Impacts of climate change on human health, HABs and bathing waters, relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

- Human health can be affected by toxin-producing phytoplankton, pathogenic *Vibrio* species (bacteria) and noroviruses (NoV) in UK waters.
- The influence of climate change on toxin-producing phytoplankton is complex. This can be difficult to distinguish from shorter-term weather events and larger-scale circulatory processes. Confidence in current long-term prediction for harmful algal bloom (HAB) species is low. Data characterising the response of different HAB species to a broad range of environmental parameters are needed to improve short term (one to two week) forecasts and longer-term predictive models.
- During the 2018 heatwave experienced in the UK (June–July), record water temperatures coinciding with elevated levels of pathogenic *Vibrio* species were identified from several sites along the south-west coast of the UK.
- Climate change will modify the geographical distribution and seasonality of NoV. However, it is difficult to predict the effects of these changes on disease risk because NoV infectivity is determined by a complex set of factors, including host availability and susceptibility, emergence of new strains, and multiple environmental transmission pathways.
- Surveillance studies indicate that NoV prevalence in water and shellfish is related to temperature, but it is not known how projected

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increases in sea-surface temperatures will affect the risk of illness. Runoff from more frequent and intense extreme rainfall events will increase NoV contamination from sewage sources and compromise water quality, particularly in areas served by combined sewerage infrastructure. Following sewer overflows, NoV concentrations in nearshore waters can be 10 times higher than concentrations during 'no discharge' conditions.

- A survey of tetrodotoxin (TTX) in shellfish from around the UK revealed the toxin to be present in quantifiable amounts in shellfish from southern England and in one sample from Scotland. Highest TTX concentrations were recorded when water temperatures exceeded 15°C (maximum concentration of total TTXs; 253 µg/kg) although the toxin was also present at other times of the year. The role of water temperature on the occurrence and distribution of this toxin in UK shellfish and biota merits further investigation.

1. BACKGROUND

Climate change has the potential to impact coastal ecosystems in multiple ways, altering human exposure to water-related contaminants that can cause illness. The main groups of relevance to water-related illnesses in the UK marine environment are toxin-producing phytoplankton and pathogenic bacteria and viruses.

Harmful Phytoplankton

Marine phytoplankton are single-celled algae that inhabit the water column. They play an important ecological role in the marine ecosystem as primary producers, harvesting light energy from the Sun to produce food which gets passed up through the marine food web (Chavez *et al*., 2011). A number of marine phytoplankton species can produce toxins that can accumulate in the flesh of shellfish and can pose a risk to human health if consumed. When environmental conditions are favourable these toxin-producing phytoplankton can increase in abundance. This is called a 'harmful algal bloom' (HAB). The main HAB genera of concern for human health in UK waters are the dinoflagellates *Alexandrium* (associated with the production of toxins responsible for paralytic shellfish poisoning (PSTs), *Dinophysis* (toxins associated with diarrhetic shellfish poisoning (DSTs)) and the diatom *Pseudo-nitzschia* (toxins associated with amnesic shellfish poisoning (ASTs); Davidson and Bresnan, 2009). The dinoflagellates *Azadinium* (azaspiracid toxins, AZAs), *Protoceratium reticulatum*, *Lingulodinium polyedra* and *Gonyaulax spinifera* (yessotoxins, YTX) are less of an issue in UK waters although AZAs have caused significant problems for the Irish shellfish industry (Chevallier *et al*., 2015). The threat to human health from these shellfish toxins is managed by the Food Standards Agency (in England, Northern Ireland and Wales) and Food Standards Scotland who oversee a monitoring programme for shellfish and causative phytoplankton in fulfilment of Food Hygiene Regulations (primarily Regulation (EC) No. 854/2004) to prevent the consumption of contaminated product.

Vibrio species and Noroviruses

One group of environmental bacteria (pathogenic *Vibrio*) are an increasingly important cause of disease around the world. These bacteria can cause a range of infections in humans, such as gastroenteritis, wound infections and sepsis (blood poisoning). Transmission is mostly driven by the consumption of contaminated seafood and/or exposure to seawater, often recreationally through swimming. The species *Vibrio vulnificus*, *V. parahaemolyticus* and *V. cholerae* are commonly implicated in human diseases. These bacteria grow in warm, low-salinity waters and their abundance in the natural environment mirrors ambient environmental temperatures.

Human noroviruses (NoV) are the most common pathogenic virus causing epidemic infectious intestinal disease (IID) and a major cause of waterborne illness worldwide. In the UK, approximately 17 million cases of illness and one million general practice consultations due to IID occur annually (Tam *et al*., 2012). The number of cases of shellfish-borne NoV in the UK has been estimated to be approximately 21,000/year (Hassard *et al*., 2017). Norovirus are highly contagious, rapidly and prolifically shed by symptomatic and asymptomatic individuals, very stable in the environment outside the human host and resistant to many forms of disinfection (Campos and Lees, 2014).

Human exposure to these organisms occurs through ingestion, inhalation or direct contact with contaminated water and shellfish. Worldwide, the most common manifestations of waterborne illness are gastrointestinal (nausea, vomiting, diarrhoea). However, the effects can be more severe in persons who are more vulnerable to illness (the young, the elderly, and the immunocompromised). In the UK, there is no statutory mechanism for reporting water-related disease and the evidence about the burden of disease comes primarily from recording of outbreaks. It is widely accepted that the total incidence of these diseases is largely underestimated. There is no specific legislation to control risks from *Vibrio* and NoVs.

Assessing climate change impacts and human health

The complexity of how climate change impacts the marine environment is increasingly acknowledged. The waters around the UK are showing a long-term warming trend over the last 30 years. However, there has been some short-term variability recorded with the period from 2008–2013 being cooler than that from 2000–2008 and 2014–2017. Local and regional variations have also been observed and the influence of cold ocean temperature anomalies in the mid-high latitude North Atlantic has weakened the warming along the UK’s south-west coast since the last relevant MCCIP Report Card (Tinker and Howes, 2020). The recent UK Climate Predictions (UKCP18) also present a latitudinal aspect to predicted changes in air temperature and precipitation (Lowe *et al*., 2018). Separation of climate-change impacts from short-term fluctuations, such as weather events and long term multidecadal cycles such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO), are difficult and must be considered when examining the impacts of climate change on biota. The impacts from additional anthropogenic pressures on organisms harmful to human health, such as ocean acidification is complex, in many cases potentially acting in synergy with changes in other environmental parameters such as temperature (Raven *et al*., in press).

