

Impacts of climate change on harmful algal blooms

Eileen Bresnan ^a, Keith Davidson ^b, Martin Edwards ^c, Liam Fernand ^d, Richard Gowen ^e, Ailsa Hall ^f,
Kevin Kennington ^g, April McKinney ^e, Steve Milligan ^d, Robin Raine ^h and Joe Silke ⁱ

^a Marine Laboratory, Marine Scotland Science, Aberdeen, AB11 9DB, UK

^b The Scottish Association for Marine Science, Oban, PA37 1QA, UK

^c Sir Alister Hardy Foundation for Ocean Science, Plymouth, PL1 2PB, UK

^d Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, NR33 0HT, UK

^e Agri-Food and Biosciences Institute, Belfast, BT9 5PX, UK

^f Sea Mammal Research Unit, University of St Andrews, St Andrews, KY16 8LB, UK

^g Isle of Man Government Laboratory, Douglas, IM1 4BR, Isle of Man

^h National University of Ireland, Galway, Galway, Ireland

ⁱ The Marine Institute, Rinville, Galway, Ireland

EXECUTIVE SUMMARY

High biomass Harmful Algal Blooms (HABs) such as *Karenia mikimotoi* and shellfish toxin producing HAB species continue to be observed in UK and Republic of Ireland waters. Regional differences continue to be seen in the distribution of HABs in UK and RoI waters with impacts mainly observed in the south and west coast of Ireland and regions in the UK with a strong Atlantic influence, e.g. Regions 1, 3, 4, 6 and 7. There is little monitoring aside from the continuous plankton recorder (CPR) in Region 8. The impacts from HABs in Wales, Northern Ireland and the Isle of Man are generally low.

Since the last MCCIP report card was issued, blooms of *Karenia mikimotoi* have caused problems in Ayrshire, Scotland, and also in the north-west coast of Ireland where concerns about the quantity of dead wild fish washing on shore during an event in Ireland in 2012 resulted in two beaches being closed to the public.

No clear trend that can be attributed to climate change can be observed in the incidence of shellfish toxin producing HABs since the last report card was issued. During the last two years the incidence of some shellfish toxins has continued to decrease (e.g. paralytic shellfish poisoning toxins in Scotland). High concentrations of yessotoxins (YTX) and azaspiracids (AZAs) have been recorded for the first time in Scotland. Northern Ireland enforced its first shellfish harvesting closure for high concentrations of domoic acid (the toxin responsible for amnesic shellfish poisoning, ASP) in 2012.

A recent survey in Scottish waters (Regions 1, 6 and 7) has revealed the presence of domoic acid in the urine and faeces of harbour seals (*Phoca vitulina*). The impacts of these toxins on the health of marine mammals are unknown and a more detailed study is currently being undertaken.

Many of the future impacts of climate change are unknown. Increasing sea surface temperatures as a result of climate change may increase the potential for blooms of species that are not currently found in UK and RoI waters through range expansion or human mediated introduction. There is evidence that no new HAB species have become established during the last two years.

An increase in the duration of stratification of the water column may influence the abundance of HABs in UK and RoI waters. This is particularly relevant in shelf areas and Region 8, an area where offshore high biomass *K. mikimotoi* blooms have been hypothesized to initiate and impact coastal areas along the west of Ireland and Regions 6, 7 and 1. Conversely, an increase in wind speed and duration may reduce the duration of stratification in the water column. This may result in a decrease of some HAB dinoflagellate species and an increase in HAB diatom species. Little is known about the impacts of ocean acidification or changes in offshore circulation on the incidence of HABs. The role of offshore blooms in seeding coastal blooms (e.g. of *K. mikimotoi*) remains unknown and the lack of monitoring in Region 8 and on the shelf edge compounds this knowledge gap.

INTRODUCTION

Phytoplankton (also termed algae) play a critical role in the marine ecosystem. They are the primary producers, harvesting light energy from the sun and passing it up to higher trophic levels (Chavez *et al.*, 2011). When the abundance of phytoplankton increases above background concentrations, this event is called an 'algal bloom'. Algal blooms are a natural part of the phytoplankton seasonal cycle but some can have a negative impact on marine ecosystems and the resources they provide such as fish and shellfish. These are termed 'Harmful Algal Blooms' or HABs (Gowen *et al.*, 2012). HABs have impacted ecosystem services in UK and Republic of Ireland (RoI) waters in two distinct ways. High biomass HABs can cause mortalities of farmed fish and the marine benthos through clogging of gills, anoxia and, in some instances, the production of ichthyotoxins. Examples of this are blooms of the dinoflagellate *Karenia mikimotoi* (Silke *et al.*, 2005; Davidson *et al.*, 2009). Other HAB species can have a negative impact at much lower cell densities through the production of potent toxins that can accumulate in filter feeding shellfish. The toxins are not harmful to shellfish but can pose a severe risk to human health if consumed. Closures of shellfish harvesting areas are enforced to protect human health. Repeated and lengthy closures can have a negative impact on local rural economies (Davidson and Bresnan, 2009). In UK and RoI waters the main shellfish toxin producing genera are the dinoflagellates *Alexandrium*, associated with the production of paralytic shellfish poisoning (PSP) toxins and *Dinophysis*, associated with the production of lipophilic shellfish toxins (LSTs) including those associated with diarrhetic shellfish poisoning (DSP). The diatom genus *Pseudo-nitzschia* is also of concern as a number of different species in this region are confirmed producers of domoic acid (DA), the toxin responsible for amnesic shellfish poisoning (ASP) (Gowen *et al.*, 2009). In RoI waters, high concentrations of azaspiracid (AZA), produced by the dinoflagellate *Azadinium*, has caused major problems to the Irish shellfish industry (Salas *et al.*, 2011) The Shellfish Hygiene Directive 91/492/EEC and subsequent recommendations EC/853/2004, EC/2074/2005 and EC/1664/2006 are enforced in EU member states and ensure that human health is protected.

