Stemming the rising tide of *Vibrio* disease

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Globally, the diverse bacterial genus *Vibrio* is the most important group of bacterial pathogens found in marine and coastal waters. These bacteria can cause an array of human infections via direct exposure to seawater or through the consumption of seafoods grown and cultivated in coastal and estuarine settings. Crucially, we appear to be on the cusp of an alarming global increase in *Vibrio* disease. A worldwide increase in seafood consumption, the globalisation of the seafood trade, the more frequent use of coastal waters for recreational activities, and climate change all contribute to greatly increased human health risks associated with *Vibrio* bacteria. Coupled with a population that is increasingly susceptible to more serious infections, we are likely to see a marked increase in both reported cases and fatalities in the near future. In this Personal View, we discuss and frame this important and emerging public health issue, and provide various contemporary case studies to illustrate how the risk profiles of pathogenic *Vibrio* bacteria have transformed in the past two decades—particularly in response to changing climatological and meteorological drivers such as marine coastal warming and extreme weather events such as heatwaves and storms. We share various approaches to help better understand and manage risks associated with these bacteria, ranging from risk mitigation strategies to enhanced epidemiological monitoring and surveillance approaches.

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Introduction

Throughout history, the spread of many pathogens and transmissible diseases have been inextricably linked with human use of water and water-derived resources. Of these, *Vibrio* bacteria are perhaps the most important and persistent worldwide, causing a wide range of human diseases from pandemic cholera to wound infections and fulminating sepsis. *Vibrio* bacteria are Gram-negative and rod-shaped and are—except for serotypes O1 and O139, the causal agents of cholera pandemics—typically natural constituents of estuarine and marine environments. Around a dozen *Vibrio* species can cause infections in humans.[1] Typically, human infections can be acquired from two direct routes: the consumption of seafood and exposure to contaminated water. From an epidemiological and microbiological context, four species represent the most important pathogens associated with this genus: non-O1 or O139 *Vibrio cholerae, Vibrio vulnificus, Vibrio parahaemolyticus,* and *Vibrio alginolyticus*.[2] These bacteria can cause sporadic but potentially severe gastrointestinal illnesses and wound infections, which can advance to severe outcomes such as necrotising fasciitis, amputation, septicaemia, and death.[1,3] Globally, although these four species disproportionately dominate human infection reports associated with non-cholera Vibrio-related diseases, a wide range of other *Vibrio* species, including *Vibrio damsela, Vibrio hollisae, Vibrio mimicus,* and *Vibrio metshnikovii*, are also implicated in human infections.[1] This Personal View focuses on the emergence of these non-O1 and non-O139 *Vibrio* (non-cholera) species, and largely omits discussion of species that cause cholera.

There are several key factors that make *Vibrio* bacteria a key global and emergent public health risk in the 21st century. Firstly, these bacteria grow in warm (>15°C) low salinity waters, with their relative abundance in the natural environment tending to track permissive environmental conditions. The majority of human pathogenic diseases have been shown to be aggravated in some way by climate change,[4] but the relative simplicity of the relationship between ambient climate warming and *Vibrio* abundance is so clear that they have been deemed a key barometer of climate change and climate-associated effects.[2] *Vibrio* bacteria can replicate very quickly,[2] and, when conducive environmental conditions persist, can proliferate to very high concentrations in both seawater and seafood—particularly filter-feeding bivalve molluscs, where they can cause a variety of human health effects including wound infections, gastroenteritis, and sepsis. Secondly, several *Vibrio* species are highly pathogenic to humans; for example, foodborne *V vulnificus* carries a case fatality rate of around 50%,[1,5] similar to biosecurity level-4 pathogens such as Ebola virus and Marburg virus.[5] Finally, *Vibrio* species are ubiquitous in the natural environment, with potentially pathogenic species present in virtually all temperate and tropical coastal and marine settings.[6] Their proliferation makes them a substantial, nascent global public health threat. Conducive climate conditions could select for such bacteria, particularly during episodes of rapid warming.[2] In this Personal View, we outline the growing importance of this group of bacteria and frame these issues, alongside presenting various case studies that outline approaches to better understand their associated risks and manage and control preventable public health, water, and food security impacts.