To date, most research has focused on understanding how climate drivers affect physical and ecological processes that act as key exposure pathways for pathogens and toxins. There is currently much less information and fewer methods with which to measure actual human exposure and incidence of illness based on physical and ecological metrics from harmful events (Berdalet *et al*., 2016). Studies examining societal impact in UK waters are scarce (Willis *et al*., 2018). Furthermore, much of the related research is either global or highly localised and therefore does not allow quantitative projections of future health outcomes from water-related illnesses at temporal and spatial scales appropriate for decisions to be made (Watts *et al*., 2015).

This review presents the current status of harmful phytoplankton, *Vibrio* species and NoVs in UK waters, as well as providing an update on improved understanding of the dynamics behind some of these issues since the last update (Bresnan *et al*., 2017). Based on the available data and research, many of the examples reported in the literature are site-specific. Environmental, public health and food safety agencies in the UK maintain monitoring programmes to reduce the risk of exposure to these hazards and water companies undertake water quality investigations and implement programmes of sewerage infrastructure upgrading to protect human health. The scientific research community has also completed a number of studies which contribute to improved understanding of the dynamics of the causative organisms, essential to understanding and improving the ability to predict impacts from climate change.

2. WHAT IS ALREADY HAPPENING?

Harmful Algae

Identification of climate change impacts on harmful algae is complex with multiple factors such as temperature, water column stability, turbidity, nutrients, grazing pressure, ocean acidification, wind mediated transport all potentially influencing abundance, distribution and toxicity (Hallegraeff *et al*., 2010, Wells *et al*., 2015, Trainer *et al*., 2019). HAB species in UK waters are diverse, observe a variety of different lifecycle and feeding strategies (e.g. *Alexandrium*, obligate cyst formation, *Dinophysis*, complex mixotrophy, *Pseudo-nitzschia*, chain forming autotroph) and are regionally distributed around the UK coast (Davidson and Bresnan 2009, Bresnan *et al.*, 2013, Lewis *et al.*, 2018). In some instances, information on species level diversity, toxin production, distribution and ecology of these different HAB species is still being collected in the UK. Since the last report card and update (Bresnan *et al.*, 2013; 2017) there has not been a dedicated investigation into the impact of climate change on HABs in UK waters. A number of studies have improved understanding of the diversity and distribution of selected HAB species and how biological and physical drivers influence toxicity and bloom formation in this region. These studies improve baseline understanding of the dynamics of HABs in UK waters which is essential to understand the impacts of environmental change on this group of organisms.

Analysis of historical data from the Continuous Plankton Recorder (CPR) collected over the last 50 years provides evidence of the impact of changing environmental conditions on the phytoplankton community in the seas around the UK. These analyses have identified a 'cold boreal' anomaly in the late 1970s, a 'warm temperate' event resulting in a regime shift at the end of the 1980s, and an additional shift in the phytoplankton community in 2008 (Edwards *et al.*, 2002; Alheit *et al.*,2005; Edwards *et al.*, 2006; Wiltshire *et al.*, 2008; Alvarez-Fernandez *et al.*, 2012). Analysis of this dataset has shown a change in the abundance and distribution of selected HAB genera (*Dinophysis*, *Ceratium* (renamed *Tripos*, Gomez 2013), *Prorocentrum*), within the North Sea since the 1960s (Edwards *et al.*, 2006). Sea-surface temperature and changing wind speeds have been shown to influence increases in the diatom *Pseudo-nitzschia* and decreases in the dinoflagellate *Tripos* in the north east Atlantic since the mid-1990s (Hinder *et al.*, 2012), although there is some evidence of recovery in the latter over the last five years (Edwards *et al.*, 2020).

The influence of weather on HAB events has been confirmed in multiple studies. A DST intoxication event in 2013 where human illness was recorded after consumption of shellfish harvested from Shetland, was revealed to be driven by a sudden change in wind direction, transporting a population of *Dinophysis* onshore, resulting in a rapid increase in DSTs in *Mytilus edulis* (Whyte *et al.*, 2014). Wind direction and intensity has also been seen as a driving factor behind prolonged DST events in Loch Fyne in Scotland (Morris *et al.*, 2010) as well as contributing to changes in phytoplankton community composition over multiple decades recorded by the CPR (Hinder *et al.*, 2012).

The establishment of HAB species from more southern waters (e.g. *Gymnodinium catenatum* from the Iberian Peninsula) has yet to be recorded in the UK (Bresnan *et al.*, 2017). A dedicated study to establish the methodologies for new and emerging HAB toxins (e.g. brevetoxins, pinnatoxins, cyclic amines) did not detect any in UK shellfish (Turner *et al*., 2015a; Davidson *et al*., 2015).

There is a strong regional distribution in management actions (closure of shellfish harvesting areas) and impacts associated with harmful phytoplankton around the UK with the majority of management actions recorded in Scotland (Figure 1). This is governed by the spatial distribution of the causative phytoplankton and the location of shellfish harvesting activities. Algal toxins have also been detected in marine mammals in Scottish waters (Hall and Frame 2010, Jensen *et al*., 2015). Since the last MCCIP Report Card (Bresnan *et al*., 2017) the incidence of closures of shellfish harvesting areas due to the presence of algal toxins above the closure limit has followed the regional pattern, but with an unusual record of PST in shellfish in Swansea. An exceptional event was observed in December 2017–January 2018. A strong storm resulted in mass strandings of Dab (*Limanda limanda*), and multiple species of crabs and starfish on the beaches of East Anglia. A number of dogs who consumed these stranded fish and starfish became ill and two died as a result of intoxication by PSTs (Turner *et al*., 2018a). This is the first report of canine fatalities in the UK as a result of PSTs. This result is surprising in this area due to the time of year this event was recorded. *Alexandrium* has only been recorded occasionally and in low abundance and PSTs have not been recorded in this region since chemical testing began in 2008.

Since the last MCCIP Report Card, a review of the potentially PST producing *Alexandrium minutum* suggest two different strains to be present in UK waters, a non-toxic strain in Scotland and a toxic strain in the south coast of England (Lewis *et al*., 2018). This review provides further support to the regional distribution of PSTs detected in shellfish flagged in previous report cards with *A. catenella* responsible for PSTs in shellfish in Scotland and *A. minutum* in England (Collins *et al*., 2009; Turner *et al*., 2014). This also highlights the complexity in examining the impacts climate change on industries impacted by HABs given the regional diversity within the causative genera.