Since the last report card was produced a review has been published which details the complex influence of climate change on HABs (Hallegraeff, 2010). HABs occupy a variety of ecological niches in the ocean and climate change can have an impact in diverse ways. These include sea surface temperature change, sea-level rise, changes in wind (direction and strength), mixed layer depth and precipitation, ocean acidification, UV radiation and feedback mechanisms. These factors can interact to impact HAB distribution and abundance. Many laboratory studies have examined these influences in isolation and more work is required to examine the interaction between them. Accurately predicting the future impact of climate change on HABs presents a considerable challenge. Expected impacts on a global scale include species-specific changes in abundance, changes in seasonality of growth and range expansions of warm water

species with cold species driven pole-ward (Hallegraeff 2010).

Data from a number of sources (Hughes *et al.*, 2010; 2012; Frost *et al.*, 2012) all report an increase in sea surface temperature (SST) in the North-East Atlantic area over the last number of decades. Considerable interannual variability can be observed in SST in both coastal and offshore areas (Hughes *et al.*, 2010; 2012). Lowe *et al.* (2009) predict that temperatures in UK and RoI waters will continue to increase by up to 2.5 – 4°C over the next century. Changes in wave height, wind speed, salinity, ocean acidification, the distribution and intensity of precipitation have all been reported to impact the UK and RoI waters (Frost *et al.*, 2012). The variability in atmospheric forcing has also been observed in decadal cycles such as the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) (Hughes *et al.*, 2012). Changes such as these all have the potential to impact on the phytoplankton community and HAB occurrences.

1. WHAT IS ALREADY HAPPENING?

Data from the Continuous Plankton Recorder (CPR) have already revealed distinct 'events' in the North Sea phytoplankton community over the last six decades. A 'cold boreal' anomaly was identified in the late 1970s which was associated with low temperature and salinity and resulted in a reduction of the intensity of the spring diatom bloom (Edwards *et al.*, 2002). A 'warm temperate' event was identified at the end of the 1980s as a regime shift was associated with marked synchronous changes in plankton in the CPR and other time series from the North Sea and Baltic areas (Edwards *et al.*, 2002; 2006; Alheit *et al.*, 2005; Wiltshire *et al.*, 2008). More recently, Alvarez-Fernandez *et al.* (2012) have reported another shift in the North Sea plankton community in 1998. This shift has been associated with a reduction in dinoflagellates and neritic copepods.

There has been a considerable increase in phytoplankton biomass (Phytoplankton Colour Index) on samples collected by the CPR over the last decades in certain regions of the North-East Atlantic and North Sea, particularly over the winter months. In the North Sea a significant increase in phytoplankton biomass has been found in both heavily anthropogenically-impacted coastal waters and the comparatively less-affected open North Sea. Significantly decreasing trends in nutrient concentrations suggest that these changes are not being driven by nutrient enrichment. The increase in biomass appears to be linked to warmer temperatures and evidence that the waters are also becoming clearer (i.e. less turbid), thereby allowing the normally light-limited coastal phytoplankton to more effectively utilise lower concentrations of nutrients (McQuatters-Gollop *et al.*, 2007).

Examination of the HAB data collected by the CPR shows that the distribution of some HAB species in the North Sea has altered since the 1960s with a general decrease in abundance observed along the east coast of the UK (Regions 1 and 2) (Edwards *et al.*, 2006). A study of individual phytoplankton groups has shown increased temperatures were associated with an earlier timing of the maximum

abundance of some dinoflagellate species. In contrast, the diatom species examined did not show such a shift (Edwards and Richardson, 2004). A recent analysis of six phytoplankton taxa from the CPR showed that an increase in wind speed and SST were associated with a decrease in some dinoflagellates genera, while these climatic conditions favoured some diatom taxa, including the toxin producing *Pseudo-nitzschia 'seriata'* type diatom (Hinder *et al.*, 2012). Gowen *et al.* (2012) reviewed the relationship between HABs and anthropogenic nutrients and have not observed an increase in the incidence of blooms of the HAB species in the Northern and Central North Sea.

Coastal time series of HAB phytoplankton are much shorter in duration. Most began in the 1990s in response to the EU Shellfish Hygiene Directive. A review of the distribution of HAB species around the UK and RoI coast revealed regional differences in distribution with HAB species more abundant along the west coast of Ireland and Scotland (Gowen *et al.*, 2009). This is believed to be due to the thermo-haline stratification of these waters favouring the growth of some dinoflagellate genera. Gowen *et al.* (2009) also investigated the relationship between HAB genera and nutrient input in the UK and RoI and found no evidence to support the hypothesis that HABs are promoted by anthropogenic nutrient enrichment in this region. The role of nutrient ratios in the promotion of HABs has also been reviewed (Davidson *et al.*, 2012). At non-limiting concentrations the influence of nutrient ratios on HABs is seen as limited. Little is known about the role of organic forms of nutrients or mixotrophy in promoting HABs. Both require further investigation if the nutrient requirement for HAB development is to be fully understood.

Since the last report card, interannual variability has been observed in the occurrence of HABs around the UK and RoI coastline. However, no changes have been observed that have been directly attributed to climate change. Recent molecular studies of HAB genera such as *Alexandrium* and *Karenia* have revealed a complex diversity in European waters (Collins *et al.*, 2009; Brosnahan *et al.*, 2010; Al – Kadari *et al.*, 2011; Brown *et al.*, 2011). Based on the UK and RoI national monitoring programmes for HAB species, there is evidence that no 'new' HAB species have become established in UK and RoI waters through climate driven range expansion or human introductions.

