economic loss (Raine et al., 2010).

The toxin DTX-2 is a dinophysistoxin and its production is often linked with the presence of *D. acuta* (Aune et al., 2007; MacMahon and Silke, 1996; Vale and Sampayo, 2000). This toxin may be depurated from shellfish flesh more slowly than other lipophilic toxins causing a build-up of DTX-2 relative to OA (Vale, 2004) thus potentially prolonging closures of shellfish harvesting areas. While *D. acuta* may be less frequently observed than *D. acuminata* in Scottish waters, it has the potential for greater impact on the shellfish industry. Shellfish toxicity, however, may not have a simple relationship to *D. acuta* cell abundance due to variable cellular toxin contents or toxin dilution within shellfish from other food sources (Dahl and Johannessen, 2001).

While negative impact of blooms of the diatom *Chaetoceros* (Ehrenberg) are not so frequently documented there are a number of reports relating to *Chaetoceros* mediated kills of farmed fish (Bruno et al., 1989; Treasurer et al., 2003). Diatom mediated fish kills are increasingly being reported by aquaculture businesses in Scotland with weekly alert reports now being produced for some areas of the country to provide early warning of these events (K. Davidson, unpublished data). Oceanographic studies on the western Scottish shelf demonstrate the frequent presence of *Chaetoceros* and its potential for advection to the coast (Fehling et al., 2012; Siemering et al., 2016) where it can impact on aquaculture activities.

Oceanic species typically have larger spines and setae than coastal species (Tomas, 1997) which may cause more irritation to fish gills at lower concentrations due to spines with barbs breaking off, remaining inside fish gills even after a bloom has passed (Bruno et al., 1989; Hallegraeff, 2004). Fish can be killed through capillary haemorrhage, upset to gas exchange in gills, suffocation from excess mucus production or by secondary disease from open wounds. In British Columbia, *Chaetoceros convolutus* (Castracane) and *Chaetoceros concavicornis* (Mangin) caused mass fish mortalities (2.4 t) in cultured salmonids at only 5000 cells L^{-1} (Albright et al., 1993; Hallegraeff, 2004). In Scotland, *Chaetoceros wighami* (Brightwell) caused losses of 44 t of salmonids (Bruno et al., 1989; Treasurer et al., 2003).

The genus *Chaetoceros* is often the most abundant phytoplankton community member (Bresnan et al., 2009; Fehling et al., 2012; Moschonas et al., 2017) and is a particularly species-rich genus (Rines and Hargraves, 1987). Typically, in inshore Scottish locations the coastal morphotype is most common and peaks in spring and summer (Moschonas et al., 2017). Gowen et al. (1983) found *Chaetoceros decipiens* to be common throughout spring and summer in the well-mixed Scottish Loch Ardbhair. In Narragansett Bay, USA, *Chaetoceros* blooms in early spring and again in autumn; the most abundant species being *Chaetoceros debilis* (Cleve), *Chaetoceros compressus* (Lauder) and *Chaetoceros didymus* (Ehrenberg) (Rines and Hargraves, 1987). Tomas (1997) states that *C. wighami* is present mainly in brackish water, whereas *C. convolutus* and *C. concavicornis* are cosmopolitan to northern temperate and cold-water regions. As many as fifteen different species can be observed together (Rines and Hargraves, 1987), which can make identification difficult, therefore the separation of species into groups (as in Tomas (1997) and Fehling et al. (2012)) is useful.

In common with other fjordic regions that support an aquaculture industry the Scottish west coast is characterised by complex hydrography. Currents are split around many small islands and water exchange into fjords is restricted by shallow entrance sills (Booth, 1987). In addition, conditions undergo short-