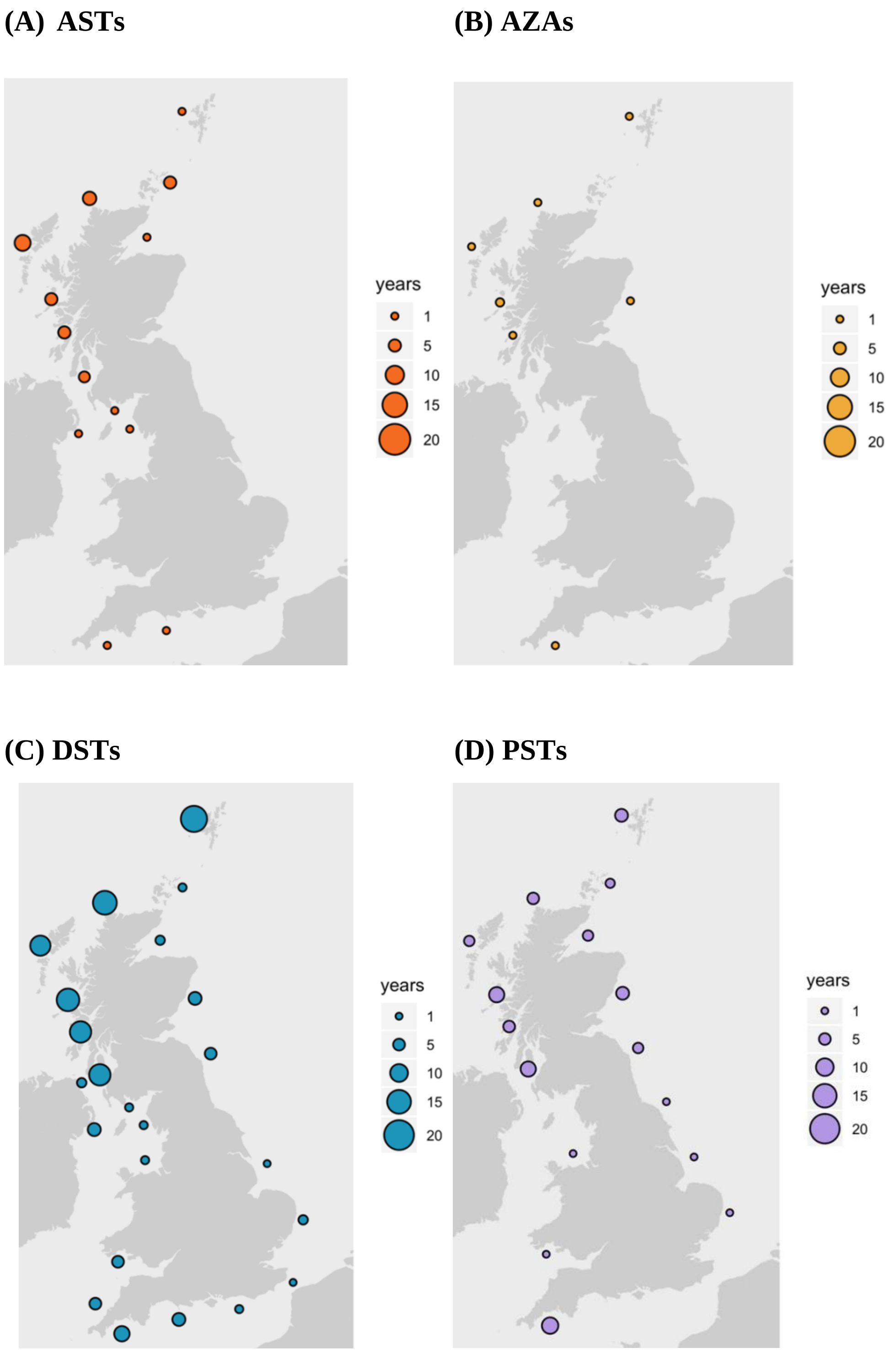


Figure 1: Number of years with management actions/negative impacts recorded at sites on the UK coast as a result of algal toxins harmful to health during the period 2000–2017. Data from the IOC-ICES-PICES Harmful Algal Event database (HAEDAT): (A) ASTs, (B) AZAs, (C) DSTs and (D) PSTs. HAEDAT divides the UK coastline into 200 km strips and summarises duration of shellfish closures and other impacts into 'events'. See ICES-IOC WGHABD (2017) for more information. Note: routine monitoring for AZAs began in the UK in 2011.

A review of the regional distribution of DST profiles associated with the genus *Dinophysis* (Okadaic Acid (OA), Dinophysistoxins 1 (DTX1) and 2 (DTX2) between 2011 and 2016 was performed. This revealed the majority of incidences to have been recorded in Scotland and laterally in the south-west of England (Dhanji-Rapkova *et al*., 2018). A study of *Dinophysis* species recorded in Scotland since 2001 showed *D. acuminata* to be present during the summer months while *D. acuta* occurred more sporadically. The presence of *D. acuta* was associated with a decrease of OA and DTX1 relative concentrations and an increase of DTX2 in the toxin profiles within the shellfish flesh (Swan *et al*., 2018). Investigation into the environmental control of *Dinophysis* blooms in the Clyde Sea in Scotland highlighted the role that temperature driven frontal systems can play in preventing *Dinophysis* blooms being transported into sea lochs within the Clyde, thus protecting aquaculture sites from the impacts associated with *Dinophysis* toxins (Paterson *et al*., 2017). The concentration of AZAs in shellfish in the UK have shown a high degree of interannual variability since monitoring began in 2011. Since 2013 there have been no records of AZAs in shellfish over the maximum permissible limit recorded in Scotland and only one record in the south-west in 2015. Yessotoxins are rarely detected in UK shellfish and records to date mainly come from the south-west of Scotland and Shetland. Phytoplankton monitoring data associates *Protoceratium reticulatum* with YTX in these areas (Dhanji-Rapkova *et al*., 2019).

A review of ASTs in UK shellfish from the last 10 years has showed that while the concentration of Domoic Acid (DA) was below the maximum permitted limit of 20 mg/kg in the majority of cases, an increase in the frequency of occurrence of DA was observed, particularly in England during 2014 (Rowland-Pilgrim *et al*., 2019). A new study of the diversity of *Pseudo-nitzschia* in the southern North Sea showed the presence of DA (the main AST) in the water column to be associated with presence of *P. delicatissima*, *P. pungens* and *P. fraudulenta* (Delegrange *et al*., 2018). This is in contrast to recorded toxicity within this genus in Scotland, where these species were found not to produce detectable concentrations of DA while DA production was confirmed in *P. australis* and *P. seriata* (Fehling *et al*., 2006). Oomycete parasites which have the potential to infect *Pseudo-nitzschia* cells have been described from Scotland for the first time (Garvetto *et al*., 2018). This is the first study of HAB parasites in UK waters, an additional biological factor which may impact HABs by influencing bloom termination.