High Biomass HABs

Karenia mikimotoi

Blooms of *K. mikimotoi*, continue to impact the UK and RoI coastline. During the summer of 2010 a bloom of *Karenia mikimotoi* was reported along the Ayrshire coast in Scotland (Region 5). During the summer of 2012, a widespread bloom of *Karenia mikimotoi* was observed along the western coast of Ireland where it persisted from May until September. The 2012 bloom resulted in considerable mortalities of fish including turbot, flounder, scorpion fish and shore rockling. Other dead species recorded included worm pipefish, lesser weavers, grey gurnard, shanny, sand goby, pollock, sole, plaice, flounder and dabs. The worst impacted area was

the North-west of Ireland where beaches were closed in Rosstown and Murvagh due to the quantity of dead fish washing on shore.

K. mikimotoi blooms do not occur every year although an increase in the incidence of *K. mikimotoi* blooms was suggested as a potential impact of climate change by Bresnan *et al.* (2010). Blooms appear to initiate in regions of the continental shelf which have small tidal currents and are stratified in summer (Brand *et al.*, 2012). Subsequent growth and transport in coastal currents can spread their impact over large areas of the coastal zone (Davidson *et al.*, 2009). During July 2012, *Karenia* was observed in the surface waters at the shelf break off the Malin Shelf (approx 1.5×10^6 cells L^{-1}) (AFBI unpubl.) suggesting a potential offshore origin for these blooms.

K. mikimotoi does not preserve well in CPR samples owing to the preservative used and there remains a lack of data on this species from offshore areas in UK (Region 8) and RoI waters.

Chaetoceros/Phaeocystis

High biomass algal blooms can also cause water discolouration, which has an unsightly appearance. Referring to this as a 'HAB' infers a negative impact. In some cases with visual discolouration this may just be aesthetic. High biomass diatom blooms such as *Chaetoceros* may cause gill damage in farmed fish. Since the last MCCIP report card was published no negative impacts from blooms of *Chaetoceros* have been reported.

The colonial haptophytes, *Phaeocystis*, can produce large quantities of foam when the colonies are broken down. An in-depth review of this genus shows that *Phaeocystis* blooms are natural events in the southern North Sea and did not appear suddenly in the 1970s. Regional variations in abundance of this genus in the southern North Sea can be driven by climate change (Gowen *et al.*, 2012).

Shellfish toxin producing HABs

Alexandrium and paralytic shellfish poisoning (PSP) toxins

Historically PSP toxicity in shellfish has been reported more frequently in shellfish from Scottish waters (Regions 1, 6 and 7) than elsewhere in Britain or Ireland. A decline in the toxicity of Scottish shellfish has been observed over the last decade (Bresnan *et al.*, 2008; 2010) and this pattern of a low incidence of PSP toxicity in Scottish shellfish has continued since the last report card was issued.

The population of *Alexandrium* in Scottish waters is diverse with the potent PSP toxin producing *Alexandrium tamarense* (Group I) identified in Regions 1, 6 and 7 (Collins *et al.*, 2009; Brown *et al.*, 2011). The non-toxin producing *A. tamarense* (Group III) strain, previously thought to be excluded from Scottish waters has been identified in Regions 6 and 7 (Brown *et al.*, 2011) and both toxin and non-toxin producing strains were found to co-occur in the Shetland Isles (Touzet *et al.*, 2010). Cysts of *A. tamarense* have also been recorded in the sediment from Region 1 (Brown *et al.*, 2011). Since the last report card was published *A. ostenfeldii* has been identified from Region 1 and 7 and confirmed as a producer of both

PSP and spirolide toxins (Brown *et al.*, 2011). A number of non-toxin producing species and strains of *Alexandrium* have also been identified with non-toxin producing *A. minutum* identified from Region 7 and *A. tamutum* recorded from the Shetland Isles (Region 1) and Loch Creran (Region 6) (Brown *et al.*, 2011; Swan and Davidson, 2012).

PSP toxicity in English waters remains confined to the south and south-west coasts (Regions 3 and 4). In the RoI it is confined to one Irish site, Cork Harbour, on the south coast. In contrast to the situation in Scotland, these incidences of toxicity have been associated with a toxin producing strain of *A. minutum* (Percy, 2006; Touzet *et al.*, 2008). *A. ostenfeldii* and *A. peruvianum* have also been identified from the south coast of England and RoI waters as well as the non-toxin producing Group III strain of *A. tamarensense* (Percy, 2006; Touzet *et al.*, 2008). Non-toxin strains of *A. minutum*, *A. tamutum* and *A. andersonii* have also been identified from RoI waters.

In Northern Ireland (Region 5), PSP toxicity in shellfish is rarely observed. A recent study revealed the presence of cysts of both the toxin (Group I) and non-toxin producing (Group III) *A. tamarensense* in sediments in Belfast Lough. These cysts were isolated and successfully grown in laboratory culture (Brosnahan *et al.*, 2010).

In Manx waters, king scallops (*Pecten maximus*) are routinely tested for the presence of shellfish toxins. Although *Alexandrium* cells have been observed in the water column, PSP toxins in concentrations exceeding the EU closure limit have not been detected.

Since the last report card there have been no records of the PSP producing dinoflagellate *Gymnodinium catenatum* reported in UK and RoI waters.

There is no information on PSP toxin producing species from the offshore waters to the west of Scotland (Region 8).