Environmental changes and vibriosis

Water has a much larger capacity to absorb heat than the atmosphere; thus, the heat content of the oceans has increased disproportionally because of climate warming.[3] Warming of coastal areas is considered the most pervasive and obvious effect of global warming in coastal ecosystems worldwide,[7] particularly in light of observations showing substantial and rapid warming in most of the world's coastlines.[8] From the late 1970s

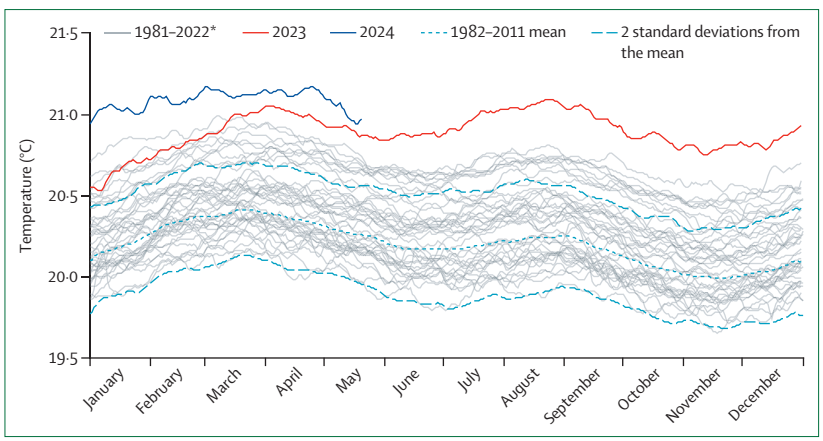

Figure 1: **Unprecedented warming of the global ocean systems**
Estimated global mean sea surface temperatures, 1981—May, 2024 based on a combination of satellite, ship, and buoy observations. The dataset spans Sept 1, 1981, to May 18, 2024, with a 1–2 day lag from the current day. Reproduced with permission from Climate Change Institute.

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onwards, global mean sea surface temperature started to rise rapidly. Over the full period, global mean sea surface temperature is estimated to have increased by close to 0·9°C and that the increase over the past four decades is around 0·6°C.[9] Data from remote sensing derived global datasets suggest a considerable and sustained warming trend, with 2023 likely to be the warmest year on record (figure 1). Marine temperate regions have been the most seriously affected; all European seas have warmed during the past few decades at four to seven times the global rate.[10] Climate change plays a substantial role in determining the dynamics of many bacterial pathogens and, for some disease agents, this is becoming better understood (eg, pandemic *V cholerae*, the causative agent of cholera).[11] Comparatively little research, however, has been directed at the role of climate change in driving the propagation and proliferation of waterborne disease agents. Many diseases are expected to increase in range and severity with projected climate changes.[12] Several studies have noted the spread of pathogenic *Vibrio* species in response to ocean warming.[13–15] In particular, non-cholera *Vibrio* species have undergone a global expansion over the past few decades reaching new areas of the world that were previously considered adverse for these organisms.[6] Several different physical manifestations of climate change have greatly modulated risks associated with pathogenic *Vibrio* bacteria. We will briefly outline some of these using various contemporary case studies and indicate in each where various mitigation and control strategies have been successfully applied.

Remote sensing-based analysis of coastal warming trends indicate that 71% of the world's coastlines are warming at a significant rate, although rates of change have been highly heterogeneous both spatially and seasonally.[8] Notable outbreaks of Vibrio-associated infections in colder and more temperate regions including Alaska (USA),[13] Canada,[16] the east coast of the USA,[17] the Baltic Sea,[18,14] and Chile,[19] and these events have corresponded with notable warming episodes. Although long-term data on the prevalence of these bacteria are scarce, compelling molecular evidence suggests these bacteria have emerged and proliferated in the past few decades in response to conducive environmental warming trends.[20,15] A 2021 study looking at projections for coastal warming showed that coastal areas suitable for *Vibrio* infections could cover 38 000 km of new coastal areas by 2100 under the most unfavourable climate warming scenarios.[6] The population at risk in suitable regions almost doubled from 1980 to 2020 (from 610 million to 1100 million under the scenario of medium challenges to mitigation and adaptation, shared socioeconomic pathway 2–4·5).[6] It is also notable that areas conducive for these bacteria will not expand uniformly. Various temperate coastal areas and marine systems, and in particular regions representative of brackish and low salinity systems are at particular risk. A recent mapping study using a global-based coastal projection and different emission scenarios suggests that the Baltic Sea, Black Sea, Eastern seaboard of Canada, and Alaska represent key hotspots of future *Vibrio* disease emergence.[6]