There is a global effort underway to investigate the global status of HABs (Hallegraeff *et al*., 2017). In other parts of the world, extreme HAB events have been recorded over the last number of years which have had devastating impacts on local ecology and aquaculture industries (Trainer *et al*., in press); a warm water anomaly in the eastern Pacific, which has persisted since 2014, resulted in a significant *Pseudo-nitzschia* bloom, extended shellfish closures as well as other multiple ecosystem impacts (Du *et al*., 2016; Trainer *et al*., in press) and a strong El Niño year resulting in catastrophic fish kills in Chile from blooms of *Pseudochattonella* and *A. catenella* (Clement *et al*., 2016). Extreme events on such a scale have not been recorded in the UK.

Norovirus

Environmental factors such as temperature, rainfall and rising sea levels can affect the abundance, distribution, growth and toxicity of the organisms which can cause water-related illness. Heavy rainfall events are increasing in frequency and intensity in parts of the UK (Jones *et al*., 2013; Otto *et al*., 2018), however, the frequency and intensity of extreme events vary by region and thus human health impacts will also vary accordingly. Air temperature in the UK is generally increasing with greater increases in summer than winter, and greater increases in the south than in the north (Watts *et al*., 2015; Lowe *et al*., 2018) but there has been little research to examine the influence of air temperature increases on coastal water quality.

Since the last MCCIP Report Card, a detailed analysis of environmental risk factors for NoV in UK coastal areas has been carried out. These are water temperature, number and volume of sewage discharges and river flows (Campos *et al*., 2017). Further quantification of NoV concentrations in sewage effluents subject to different treatment processes has been carried out since the last report card. The results indicate no appreciable differences in concentrations between untreated sewage and storm tank discharges (Campos *et al*., 2016). Previous work had shown that following storm tank discharges, mean NoV concentrations in oysters sampled in downstream waters can increase 10 times relative to mean concentrations typically found during no-discharge conditions (Campos *et al*., 2015). This indicates that, during rainfall events, stormwater discharges can mobilise high concentrations of NoV to rivers and coastal waters popular with bathing and other water-based activities. There is very little information in the peer reviewed literature about the frequency and duration of sewer overflows. However, reports based on data for two UK water companies provided by the Environment Agency indicate that 50% of overflows to rivers and 33% of overflows to coastal areas are discharging more than once a month (WWF, 2017). This suggests that despite the significant investment made by water companies in improving the sewerage infrastructure, in parts of the UK a large number of overflows are still spilling frequently.

The associations between weather and bathing water quality on infectious intestinal disease were investigated using data from two Scottish National Health Service Board areas (Eze *et al*., 2014). Monthly counts of viral and non-viral gastrointestinal infections have been modelled as a smooth function of temperature, relative humidity and average monthly counts of faecal indicator organisms (adjusted for season and long-term trend effects) in bathing waters in Scotland. In this study, humidity was used as a surrogate for rainfall which was not available for the Board areas studied. In the context of climate change modelling, changes in atmospheric humidity transport can be assumed to correlate well with daily rainfall totals (Lavers and Villarini, 2015). A significant negative association existed between weather (temperature and humidity) and viral infection (Eze *et al.*, 2014). Average levels of non-viral gastrointestinal infections (e.g. salmonellosis, campylobacteriosis) increased as temperature and relative humidity increased. Peak viral gastrointestinal infection was in May while that of non-viral gastrointestinal infections was in July. Increasing levels of faecal indicator organisms in bathing waters were also associated with an increase in the average number of viral and non-viral gastrointestinal infections at the ecological level. UKCP09 projections for 2080–90 for a 'medium emission scenario' indicate that sea-surface temperatures in the summer bathing season will be 2–2.5 ºC warmer although in north and west of Scotland may be only 1ºC warmer (UKCP09, 2017). In theory, warmer waters and drier weather create less favourable conditions for NoV to persist in the environment outside human hosts. However, it has not been possible to quantify the effects of these changes on disease prevalence because many water-related illnesses are either undiagnosed or unreported. This is discussed further in Section 3 below.

***Vibrio* species**

Pathogenic *Vibrio* species are a globally important cause of diseases in humans and aquatic animals. There is growing evidence, based on laboratory, environmental and clinical studies that demonstrate the clear association between climate change and the incidence and disease impacts caused by these bacteria. Because these Gram-negative bacterial pathogens, including the species *Vibrio vulnificus*, *Vibrio parahaemolyticus* and *Vibrio cholerae*, grow in warm, low-salinity waters, and their abundance in the natural environment mirrors ambient environmental temperatures, they represent an important marine sentinel species to study climate change impacts (Baker-Austin *et al.*, 2016a, b).

The lack of long-term datasets on *Vibrio* species precludes comparative analyses (e.g. in both time and space) of the relationship between the role of temperature and microbial diversity. However, studies carried out by Cefas in 2018, including a recent analysis of low salinity (<30) estuarine systems in southern England, demonstrate that pathogenic *Vibrio* spp. are present in water and shellfish during summer months, often in very high concentrations. These data augments previous studies carried out during 2012–2013 which identified potentially pathogenic strains in two sites along the southern coast of the UK. In particular, data from the survey carried out during June–September 2018 identified a mixture of human pathogenic strains including *Vibrio vulnificus*, *Vibrio alginolyticus*, *Vibrio parahaemolyticus* and *Vibrio cholerae* – all four of which are considered important human pathogens (Baker-Austin *et al.*, 2018). As with previous work in 2012–2013, strains carrying pathogenicity genes were regularly identified during this survey. Record high water temperatures, exceeded 30ºC in one site in July 2018 (and which were above 20°C from late June until the middle of August across all sites), were observed through the summer of 2018. These unusual conditions corresponded with a significant heatwave event in the UK from June to early August, and may have played a role in driving the abundance of these bacteria.

Analysis of archived Continuous Plankton Survey (CPR) samples has investigated bacterial DNA in formalin-preserved plankton samples collected over the past half-century (1958–2011) from the North Atlantic region. In areas of warming, data from historic plankton sampling sites showed increases in *Vibrio* bacteria abundance including the North Sea. The increases in *Vibrio* abundance were related to changes to climate warming and the Atlantic Multidecadal Oscillation (AMO). These changes parallel the rise in *Vibrio*-related illnesses documented along the US Atlantic Coast and in Northern Europe (Vezzulli *et al*., 2016).