Dinophysis and lipophilic shellfish poisoning (LST) toxins

The dinoflagellate genus *Dinophysis*, associated with the production of diarrhetic shellfish poisoning (DSP) toxins continues to show a regional distribution around Britain and Ireland. It is typically found in stratified waters and occurs in the temporal window from June-September (Raine *et al.*, 2010). There is now evidence to show it is found in high densities in horizontally retentive physical structures such as gyres or coastal jets, usually as sub-surface thin layers of thickness up to ~3-4 metres (Farrell *et al.*, 2012; Gentien *et al.*, submitted). These thin layers are transported onto the coast where they dissipate and cause DSP events. Outside of these thin layers, *Dinophysis* is commonly found in coastal waters in summer but in very low cell densities. Since the last MCCIP HAB report card was issued, closures of shellfish harvesting areas were enforced along the south and west coast of Ireland, west coast of Scotland and Shetland Isles (Regions 1, 5, 6, 7). Closures of harvesting areas as a result of high concentrations of DSP toxins are less frequently enforced in Regions (2, 3 and 4), although *Dinophysis* cell counts exceeding the action limit of 100 cells L⁻¹ were observed on 12 occasions during 2011 mainly in the south-

west of England and south Wales. *Dinophysis* cells were also regularly observed in the Wash and Thames estuary. *Dinophysis* is observed as part of the summer dinoflagellate community in Manx waters, however, concentrations of DSP toxins in *P. maximus* are not high enough to close shellfish harvesting areas.

The duration of closures due to DSP toxins can be quite long. During the summer of 2009 a prolonged closure of shellfish harvesting areas was enforced in Loch Fyne on the Scottish west coast (Region 5). A co-occurrence of classical DSP toxins (okadaic acid, dinophysistoxins and acylated esters) and yessotoxins was observed. The degree of shellfish tissue contamination in early June resulted in a toxin persistence which lasted for approximately 12 weeks. Temporal trends of toxin concentrations in shellfish during this period paralleled the bloom profile of the DSP causative dinoflagellate genus *Dinophysis*, which exhibited exceptional bloom magnitude and duration. While a definitive causal link cannot be established on the basis of available data, it is likely that this population became established and persisted through wind driven advection of a seed population into the loch.

In Irish waters, shellfish harvesting areas continue to enforce periodic closures in the south west region as a result of high concentrations of DSP toxins associated with *Dinophysis*. A study on the dynamics of the *Dinophysis acuta* populations in Irish waters showed cells of this species to accumulate in thin layers in the water column which could be transported in the coastal current (Farrell *et al.*, 2012). Along the west coast, closures in 2009 and 2012 in Killary Harbour were due to DSP toxins from *Dinophysis* at cell densities of several thousand cells per litre (Raine *et al.*, 2014). These populations had been advected into Killary Harbour.

Analysis of the historical data from the CPR shows the distribution of *Dinophysis* to have shifted in the North Sea region over a multi decadal scale. *Dinophysis* was abundant on the east coast of the UK (Region 1) in the 1970s (Dodge 1977), however, densities have declined and shifted to the north-eastern North Sea (Edwards *et al.*, 2006). During 2010, high abundances of *Dinophysis* were observed off the northern coast of Denmark. Data on *Dinophysis* from Region 8 is scarce. A report on the phytoplankton community observed along a transect in this region (Ellett line), revealed *Dinophysis* to be present both on and off the shelf, but in low numbers (Fehling *et al.*, 2012). Data from the CPR also reveals *Dinophysis* to be lower in abundance in Region 8 than in the North Sea.

Since the last report card, concentrations of yessotoxins (YTX) and azaspiracids AZAs exceeding the EU closure limit have been reported for the first time in Scottish shellfish from Regions 1, 5 and 6. This is in contrast to a previous survey by Stobo *et al.* (2008) when low concentrations of these toxins were recorded. The presence of AZA producing *Azadinium spinosum*, alongside a new non-AZA producing species *A. polongum*, has recently been confirmed in samples from the Shetland Islands (Tillmann *et al.*, 2012).

The relationship between *Azadinium* in the water column and AZA in field material has only started to be investigated

recently and it is too early to show clear patterns. In Irish waters AZA concentrations in shellfish increase during the late summer months. A recent study confirmed that shellfish can accumulate AZA in their tissues when fed *Azadinium spinosum* isolated from Irish waters (Salas *et al.*, 2011).

Pseudo-nitzschia and amnesic shellfish poisoning (ASP) toxins

Pseudo-nitzschia, continues to be routinely detected as part of the phytoplankton community in UK and RoI waters. Historically, this toxin-producing species was responsible for extensive closures of shellfish harvesting areas for king scallops in Scotland (*Pecten maximus*) (Fehling *et al.*, 2005). Since the shellfish hygiene recommendation (2002/226/EC) allowed the sale of shucked scallop product on the market, closures of harvesting areas in UK waters (regions 1- 8) have considerably reduced. Monitoring for the presence of domoic acid continues and although high concentrations were found in *P. maximus* from the Isle of Man and Northern Ireland, they were not sufficient to enforce a closure of the shellfish harvesting area.

The uptake and depuration of ASP toxins in shellfish such as blue mussels (*Mytilus edulis*) is very rapid and although high *Pseudo-nitzschia* cell densities have been observed in UK waters, virtually no closures of shellfish harvesting areas have been enforced in regions 1-8 since the last report card was issued. During the summer of 2012 domoic acid concentrations above the regulatory limit of 20 µg DA 100g⁻¹ was detected for the first time in mussels from Belfast Lough. A high cell density of *Pseudo-nitzschia* (250,000 cells L⁻¹) was associated with this event and the harvesting area was closed for two weeks.