What is almost as troubling is that extreme weather events such as heatwaves and tropical storms have increased in both their severity and impact in the past three decades in response to climate warming. For instance, in Europe, heatwave events that would occur twice a century in the early 2000s are now expected to occur twice a decade.[21] Heatwaves have been shown to drive *Vibrio*-associated infections, with a marked increase in reported cases now the norm during the summer months. Until the mid-2000s, *Vibrio* infections reported in Europe were rare and sporadic, to the point of being sufficiently novel to be reported in various medical journals. However, in the past decade, these infections have greatly increased. During 2014–18, more than 1000 cases of vibriosis were reported in northern Europe countries,[22] with the majority reported during heatwave years. Most cases are associated with recreational exposure to seawater, indicating a clear interaction between human exposure and human behaviour driving the risk. A less obvious effect of climate change is the increase in *Vibrio*-associated infections following substantial storms and hurricanes. A large increase in reported *Vibrio*-related wound infections were noted after the landfall of Hurricane Katrina in the USA during the summer of 2005.[23] These reported infections tracked the path of this hurricane and its associated floodwaters in both time and space (figure 2). A similar increase of vibriosis (again witnessed in both time and space) was reported following the landfall of Hurricane Ian in October, 2022.[24] Hurricane Katrina remains the worst natural disaster to date in US history, yet the increase in reported *Vibrio*-associated infections, including numerous fatalities, remains a footnote to

the wider devastation of both this and other hurricane events. The proportion of category four and five hurricanes has increased at a rate of around 25–30% per degree of global warming,[25] with particularly noteworthy increases in high-strength hurricanes in the past few decades.[26] More research into the frequency of such events (both heatwaves and hurricanes) in a warming climate system and how this interplays with human health risks, such as vibriosis, are urgently needed, particularly in so-called hotspot regions where increases in infections have been reported, such as the Gulf of Mexico.

Epidemiology, demographics, and changing risk

Future *Vibrio* risk will be influenced by both environmental and demographic changes. Effects of climate change, such as rising sea surface temperatures, heatwaves, and increased heavy rainfall events, are expected to expand the conditions suitable for *Vibrio* bacteria both geographically and through time.[4,6] Continued growth of coastal populations[27] in an ageing world[28] could also increase *Vibrio* risk, increasing the likelihood of more invasive infections and the proportion of people at risk of the most severe forms of *Vibrio* disease. Although anyone can become infected by a *Vibrio* pathogen, older individuals and people with underlying health conditions are at greatest risk from the most severe forms of *Vibrio* infection.[1] Decreasing rates of fertility and mortality are driving demographic shifts globally, leading to ageing populations with an increasing life expectancy.[28] In 2021, 761 million people, approximately one in ten people globally, were older than 65 years; by 2050, the UN projects that this will more than double to 1·6 billion people, or one in six people globally.[28] Unfortunately, additional years are not necessarily lived in good health; the average number of healthy years a person can expect to live has increased at a slower rate than the overall rise in life expectancy.[29] Ageing populations typically also have higher rates of chronic conditions[30] that can increase the health risk of a *Vibrio* infection, in particular infections that can proceed to systemic infections such as *V vulnificus*. A good example of this amplified risk profile can be seen by the increasing cases of the opportunistic pathogen *V vulnificus*. Most *V vulnificus* infections occur in older (45–60 years old) males and liver cirrhosis is a key risk factor.[31] Data from the US Centers for Disease Control and Prevention (CDC) suggest that after eating raw oysters, people with liver disease are 80 times more likely to become ill with a *V vulnificus* infection and 200 times more likely to die from this infection than people without liver disease.[32] WHO estimates that viral hepatitis B and C, a predominant cause of liver disease, affects 354 million people globally,[33] and is probably increasing in prevalence. In the USA, 4·5 million people have been diagnosed with chronic liver disease, representing 1·8% of US adults.[34] Given current trends in alcohol consumption in the USA, decompensated alcohol-associated cirrhosis is predicted to increase by 77% from 9·9 cases per 100 000 person-years in 2019 to 17·5 cases per 100 000 person-years in 2040.[35] *V vulnificus* infections have increased substantially over the past two decades in the USA,[36] but the factors associated with this increase remain elusive. Taken together, this increasing demographic of at-risk individuals with underlying conditions is likely to greatly increase future incidence of infections associated with these pathogens.