Heatwave events appear to play a significant role in driving human health risk. During the summer of 2018, a significant and sustained heatwave event was observed across much of Northern Europe. As with previous heatwave years in the region (e.g. 1994, 2006, 2010 and 2014) a large number of *Vibrio* infections were subsequently reported associated with recreational water exposures, and these infections have been reported in a number of countries, including cases observed in Finland, Sweden, Norway and Germany. These findings are of relevance because we have noticed an increase in heatwave events in Northern Europe over the last two decades (Barriopedro *et al*., 2011), with potential heatwave events likely to impact the UK similarly under a warming climate system. A preliminary assessment of reported cases as well as the environmental conditions driving these infections is currently ongoing, however an analysis of the event of 2018 compared to the most significant and recent heatwave observed in Northern Europe in 2014 (Baker-Austin *et al*., 2016a, b) suggests a larger, more pronounced and longer-sustained warming event. It is likely that this has corresponded with a noticeable increase in the geographical spread over which *Vibrio* bacteria may flourish (Semenza *et al*., 2017). In particular, infections have been reported extensively this year in Norway, with several severe blood (sepsis) cases and more than one fatality has also been reported by the media during the summer of 2018 in this region.

It should also be noted that there are few domestically acquired *Vibrio* infections reported each year, with the current risk deemed low. However, a recent genomic study of pathogenic strains of *Vibrio parahaemolyticus* reported in the UK, using isolates supplied from Public Health England's gastrointestinal unit has also shed some light onto potential *Vibrio* risk in the UK. A small number of potentially domestically acquired infections were identified from this work, including strains where no recent travel was suspected. With the observation that previous *V. parahaemolyticus* infections have been reported in the UK (Hooper *et al*., 1974), there remains the possibility that these unattributed infections, as well as many more based on foodborne attribution studies (Scallen *et al*., 2011) are circulating in the UK.

Tetrodotoxin

Tetrodotoxin (TTX) is a highly potent neurotoxin known to accumulate in a wide range of marine species (Turner *et al*., 2017). TTX is responsible for the highest fatality rate of all marine intoxications, being associated most commonly with accumulation in species of fish from the Tetraodontidae family, such as puffer fish (Isbister *et al*., 2005). Unlike other marine biotoxins, TTX is thought to be associated with production from a range of marine bacteria, including most notably *Vibrio* species, although others have postulated an association with certain specific phytoplankton species such as *P. cordatum* (Turner *et al*., 2017). TTX is commonly encountered in tropical and subtropical environments, and following the previous identification of TTXs in shellfish from southern England in 2014 (Turner *et al*., 2015), a recent survey of TTX in UK shellfish produce has been undertaken. Samples were collected between 2014 and 2016 from around the UK, and results showed the presence of TTX and associated analogues (TTXs) in a range of shellfish species, including Pacific oysters (*Crassostrea gigas*), native oysters (*Ostrea edulis*), common mussels (*Mytilus edulis*) and hard clams (*Mercenaria mercenaria*), but not found to date in cockles (*Cerastoderma edule),* razors (*Ensis* species) or king scallops (*Pecten maximus*). TTX-positive bivalves have been almost exclusively detected from shellfisheries along the south coast of England with one sample containing quantifiable amounts of TTX from Scotland. The highest concentrations were quantified in samples harvested during the warmer summer months, although TTXs were still evident from some areas occasionally during the winter. A greater level of risk was observed in areas of shallow, estuarine waters with temperatures above 15°C (Turner *et al*., 2017), although more work is required to elucidate the specific impacts of environmental parameters on TTX presence in shellfish. Confirmation of the causative organism is critical to begin to assess any impacts from climate change on this toxin. TTX has also been identified recently in a non-native ribbon worm *Cephalothrix simula* collected from west Cornwall. This presents another potential risk to human health from exposure to TTX and more investigation is needed to assess transfer of this toxin through different trophic levels (Turner *et al*., 2018b).

3. WHAT COULD HAPPEN IN THE FUTURE?

Climate change can impact the physical environment in UK waters in multiple ways. UKCP18 predict a move to warmer wetter winters and hotter drier summers over the next century (although some variability will be expected), increased coastal flood risk and sea level change, varying with change scenario and geographic region (Lowe *et al*., 2018). Recent MCCIP updates show warming sea temperatures (Tinker and Howes, 2020), declining oxygen concentrations in the North Sea (Mahaffey *et al*., 2020), with some uncertainty around predictions for sea-level rise and storms and waves (Horsburgh *et al*., 2019; Wolff *et al*., 2019) . The complexities in predicting how climate change will impact harmful phytoplankton species have been detailed in two key papers (Hallegraeff, 2010; Wells *et al*., 2015) with many unknowns remaining and warranting further investigation.

Ocean acidification is also likely to affect marine biota, in synergy with climate change impacts such as warming sea temperatures, thus making identification of individual drivers of change difficult (Sommer *et al*., 2015; Raven *et al*., in press) and a number of unknowns remain (Hallegraeff, 2010; Wells *et al*., 2015). Ocean acidification impacts on the plankton community was demonstrated in a recent mesocosm study where variable responses to CO_2 concentrations observed between different phytoplankton groups. The nuisance phytoplankton *Vicicitus globosus* (class Dictyochophyceae, which produces haemolytic cytotoxins that can cause fish mortalities) increased in abundance and formed blooms as CO_2 concentrations increased over 600–800 µatm. This subsequently disrupted the development of the micro- and meso-zooplankton communities and impacted trophic transfer through the food web (Riesbesell *et al*., 2018).

Modelling approaches have been used to examine the relationship of selected HAB species with temperature. Gobler *et al*. (2017a, b) modelled an increase in *Dinophysis* species growing period in the North Sea associated with increases in sea surface temperature. However, the lack of inclusion of additional drivers and phytoplankton loss terms into the model may result in an over-estimation of the HAB populations (Dees *et al*., 2017). Townhill *et al*. (2018) used species distribution models (SPDs) to reveal large shifts in the distribution of selected harmful species from the Iberian Peninsula, along the shelf edge and into the northern North Sea. While SPDs can show the potential for range expansion, their application to plankton has been questioned, with their accuracy reducing the further they project into the future (Brun *et al*., 2016).

Changes in offshore circulation over multiple decades have great potential to impact the dynamics of the North Sea. Large-scale modelling (Holt *et al*., 2018) has shown the potential for climate change to reduce Atlantic inflow into the North Sea. This will lead to a reduction in salinity and increased influence from riverine input altering the nutrient regime and turbidity particularly in the southern North Sea. This has the potential to impact the distribution of HABs which already observes a regional distribution in this region (ICES-IOC WGHABD, 2017).