During the spring in RoI waters blooms of *Pseudo-nitzschia* can be associated with high concentrations of ASP toxins in *M. edulis* tissue, which result in enforced closures of shellfish harvesting areas.

A report on the phytoplankton community composition along a transect in Region 8 (Ellett line) presents the first details of the *Pseudo-nitzschia* community both on and off the shelf edge in this region (Fehling *et al.*, 2012).

Dense blooms of *Pseudo-nitzschia*, particularly *P. 'seriata'* type cells continue to be observed in the offshore areas of the North Sea by the CPR.

Since the last report card was issued, the occurrence of algal toxins in higher trophic levels of UK waters have been reported. A small study investigating the role of zooplankton in vectoring algal toxins up the food web, recorded the presence of domoic acid in calanoid copepods in the north east of Scotland (Region 1) (Marine Scotland, unpublished data). A recent survey in Scottish waters has revealed the presence of domoic acid, the toxin responsible for ASP in the urine and faeces of harbour seals, *Phoca vitulina*, in Regions 1, 6 and 7 (Hall and Frame, 2010). Opportunistic sampling of a pregnant dead harbour seal also found traces of domoic acid in the amniotic fluid and analysis of faeces and urine from various species of cetacean that have stranded around the Scottish coast also detected exposure in harbour porpoise

(*Phocoena phocoena*). Grey seals (*Halichoerus grypus*) were also found to be exposed, but the proportion of positive faecal samples collected from a haulout site on the east coast of Scotland during the summer was much lower than in harbour seals from the same region and month (18/37, 48% in grey seals compared to 22/23, 95% in harbour seals), possibly due to their more offshore foraging behaviour (Hall, unpublished data). Domoic acid has been responsible for the mortality of sea mammals in coastal waters of California, USA (Lefebvre *et al.*, 2012), but the impact of this toxin on the health of marine mammals and seabirds in UK and RoI waters is currently unknown. A more detailed study is now underway to investigate this further.

2. WHAT COULD HAPPEN?

Sea surface temperature

Many HAB species are flagellates, life forms that are favoured by increased temperatures though direct influences on cellular processes and indirectly through increased stability of the water column. An increase in SSTs may facilitate the range expansion of HAB species from more southerly areas as suggested by Hallegraeff (2010). Examples of species that may become established in UK and RoI waters are *Gymnodinium catenatum*, a PSP toxin producer frequently observed in Spanish waters and *Ostreopsis* spp., a toxin-producing benthic dinoflagellate which is now known to have a European distribution outside of the Mediterranean. Given the complex interactions that determine the occurrence of HAB species and control bloom development, it is difficult to determine the probability of 'new' species becoming established in UK and RoI waters. Predicted temperature increases are highest in Regions 2, 3 and 4 which suggests these waters may be more at risk.

Stratification

An increase in the duration of stratification has the potential to impact the occurrence of HABs in UK and RoI waters. The onset of seasonal stratification is predicted to occur earlier in the year and persist into the autumn as a result of climate change. Such conditions may favour dinoflagellate growth. This is particularly relevant in Region 8, an area where offshore high biomass *K. mikimotoi* blooms have been hypothesized to initiate and impact coastal areas in Regions 6, 7 and 1. Increased stratification may also promote growth of selected phytoplankton through the reduction of turbidity, increasing exposure to available light.

Conversely, changes in wind speed and duration may reduce the duration of stratification in the water column. This may result in a decrease of some HAB dinoflagellate species and an increase in HAB diatom species as suggested by Hinder *et al.* (2012).

Increase in precipitation, runoff and flooding

Elevated or intense bursts of precipitation can increase the amount of runoff from the land and/or the number of flood events. This may enhance stratification in estuaries and sea lochs which can favour the growth of dinoflagellates. Humic material during these events may increase the concentration

of nutrients available which may promote phytoplankton growth (Hallegraeff, 2010). Conversely turbidity during storm/run off events may increase turbidity and result in light limitation of growth.

The impact of climate change on algal toxicity

It is known that environmental variables such as temperature, pH, light, nutrient supply and water movement/turbulence can affect algal bloom dynamics and their toxicity. Climate change is expected to impact on these variables to differing extents in different regions (Hallegraeff, 2010; Davidson *et al.*, 2012)

Ocean acidification and multiple pressures

The influence of increasing ocean acidification (OA) on the phytoplankton community (including HABs) has yet to be fully investigated. Knowledge gaps in this area have been highlighted by Fu *et al.* (2012). Increased CO₂ concentrations may influence the abundance of pH sensitive species, however, impacts from ocean acidification may also be less obvious. A lower pH has the potential to influence the speciation of nutrients (e.g. nitrogen, phosphate and silica) important for phytoplankton growth (Turley *et al.*, 2009) however many HAB species are mixotrophic (Davidson *et al.*, 2012) and thus the impact of OA on food availability has yet to be fully resolved. Some phytoplankton groups with a low affinity for CO₂ could be favoured by increased concentrations of CO₂ (Rost *et al.*, 2008), thereby altering the composition of the phytoplankton community. Culture studies on strains of *Pseudo-nitzschia* have investigated the combined impacts of pCO₂ and nutrients on toxin production. Increased domoic acid production was observed under high pCO₂ conditions and this increase was elevated in nutrient limited conditions (Fu *et al.*, 2012).

