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Changing wind patterns linked to unusually high *Dinophysis* blooms around the Shetland Islands, Scotland

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ABSTRACT

During the summer of 2013, 70 people received Diarrhetic Shellfish Poisoning following consumption of mussels harvested in the Shetland Islands, Scotland. At this time, large numbers of the biotoxin-producing phytoplankton genus *Dinophysis* was observed around the Shetland Islands. Analysis indicated this increase was not due to *in situ* growth but coincided with a change in the prevalent wind direction. A previous large bloom of *Dinophysis* during 2006 also coincided with a similar change in the prevalent wind patterns. Wind direction and speed in the North East Atlantic and the North Sea is strongly influenced by the North Atlantic oscillation (NAO) with a positive relationship between it and wind direction. It has been noted that a positive trend in the NAO is linked to climate change and predictions suggest there will be an increasingly westward component to prevalent wind directions in the North Sea which could lead to an increase in the occurrence of these harmful algal blooms. Analysis of wind patterns therefore offers a potential method of early warning of future bio-toxicity events.

1. Background

In July 2013 there was an outbreak of Diarrhetic Shellfish Poisoning (DSP) in the South East of England. Although it is not known how many people were actually affected, 70 people sought medical advice after consuming mussels which, they had been served in several prominent restaurants in London. They were later found to be suffering the symptoms of DSP. The shellfish had been supplied by a farm in the coastal waters of the Shetland Islands (Fig. 1). Although the numbers of *Dinophysis* had been slowly increasing during the preceding few weeks, analysis did not indicate that the concentration of toxins in the shellfish was high. However three days after the farmer had harvested the shellfish an unusually high level of toxins was detected by the Food Standards Agency (FSA) weekly monitoring programme (FSA, 2013), accompanied by a very rapid accumulation of *Dinophysis* cells. The area was closed and commercial harvesting was suspended, unfortunately too late for the luckless consumers of the affected mussels. This paper investigates the possibility that the unusually large blooms of *Dinophysis* observed around the coast of Shetland during 2013, and another large bloom event during 2006, were not due to high *in situ* growth rates, but rather to changes in the annual pattern of prevalent wind direction. We discuss the possibility that an analysis of wind patterns could be used to provide an early warning of biotoxic events.

Yasumoto et al. (1980) was among the first to suggest that gastro-intestinal pain, accompanied by diarrhoea, nausea and vomiting, following the consumption of mussels (*Mytilus edulis*) was linked to the presence of dinoflagellates in the water column, in particular *Dinophysis fortii*. This link was confirmed after outbreaks of severe gastro-intestinal shellfish poisoning in Japan during 1976 and 1977 and led to the identification of a new set of toxins associated with the genus *Dinophysis* (Reguera et al., 2012).

Identified as Diarrhetic Shellfish Poisoning (DSP) causative toxins, these lipophilic compounds are comprised principally of Okadaic Acid (OA) and its derivatives DTX-1, DTX-2 and DTX-3 (Smayda, 2006; Taylor et al., 2013). They have been found to bind with protein phosphatase receptors in the body, leading to an accumulation of phosphorylated proteins with symptoms of lethargy, general weakness, vomiting, cramps and diarrhoea,

Abbreviations: ASIMUTH, Applied Simulations and Integrated Modelling for the Understanding of Toxic and Harmful Algal Blooms; BADC, British Atmospheric Data Centre; DSP, Diarrhetic Shellfish Poisoning; DTX (1–3), dinophysistoxins; GDP, Gross Domestic Product; FSA, Food Standards Agency; NAO, North Atlantic Oscillation; OA, okadaic acid; SAMS, Scottish Association for Marine Science.

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symptoms that can appear from 30 min to several hours after ingestion of the contaminated shellfish (Gerssen et al., 2010).

The *Dinophysis* species most commonly found in Scottish waters are *D. acuminata*, *D. acuta*, and *D. norvegica*, all of which have been confirmed to produce toxins with particular emphasis on *D. acuminata* and *D. acuta* (Bresnan et al., 2005; Hart et al., 2007). While contamination of both farmed and wild shellfish by OA and DTX's is sporadic, it is widespread and has been reported from eleven countries across Europe including Denmark, France, Germany, Ireland, Italy, Norway, Portugal, Spain, Sweden and the Netherlands (Smayda, 2006). Perhaps the severest outbreak occurred in Spain during 1981 when an outbreak of DSP affected approximately 5000 people, mostly from Madrid (Fraga et al., 1984, 1988; Gestal-Otero, 2000).

While unrecorded cases are likely to have occurred, the first reliable record of Diarrhetic Shellfish Poisoning in the UK was in 1997 when 49 people became ill after eating shellfish in two London restaurants (Hinder et al., 2011; Scoging and Bahl, 1998). Since then the frequency of closures due to DSP around the UK appears to be increasing. This may simply be due to a better understanding of the underlying causes of shellfish poisoning, a greater awareness of the problem and a more rigorous monitoring programme. Unlike some species of harmful algae, *Dinophysis* does not need to be present in large numbers to cause toxicity in shellfish. A few hundred cells/l can be enough to lead to the closure of a harvesting area. In 2000, DSP toxins were found in shellfish in areas on the East coast of Scotland, Orkney, the Outer Hebrides, the Shetland Islands and the Firth of Clyde. In all, closures of the various shellfish harvesting areas amounted to 24 weeks (Howard et al., 2001). In 2002, DSP toxins were found throughout Scotland with the majority of the closures lasting between four to six weeks, although some areas were closed for up to seven months. Between 2008 and 2009, thirteen areas were closed in the Shetland Islands and seven areas in Argyll and Bute (Hinder et al., 2011) and most recently, large areas of Shetland were closed for several weeks during 2013.