Norovirus

More frequent extreme rainfall events and associated runoff and storm surges will exert greater pressure on the sewerage infrastructure and increase virus loading, thus compromising the quality of the waters used for recreational activities and shellfish harvesting (Hassard *et al.*, 2017). Sewerage systems in medium to highly urbanised catchments will be at greater risk of exceedance of system capacity or failure due to damage. The risk of extreme winter rainstorms in southern England, such as those that caused widespread flooding in January 2014, has increased because of climate warming (Schaller *et al.*, 2016). In a large ensemble of climate model simulations, Schaller *et al*. (2016) found that, as well as increasing the amount of moisture the atmosphere can hold, anthropogenic warming caused a small but significant increase in the number of January days with westerly flow, both of which increased extreme precipitation. A significant risk of gastrointestinal illness associated with contact with urban floodwater, particularly during clean-up periods, has been demonstrated in two flood-related scenarios examined in the UK (Fewtrell *et al.*, 2011).

Some changing river flow regimes agree with future change projections, while others are in apparent contradiction. Observed changes generally have not been attributed to climate change, largely because of large direct human disturbances on river flows and because river flow records are limited in length and the identification of short-term trends is confounded by natural variability (Hannaford, 2015).

Quantification of spill volume, duration and frequency for 19 combined sewer overflows to coastal waters in the north-west of England under two climate change scenarios (high and low emission scenarios) simulated by three global climate models predicted an annual increase of 37% in total spill volume, 32% in total spill duration and 12% in spill frequency for the shellfish water by 2080. The study further showed that CSO spill metrics are likely to reduce substantially during the bathing season under both emission scenarios (Abdellatif *et al.*, 2015). A further study that used a high-resolution dynamic climate model to estimate changes in UK rainfall intensities at short durations (1, 3 and 6 hours) as a result of climate change found greater numbers of spills on an annual basis and greater spill volumes during the bathing season than previous projections based on UK climate change allowances for rainfall intensity (Dale *et al.*, 2015).

Changes in water temperatures will also alter the seasonality, abundance and distribution of NoV in coastal waters. In UK coastal areas where increasing temperatures lengthen the periods for bathing and other water-based activities, exposure risks are expected to change. Current ‘regulatory’ microbial monitoring practices are time consuming, expensive and may not reveal the actual health risk. Catchment-based modelling combining targeted *in situ* monitoring and rainfall and temperature projections offer the potential for more accurate estimates of health risk (Coffey *et al.*, 2014). Source attribution, through quantified microbial source apportionment, linked with appropriate use of microbial source tracking methods should, therefore, be employed as an integral part of future epidemiological surveys (Fewtrell et al 2011).

Improvements in the predictive capability of global and regional climate models (GCMs/RCMs) provide better insights into areas currently undergoing change and areas where potential risks may greatly increase or emerge in the future. While considerable work is underway to better understand the capacity and resilience of sewerage networks and in planning the investment in infrastructure required to take account of increasing populations and climate change, information on the consequential reductions of overflow events and associated microbial water quality improvements is lacking in the peer-reviewed literature. This type of information is extremely important for risk managers, clinicians and public health bodies as a proactive means of ameliorating and managing changing risk, particularly in regions where these types of pathogens may emerge in the short to medium term. These future projections are allowing regions to be identified where it is possible to provide detailed advice for risk assessment purposes.

Vibrio species

The environmental parameters that drive pathogenic *Vibrio* species in the environment are well established. Pathogenic *Vibrio* grow well in warm (>15°C) low salinity waters (<30), with their abundance in the environment effectively tracking ambient sea surface temperatures. Validation of tools such as those that use temperature and salinity datasets (Semenza *et al*., 2017; Baker-Austin *et al.*, 2013) have allowed us to predict when and where human infections are likely to occur (Figure 2). In particular, sea surface temperatures (SST) that exceed 18°C for sustained periods of time have previously been implicated in disease emergence in Europe, in particular in the Baltic Sea (Baker-Austin *et al.*, 2013) (Figures 2 and 4).

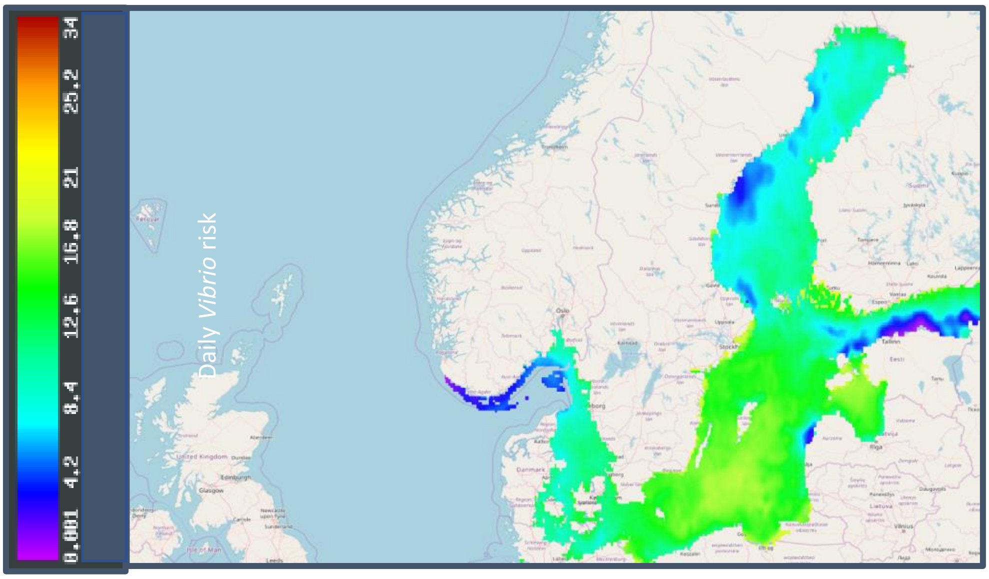


Figure 2: Variation of Vibrio: *1st August 2018. A significant swathe of warm, low salinity (<30) water is apparent, stretching from the northern Baltic Sea to the transitional waters of the North Sea/Baltic between southern Norway and Denmark. Based on data from previous studies (Baker-Austin* et al.*, 2013) these waters are capable of supporting vibrios at high concentrations. (Data courtesy NOAA,* ***http://cwcgom.aoml.noaa.gov/cgom/OceanViewer/#****)*

Alongside general warming trends observed in northern latitude marine systems (Lima and Wethey, 2012), the recent increase in the number, size, length and severity of European heatwaves should also be noted (Barriopedro *et al.*, 2011), Figure 3. There is now a considerable body of research providing climate projections of sea temperature for the UK waters and the North-West European Shelf seas (NWS) (Tinker and Howes, 2020). For instance, there is now good agreement on the sign of the temperature change on the NWS among the end-of-century climate projection. However, there is a spread in the magnitude of this warming. Most projections give a warming between 1–4°C (Tinker and Howes, 2020). Irrespective of this, based on our knowledge regarding the ecology of *Vibrio* pathogens, this increase in warming is likely to greatly extend both the potential abundance as well as risk window over which *Vibrio* infections are likely to occur in the UK and NWS area. Such generalised warming trends can also be useful when assessing potential risks from the presence of TTXs in shellfish, given the widely accepted but not yet conclusively proven links between *Vibrio* and other marine bacteria, and TTX (Turner *et al.*, 2015a, b).