Changes in offshore circulation

Changes in offshore circulation can influence the abundance and diversity of phytoplankton in UK waters and have already been identified in Region 1 (Edwards *et al.*, 2002). where influx of polar water into the North Sea in the late 1970s resulted in a decrease in phytoplankton abundance, with one species *Ceratium macroceros* being lost from the North Sea dinoflagellate community. Variation in the circulation of the subpolar gyre may influence variability in ecosystem structure on the eastern margin of the North Atlantic (Hatún *et al.*, 2009) and should be considered when interpreting longer term phytoplankton time series data as well as making predictions for the future. Studies into the impact of regional climate change on harmful algal blooms in the north-east Atlantic concluded that harmful algal blooms in Norwegian coastal waters and the Skagerrak are particularly sensitive to climate induced changes in temperature, salinity, and the North Atlantic Oscillation (NAO) (Edwards *et al.*, 2006). McDermott and Raine (2006) give suggestions for the groups of species, from the genus *Ceratium* that could be used as evidence of such changes.

3. KNOWLEDGE GAPS

Some knowledge gaps remain:

- a. The majority of HAB monitoring is performed in coastal areas. The role of advection from the offshore in seeding blooms in coastal areas requires further attention. The lack of monitoring/modelling studies in shelf areas and Region 8 contributes towards this.
- b. Limited work has been performed in modelling the different HAB species in UK waters. Therefore it is difficult to predict the response of different HAB groups and genera to the influences of climate change.
- c. The impact of increasing ocean acidification on UK HAB species is largely unknown.
- d. Ichthyotoxic species such as *Karenia mikimotoi* have yet to be investigated to a level that would allow a proper evaluation of their impacts on the marine ecosystem (including critical life phases of exploited species).

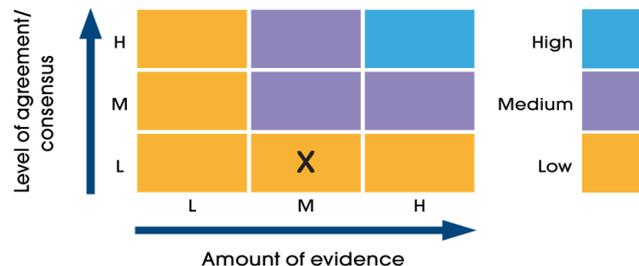
4. SOCIO-ECONOMIC IMPACTS

Increased HAB events may have a direct detrimental effect on ecosystems (e.g. benthic mortalities resulting from *K. mikimotoi* blooms) and they can often have a direct commercial impact on aquaculture, either shellfish or fish production farms, depending on the type of HAB. Predictions of future food consumption indicate that these two sources will be of much greater importance in the future and thus the economic impacts may be severe. In rural areas impacts to the aquaculture industry will have a disproportionate impact on the economy of the local area.

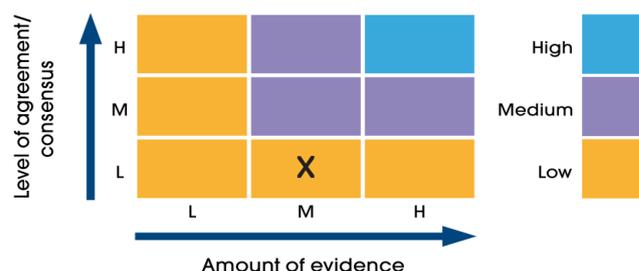
5. CONFIDENCE ASSESSMENT

Time series data from the CPR and coastal monitoring sites in UK and RoI waters reveal changes in the occurrence and distribution of HABs and HAB species over the last number of decades. Limited modelling work makes it difficult to predict the response of HABs to the influences of climate change.

What is already happening?



What could happen?



CITATION

Please cite this document as:

Bresnan, E., Davidson, K., Edwards, M., Fernand, L., Gowen, R., Hall, A., Kennington, K., McKinney, A., Milligan, S., Raine, R. and Silke, J. (2013) Impacts of climate change on harmful algal blooms, *MCCIP Science Review 2013*, 236-243, doi:10.14465/2013.arc24.236-243