In addition to the extremely distressing effects contaminated shellfish can have on anyone who consumes them, a DSP outbreak can have far reaching consequences for the shellfish industry. While there is an obvious detrimental effect on farmers, processors and distributors, the impact can extend well outside the closed harvesting area. In what is sometimes referred to as a "halo" effect (Rural Affairs Committee, 1999) consumer confidence is often lost, not only in the closed fishery, but in shellfish products in general, regardless of the area where they were harvested. This loss of confidence can easily outlast the closure itself and, as much of Scotland's production is destined for overseas markets, can have serious economic impacts for the country's GDP (Rural Affairs Committee, 1999).

DSP events are particularly damaging to aquaculture in the South West of Ireland, an area responsible for 80% of the rope grown blue mussel (*Mytilus edulis*) and 50% of the pacific oyster (*Crassostrea gigas*) cultivated in Ireland. Production in this area suffers from a history of harmful algal events; often closing the area for months at a time (Raine et al., 2010). The frequency of shellfish harvesting area closures due to DSP events in Southern Ireland, particularly in the large bays of Bantry, Dunmanus and Long Island, would suggest that these areas are particularly suited for the growth of *Dinophysis*. However the hydro-dynamic processes, in particular, the exchange of substantial fractions of the bay volume during thermal stratification, present in these bays suggests that they are unsuited to the development of indigenous phytoplankton populations (Raine et al., 2010). Instead, it is believed to be wind driven water exchange between the Irish coast and the continental shelf that is responsible for these events (Raine et al., 2010). Similarly, Escalera et al. (2010) have confirmed that accumulations of *Dinophysis* species in Galician rías during October and November were due not to intrinsic growth but to physical transport from other areas.

In Scottish waters *Dinophysis* are widely distributed, usually in low numbers (Tett and Edwards, 2002; Davidson and Bresnan, 2009) and are generally found in offshore waters. Once advected onshore, however, they can accumulate in semi-enclosed areas where in the right conditions they may thrive. Given their widespread distribution, outbreaks of DSP can occur almost anywhere around the Scottish coast.

Responsible for 54% of the mussel production in Scotland with 105 businesses involved in shellfish production (Shetland in Statistics, 2011), Shetland plays an important role in the Scottish economy. Given its geographical location and its topography, comprised of numerous fjords and embayments, it provides an ideal environment for shellfish aquaculture. However, as the closures due to an exceptionally large bloom of *Dinophysis* experienced during the summer of 2013 illustrate, it is also vulnerable to blooms of these harmful algae. The Scottish Government has called for an increase in shellfish production from 6,525 tonnes in 2012 to a proposed 13,000 tonnes by 2020. It is important therefore to understand the mechanism underlying this unusual event and try to estimate its likelihood of recurrence.

2. Methods

Following the FSA guidelines, seawater samples integrated over a depth of 10 m were collected by Lund tube as part of the FSA phytoplankton monitoring programme for Scottish waters. The samples were gently mixed and 500 ml sub-samples transferred to brown, Nalgene bottles and immediately treated with acidified Lugol's solution to obtain a final concentration of 1% by volume. Samples were collected weekly from nine distinct sites around Shetland between April and October. From November to March the frequency of sampling was reduced to one sample per month. After collection, these samples were sent to the Scottish Association for Marine Science (SAMS) where 50 ml aliquots were settled using the Utermőhl sedimentation method as outlined in Lund et al. (1958). Following FSA protocols the phytoplankton was allowed to settle for a minimum of 20 h before examination. Full chamber counts at 200× magnification were carried out using Carl Zeiss Axiovert inverted microscopes.

While regulatory biotoxin phytoplankton surveillance and monitoring has occurred in Scotland since 1991, early sampling was spatially and temporally variable. However, since 2006 a more structured collection regime has been used, with FSA-funded sampling officers collecting waters samples from designated representative monitoring points within classified shellfish production areas. Hence, to determine whether the number of *Dinophysis* cells recorded in Shetland during 2013 had changed significantly, a plot of all the *Dinophysis* counts made between 2006 and 2013 was created. The median was calculated for each day of the year between 2006 and 2013 and was drawn onto this plot (see Fig. 2 solid line) along with the 5th and 95th percentiles. These are represented in the figure by the dashed lines and form an envelope encompassing 90% of the observations made. The individual datum points have been omitted for clarity. Counts of *Dinophysis* recorded during 2013 were then plotted against this median and a Chi square test was performed, making the assumption that values recorded during 2013 would be equally distributed around the median. Using the same envelope for counts made between 2006 and 2013 this method was used to investigate *Dinophysis* counts made during 2006 (see Fig. 3).

Active phytoplankton growth in Scottish waters occurs mostly between spring and autumn when light, water temperature and nutrients are sufficient (Davidson et al., 2011). As the monitoring