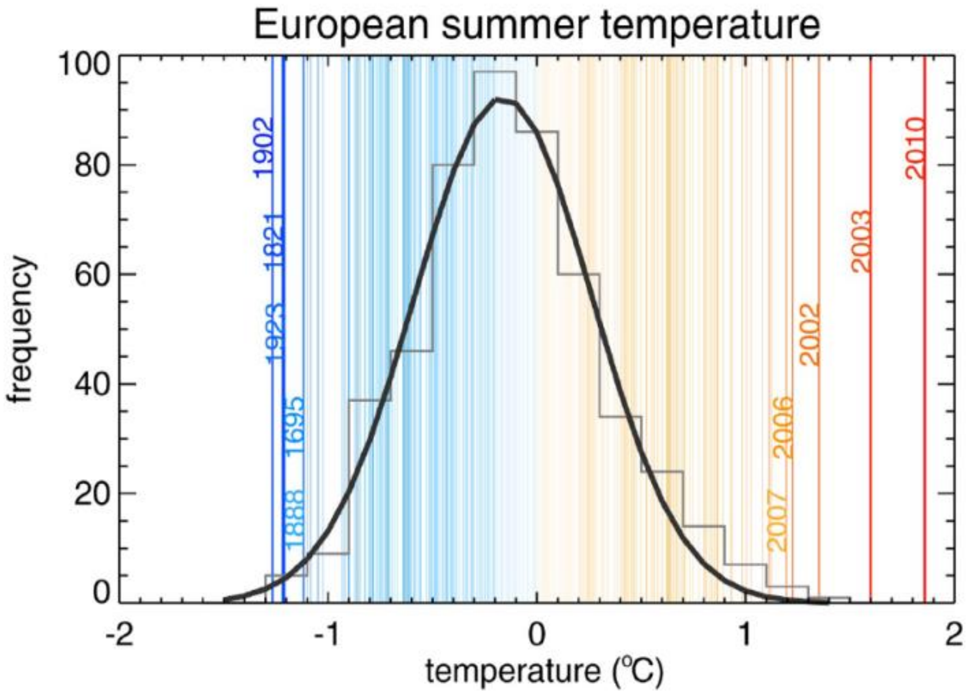


Figure 3: European summer temperatures for 1500–2010. Statistical frequency distribution of best-guess reconstructed and instrument-based European ([35°N, 70°N], [25°W, 40°E]) summer land temperature anomalies (degrees Celsius, relative to the 1970–1999 period) for the 1500–2010 period (vertical lines). The five warmest and coldest summers are highlighted. (Reproduced with kind permission from Barriopedro et al., *(2011),* Science, *10.1126/science.1201224.)*

Extreme localised warming of coastal areas has previously been associated with seafood-related outbreaks in mid- and high-latitude areas, including *V. parahaemolyticus* outbreaks in Alaska (McLaughlin *et al.*, 2005) and Northern Spain (Martinez-Urtaza *et al*., 2016). Critically, warmer summers, predicted in the UKCP18 (Lowe *et al*., 2018) are likely to greatly moderate *Vibrio* risk, especially heatwave events. For instance, using previously employed temperature thresholds to define extremely hot summers, recent studies have found that heatwave events that would occur twice a century in the early 2000s (e.g. the 2003 European heatwave event) are now currently expected to occur twice a decade. Critically, all RCPs indicate that by the 2040s a summer as hot as 2003 will be very common, and RCPs with the strongest anthropogenic influence (e.g. RCP6.0 and RCP8.5) suggest the 2003 summer will be deemed an extremely cold event by the end of the century (Christidis *et al*., 2015). Even a casual analysis of '*Vibrio* risk years' (e.g. where elevated numbers of cases are reported) across Europe indicates that the number and severity of extreme heatwave events has increased recently (e.g. 2010, 2014, 2018 – notable years with increased reports of infections linked to heatwave events). Statistical analysis using past climate warming trends also suggests a longer ‘at risk’ period, with infections likely to be reported earlier in the summer and into the autumn, correlating with an increased time period over which these bacteria can flourish in the environment (Baker-Austin *et al*., 2013). Other extreme climatic events have also been linked to an increase in reported *Vibrio* infections (e.g. extreme rainfall events reducing salinity, storm surges, etc.) (Baker-Austin *et al*., 2016a), however the potential for these events to modulate risk is difficult to ascertain. There is considerable uncertainty regarding future salinity around the UK coastline, however most of the projections over the 21st Century suggest that shelf seas and adjacent ocean will be fresher in the future than at present (Dye *et al*., 2020). A freshening of marine waters is likely to potentially increase *Vibrio* risk, however the interaction of salinity and temperature in this regard is highly uncertain.