REFERENCES

- Alheit J., Mollmann C., Dutz J., Kornilovs G., Loewe P., Mohrholz V. and Wasmund N. (2005) Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. *ICES J. Mar. Sci.*, **62**, 1205 - 1215.
- Al-Kandari, M.A., Highfield, A.C., Hall, M.J., Hayes, P. and Schroeder, D.C. (2011) Molecular tools separate harmful algal bloom species, *Karenia mikimotoi*, from different geographical regions into distinct sub-groups. *Harmful Algae*, **10**(6), 636-643.
- Alvarez-Fernandez, S., Lindeboom, H. and Meesters, E. (2012) Temporal changes in plankton of the North Sea: community shifts and environmental drivers. *Mar. Ecol. Prog. Ser.*, **462**, 21 - 38.
- Brand, L.E., Campbell, L. and Bresnan, E. (2012) *Karenia*: The biology and ecology of a toxic genus. *Harmful Algae*, **14**, 156-178.
- Bresnan E., Turrell, E. A. and Fraser, S. (2008) *Monitoring PSP and Alexandrium hotspots in Scottish waters*. In: Proceedings of the 12th International Conference on Harmful Algae. (Moestrup, Ø., G. Doucette, G., Enevoldson, H., Godhe, A., Hallegraeff, G., Luckas, B., Lundholm, N., Lewis, J., Rengefors, K., Sellner, K., Steidinger, K., Tester, P. and Zingone, A., editors), Intergovernmental Oceanographic Commission of UNESCO, Copenhagen, 51-54.
- Bresnan, E., L. Fernand, K. Davidson, M. Edwards, S Milligan, R. Gowan, J Silke, S Kröger and R. Raine (2010) Climate Change impacts on Harmful Algal Blooms (HABs) in MCCIP Annual Report Card 2010-11, MCCIP Science Review, 10pp. www.mccip.org.uk/arc
- Brosnahan, M.L., Kulis, D.M., Solow, A.R., Erdner, D.L., Percy, L., Lewis, J. and Anderson, D.M. (2010) Outbreeding lethality between toxic Group I and nontoxic Group III *Alexandrium tamarense* spp. isolates: Predominance of heterotypic encystment and implications for mating interactions and biogeography. *Deep-Sea Res. Part II-Topical Studies in Oceanogr.*, **57**(3-4), 175-189.
- Brown, L., Bresnan, E., Graham, J., Lacaze, J.P., Turrell, E. and Collins, C. (2011) Distribution, diversity and toxin composition of the genus *Alexandrium* (Dinophyceae) in Scottish waters. *Eur. J. Phycology*, **45**(4), 375-393.
- Chavez, F.P., Messie, M. and Pennington, J.T. (2011) *Annual Review of Marine Science, Vol 3. Marine Primary Production in Relation to Climate Variability and Change*. Carlson, C.A. and Giovannoni, S.J. (eds), pp. 227-260.
- Collins, C., Graham, J., Brown, L., Bresnan, E., Lacaze, J.P. and Turrell, E.A. (2009) Identification and toxicity of *Alexandrium tamarense* (Dinophyceae) in Scottish waters. *J. Phycology*, **45**(3), 692-703.
- Davidson, K. and Bresnan, E. (2009) Shellfish toxicity in UK waters: a threat to human health? *Env. Health*, **8**.
- Davidson, K., Miller, P., Wilding, T.A., Shutler, J., Bresnan, E., Kennington, K. and Swan, S. (2009) A large and prolonged bloom of *Karenia mikimotoi* in Scottish waters in 2006. *Harmful Algae*, **8**(2), 349-361.
- Davidson K., Gowen R.J., Tett P., Bresnan E., Harrison P.J., McKinney A., Milligan S., Mills D.K., Silke J. and Crooks A-M. (2012) Harmful Algal Blooms? How Strong is the evidence that nutrient ratios and forms influence their occurrence. *Estuarine Coast. Shelf Sci.*, **115**, 399 - 413.
- Dodge, J. D. (1975) A survey of chloroplast ultrastructure in the *Dinophyceae*. *Phycologia*, **14**, 253-263.
- Edwards, M. and Richardson, A.J. (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature*, **430**(7002), 881-884.
- Edwards, M., Beaugrand, G., Reid, P.C., Rowden, A.A. and Jones, M.B. (2002) Ocean climate anomalies and the ecology of the North Sea. *Mar. Ecol. Prog. Ser.*, **239**, 1-10.
- Edwards, M., Johns, D.G., Leterme, S.C., Svendsen, E. and Richardson, A.J. (2006) Regional climate change and harmful algal blooms in the northeast Atlantic. *Limnol. Oceanogr.*, **51**(2), 820-829.
- Farrell, H., Gentien, P., Fernand, L., Lunven, M., Reguera, B., Gonzalez-Gil, S. and Raine, R. (2012) Scales characterising a high density thin layer of *Dinophysis acuta* Ehrenberg and its transport within a coastal jet. *Harmful Algae*, **15**, 36-46.
- Fehling, J., Davidson, K. and Bates, S.S. (2005) Growth dynamics of non-toxic *Pseudo-nitzschia delicatissima* and toxic *P. seriata* (Bacillariophyceae) under simulated spring and summer photoperiods. *Harmful Algae*, **4**(4), 763-769.
- Fehling, J., Davidson, K., Bolch, C.J.S., Brand, T.D. and Narayanaswamy, B.E. (2012) The relationship between phytoplankton distribution and water column characteristics in north west European shelf sea waters. *PLOS ONE*, **7**(3).
- Frost, M., Baxter, J.M., Buckley, P.J., Cox, M., Dye, S.R. and Harvey, N.W. (2012) Impacts of climate change on fish, fisheries and aquaculture. *Aquatic Cons. Mar. Freshw. Ecosyst.*, **22**(3), 331-336.
- Fu, X. F., Tatters, A. O. and Hutchins D. A. (2012) Global change and the future of harmful algal blooms in the ocean. *Mar. Ecol. Prog. Ser.*, **470**, 207 - 233.
- Gentien, P., Lazure, P., Crassous, M-P., Daniélou, M-M., Nézan, E., Reguera, B., Gonzales-Gil, S., Farrell, H., and R. Raine (submitted). *Meeting for mating: how rare marine protists (Dinophysis, Dinophyceae) exploit physical structures for sex and population growth*.
- Gowen R., Tett, P., Bresnan, E., Davidson, K., Gordon, A., McKinney, A, Milligan, S., Mills, D., Silke, J. and Crooks, A-M. (2009) *Anthropogenic nutrient enrichment and blooms of harmful microalgae*. Report to DEFRA, 224 pp.
- Gowen, R.J., Tett, P., Bresnan, E., Davidson, K., McKinney, A., Harrison, P.J., Milligan, S., Mills, D.K., Silke, J., and Crooks, A.M. (2012) Anthropogenic nutrient enrichment and blooms of harmful phytoplankton. *Oceanogr. Mar. Biol. Ann. Rev.*, **50**, 65 -126.
- Hall, A.J. and Frame, E. (2010) Evidence of domoic acid exposure in harbour seals from Scotland: A potential factor in the decline in abundance? *Harmful Algae*, **9**(5), 489-493.
- Hallegraeff, G.M. (2010) Ocean climate change, phytoplankton community responses and harmful algal blooms: a formidable predictivev challenge. *J. Phycology*, **46**(2), 220-235.
- Hátún, H., Payne, M.R., Beaugrand, G., Reid, P.C., Sandø, A.B., Drange, H., Hansen, B., Jacobsen, J.A. and Bloch, D. (2009) Large bio-geographical shifts in the north-eastern Atlantic Ocean: From the subpolar gyre, via plankton, to blue whiting and pilot whales. *Prog. Oceanogr.*, **80**, 149-162.