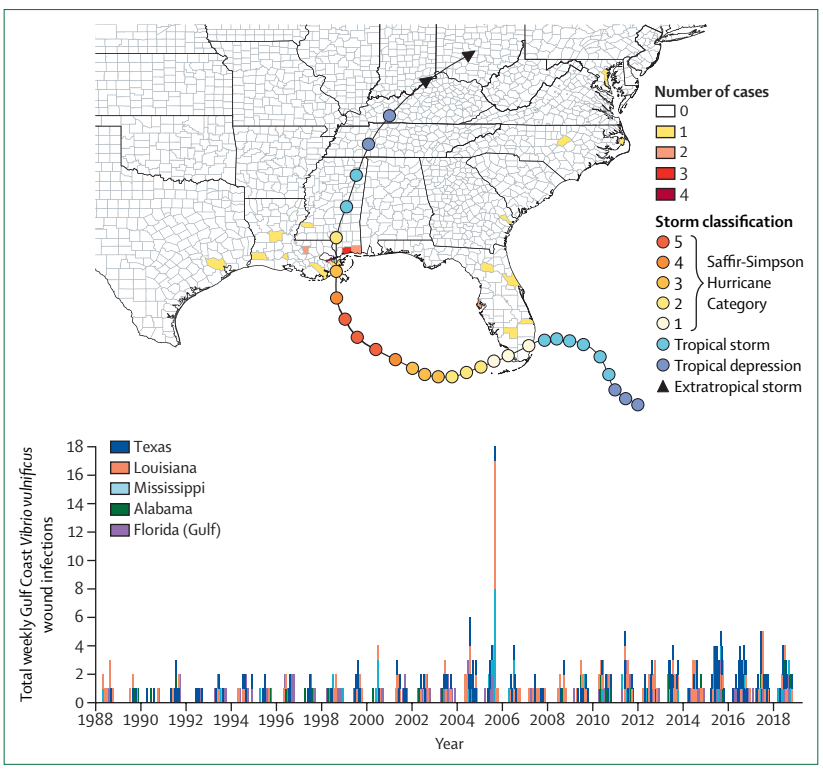

Figure 2: **Extreme storm events**
Storm track of Hurricane Katrina, August 2005, with associated county-level reports of *Vibrio vulnificus* wound infections. Total weekly *V vulnificus* wound infection case numbers for the Gulf Coast States (stacked). Only infections reported within 200 km of the coast are included. Adapted from data in Archer et al (2023).[36]

Globally, coastal populations are growing faster than those inland[37]—a trend that is expected to continue with the ongoing urbanisation of coastal regions.[27] Furthermore, people spend more time when it is warmer, suggesting that climate warming could boost interaction with near-shore waters during times when temperatures are more favourable for *Vibrio* growth. Wild swimming in open water, including the sea, has increased in popularity in the past decade, particularly since the COVID-19 pandemic, thanks to the associated mental and physical health benefits.[38,39] Nonetheless, swimming in coastal waters that are suitable for *Vibrio* bacterial growth increases a person's risk of infection and greater awareness of *Vibrio* among wild swimmers is needed.