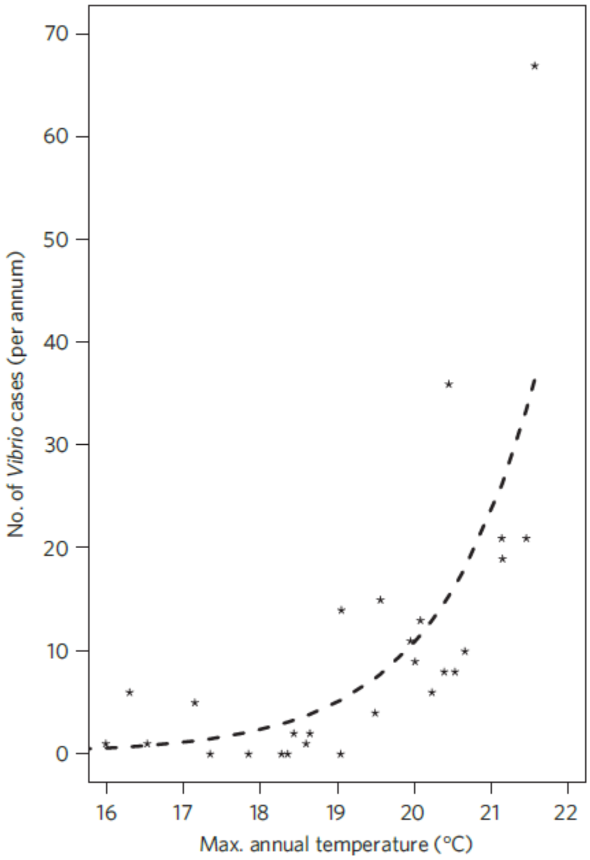
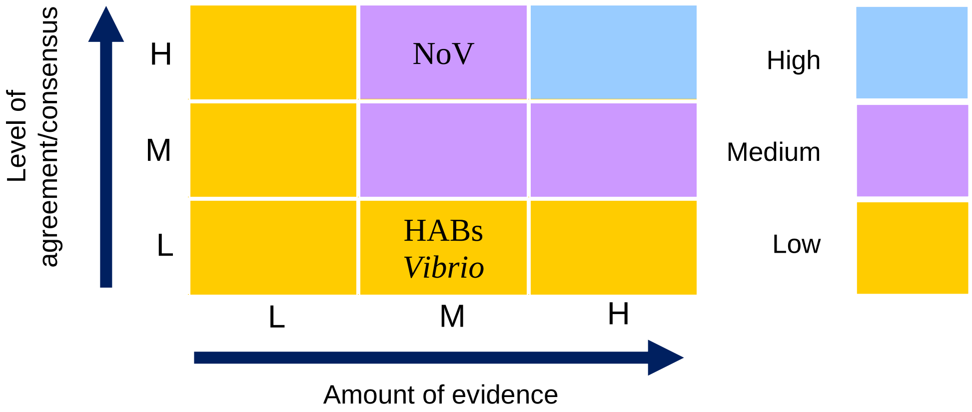


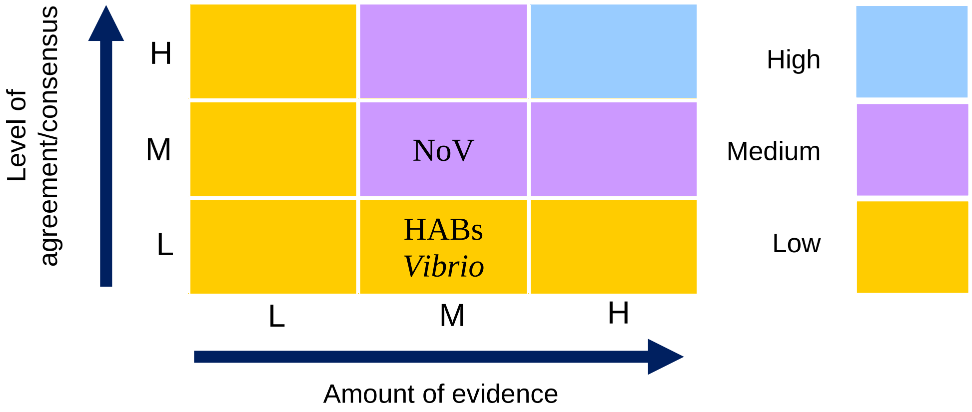
Figure 4: The relationship between Vibrio *infections reported in the Baltic Sea and maximum annual sea surface temperature (SST). Stars show observed data, dashed line shows model predictions based on the influence of SST alone. Figure courtesy of Baker-Austin* et al. *(2013a, b).*

4. CONFIDENCE ASSESSMENT

What is already happening?



What could happen in the future?



During the 2013 assessment HABs were assessed in a separate report card to Human Health. HABs, pathogenic *Vibrio* species and NoV are three different biological entities and thus their response to impacts of climate change and confidence about them should not be expected to be the same. Analysis of historical HAB data has shown evidence of change along with other members of the phytoplankton community; however confidence in predicting change remains low. As the causative organism of TTX in UK shellfish has yet to be identified, this has not been assessed here. These different confidence assessments flag the complexity of assessing the impacts of climate change on human health. Efforts to provide field-based and retrospective environmental data have greatly improved our understanding of how environmental cues modulate *Vibrio* risk. However, data gaps still exist, in particular the role of salinity in impacting these bacteria in the environment as well the lack of long-term environmental studies regarding these pathogens. In addition, although the presence of pathogenic strains in the environment has been observed, there has been a lack of clinical cases reported in the UK.

5. KEY CHALLENGES AND EMERGING ISSUES

- There is a lack of information and few methods with which to measure actual human exposure and incidence of illness from HAB-related toxins, Vibrios, NoV and TTX and studies of the societal impact coming from these harmful events are scarce. Likewise, there is a need to develop a framework for sharing of data between different stakeholders involved with these emergent risks (e.g., clinicians, scientists, microbiologists, risk assessors, etc.). Without supporting data from the medical community, it will be difficult to quantitatively project health outcomes from water-related illnesses resulting from climate change.
- Development of HAB models remains a challenge, both in the short term (one to two week forecasts) to aid industry as well a longer term projections into the future under different climate scenarios. Expanding current models to include physical, chemical and biological processes in addition to temperature will better recreate the impacts of a changing climate in UK waters. Given the regional diversity of HAB species in the UK, consideration to species level differences may also be required.
- Further research is needed on the development of wastewater treatment processes for enhanced NoV removal, and on the likelihood of human exposure to NoV in communities served by combined sewerage infrastructure versus those served by separate infrastructure. This should help better targeting of investment by water and sewerage undertakers to reduce NoV loading to bathing and shellfish waters. Improved understanding of how climatic factors affect the fate and behaviour of NoV in the marine environment can facilitate the development of predictive models for human health protection.
- The ability to predict when and where different ‘at risk’ systems are undergoing rapid warming using process-driven climate models will greatly improve our understanding of future risk (Baker-Austin *et al*., 2016a, b). In particular, models that can provide reliable data on areas undergoing warming, with sufficient granularity to ascribe risk are required, in particular using a range of different warming scenarios as well as timescales. A key data gap in this regard in the availability of salinity and temperature data at regional levels to feed into risk assessment models. There are currently uncertainties regarding modelling for salinity in many climate models. Regional model projections are important because they will enable the scientific

community to assess in greater detail over the UK how risks are modulated by climate extremes.

- The relatively recent discovery of TTX in European bivalves has demonstrated a new threat to shellfish food safety, the causes of yet which have yet to be confirmed. Studies on TTX-production mechanisms, together with the experimental assessment of shellfish uptake routes are urgently required to enable a full risk assessment of the impacts of climate change on TTX-related risks.

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