- Hinder, S.L., Hays, G.C., Edwards, M., Roberts, E.C., Walne, A.W. and Gravenor, M.B. (2012) Changes in marine dinoflagellate and diatom abundance under climate change. *Nature Climate Change*, **2**(4), 271-275.
- Hughes, S.L., Holliday, N.P., and Beszczynska-Möller, A. (2010.) *ICES Report on Ocean Climate 2009*. ICES Cooperative Research Report No. 304. 67 pp.
- Hughes, S.L., Holliday, N.P., Gaillard, F. and ICES WGOH (2012) Variability in the ICES/NAFO region between 1950 and 2009: observations from the ICES Report on Ocean Climate. *ICES J. Mar. Sci.*, **69**(5), 706-719.
- Lefebvre, K.A., Frame, E.R. and Kendrick, P.S. (2012) Domoic acid and fish behavior: A review. *Harmful Algae*, **13**, 126-130.
- Lowe, J.A., Howard, T., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K. et al. (2009) *UK Climate projections science report: marine and coastal projections*. Met Office Hadley Centre, Exeter, UK.
- McDermott, G. and Raine, R. (2006) *The dinoflagellate genus Ceratium in Irish shelf seas*. The Martin Ryan Institute, University of Ireland. 86pp.
- McQuatters-Gollop, A., Raitsos, D.E., Edwards, M., Pradhan, Y., Mee, L.D., Lavender, S.J. and Attrill, M.J. (2007) A long-term chlorophyll data set reveals regime shift in North Sea phytoplankton biomass unconnected to nutrient trends. *Limnol. Oceanogr.*, **52**(2), 635-648..
- Percy, L.A. (2006) *An investigation of the phytoplankton of the Fal Estuary, UK and the relationship between the occurrence of potentially toxic species and associated algal toxins in shellfish*. PhD, University of Westminster, UK.
- Raine, R., McDermott, G., Silke, J., Lyons, K., Nolan, G. and Cusack, C. (2010) A simple short range model for the prediction of harmful algal events in the bays of southwestern Ireland. *J. Mar. Syst.*, **83**(3-4), 150-157.
- Raine, R., Wilson, A.M., Hermann, G. and Lacaze, J.P. (2014) *A Comparison Of Assay Techniques For The Analysis Of Diarrhetic Shellfish Poisoning Toxins In Shellfish*. In: (G. Sauve, ed.) *Proceedings of the 8th International Conference on the Molluscan Shellfish Safety*. Springer, New York.
- Rost, B., Zondervan, I. and Wolf-Gladrow, D. (2008) Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Mar. Ecol. Prog. Ser.*, **373**, 227 - 237.
- Salas, R., Tillmann, U., John, U., Kilcoyne, J., Burson, A., Cantwell, C., Hess, P., Jauffrais, T. and Silke, J. (2011) The role of *Azadinium spinosum* (Dinophyceae) in the production of azaspiracid shellfish poisoning in mussels. *Harmful Algae*, **10**(6), 774-783.
- Silke, J., O'Beirn, F., and Cronin, M. (2005) *Karenia mikimotoi: An exceptional dinoflagellate bloom in Western Irish Waters, Summer 2005*. Marine Environment and Health Series No. 21. Marine Institute Ireland
- Stobo, L.A., Lacaze, J., Scott, A.C., Petrie, J. and Turrell, E.A. (2008) Surveillance of algal toxins in shellfish from Scottish waters. *Toxicon*, **51**(4), 635-648.
- Swan, S. and Davidson, K. (2012) *Monitoring Programme for the presence of toxin producing plankton in shellfish production areas in Scotland*. Reporting period 01 Jan 2011 – 31 Dec 2011. Food Standards Agency Report. 50pp.
- Tillmann, U., Soehner, S., Nezan, E. and Krock, B. (2012) *First record of the genus Azadinium (Dinophyceae) from the Shetland Islands including the description of Azadinium polongum sp. nov.*
- Touzet, N., Franco, J.M. and Raine, R. (2008) Morphogenetic diversity and biotoxin composition of *Alexandrium* (Dinophyceae) in Irish coastal waters. *Harmful Algae*, **7**(6), 782-797.
- Touzet, N., Davidson, K., Pete, R., Flanagan, K., McCoy, G.R., Amzil, Z., Maher, M., Chapelle, A. and Raine, R. (2010) Co-Occurrence of the West European (Gr.III) and North American (Gr.I) Ribotypes of *Alexandrium tamarense* (Dinophyceae) in Shetland, Scotland. *Protist*, **161**(3), 370-384.
- Turley, C., Findlay, H.S., Mangi, S., Ridgwell, A. and Schmidt, D.N. (2009) *CO₂ and ocean acidification in Marine Climate Change Ecosystem Linkages Report Card 2009*. (Eds. Baxter JM., Buckley P.J. and Frost M.T.) Online Science Reviews, 25pp. www.mccip.org.uk/elr/acidification
- Wiltshire, K.H., Malzahn, A.M., Wirtz, K., Greve, W., Janisch, S., Mangelsdorf, P., Manly, B.F.J. and Boersma, M. (2008) Resilience of North Sea phytoplankton spring bloom dynamics: An analysis of long-term data at Helgoland Roads. *Limnol. Oceanogr.*, **53**(4), 1294-1302.