Vibrio bacteria and seafood: a global issue

Disease risks associated with *Vibrio* bacteria are likely to be affected by changing and increasing patterns of seafood consumption at the regional, national, and global level. Although global food demand is rising, expansion of land-based production is limited by the decreasing availability of new productive land, degradation of existing agricultural areas, and food safety and sustainability concerns.[40] Seafood is nutritionally diverse and avoids or lessens many of the environmental burdens of terrestrial food production, and as such is uniquely positioned to contribute to both food provision and future global food and nutrition security.[41] Seafood consumption has increased globally since the 1960s due to factors such as population growth, increasing disposable incomes, and changing dietary preferences. Global consumption of aquatic foods (excluding algae) has increased at an average annual rate of 3% since 1961, compared with a population growth rate of 1·6%.[42] The Food and Agriculture Organisation's *State of the Worlds Fisheries and Aquaculture* report identifies the so-called blue transformation needed to achieve the sustainable, inclusive, and efficient supply of aquatic foodstuffs to meet increased demand.[42] It is anticipated that globally aquaculture will supply the majority of aquatic dietary protein by 2050,[43] prescribing the need for further sustainable growth of the sector to achieve global food security. In 2020, 17·7 million tonnes of bivalve shellfish—the seafood species most frequently associated with *Vibrio* bacteria —were produced with a first sale value of US$29·8 billion.[42] Aquaculture of bivalve shellfish is predicted to increase globally in the coming decades,[41] particularly in low-income and middle-income countries due to the low infrastructural start-up costs of production and global ubiquity of commercial seafood species. Seafoods are one of the most readily traded food commodities in the world, and although bivalves currently account for less than 3% of global trade, this sector is set to expand. International microbiological standards for live and raw bivalve molluscs does not include *Vibrio* bacteria;[43] consequently, many countries and trading blocs have yet to include regulatory controls for domestic or internationally traded products.[42] Increased trade in seafoods, especially bivalve molluscs, compounds the potential risks of seafood-mediated *Vibrio* infections.[40]

See Online for appendix

Living in a *Vibrio* world

Although the factors already outlined here (including various climatic, demographic, clinical and seafood-associated issues) paint a concerning future regarding these risks, there are causes for optimism. Numerous approaches have been developed in the past two decades that provide a useful blueprint to help manage risks associated with *Vibrio* bacteria. Many of the risks associated with non-cholera *Vibrio* are driven by favourable environmental conditions (warm, low salinity waters, rapid heating of temperate coastal areas, etc). For instance, various remote sensing-based approaches have been developed that can be used to predict when and where *Vibrio* infections are likely to occur, typically using temperature and salinity datasets. The European Centre for Disease Prevention and Control (ECDC) developed a platform (the ECDC *Vibrio* map viewer) to monitor the environmental suitability of coastal waters for *Vibrio* spp using remotely sensed sea surface temperatures and salinity.[44] Such approaches can be implemented quickly, effectively, and with little cost. We have used this approach regularly during the summer months, and the risk modelling corresponds closely with reported infections in Northern Europe (appendix p 1). Such platforms have global coverage, predictive functions (eg, 7-day forecasting), and can serve as an early warning system for *Vibrio* infection increase in a warming environment. Practical interventions such as the rapid cooling of shellfish and post-harvest processing of live bivalve shellfish have been shown to be extremely effective in reducing (and, in many instances, eliminating) *Vibrio*-associated health risks such as *V vulnificus* and *V parahaemolyticus*.[46]

Another good starting point is to look at areas with longstanding experience in managing vibriosis. In the USA, *Vibrio* infections have been prevalent, particularly in the Gulf of Mexico, for several decades. The US CDC established a dedicated framework for surveillance and monitoring called the Cholera and Other *Vibrio* Information System (COVIS) in 1988. COVIS provides reliable temporally and spatially relevant information regarding illnesses associated with *Vibrio* species.[45] Participating health officials collect clinical data from for all laboratory-confirmed *Vibrio* infections, including relevant clinical and exposure information, such as detailed seafood traceback information and exposure to seawater during the 7 days before the onset of symptoms. The information generated by COVIS is used to determine pertinent epidemiological information, such as routes of transmission, food, geographical, and environmental risk factors. By the early 2000s, nearly all states in the USA were voluntarily reporting case information to the Centers for Disease Control and Prevention and in 2007, all laboratory-confirmed *Vibrio* infections became nationally notifiable.

Surveillance systems such as COVIS represent an exemplar and clear framework for how other nations could develop monitoring and epidemiological data gathering for *Vibrio* pathogens. For instance, analysis of the COVIS datasets have shown effectively how particular risks have changed in the USA; the spread of *V vulnificus* infections and an increase in wound infections now predominate,[36] changes in reported species have altered over time,[45] and mandated interventions to reduce public health risks, such as those from shellfish, have been implemented.[46] Where there are notable increases in infections, these can be quickly and efficiently articulated to various stakeholders such as public health practitioners, clinicians, and public health

laboratories. The CDC health alert regarding the spread of *V vulnificus* wound infections along the eastern seaboard of the USA (August, 2023) is an excellent example of how these data can be used quickly and judiciously.[47] The availability of good-quality epidemiological data that can be shared both nationally and internationally and the sharing of such datasets are crucial for a more cohesive understanding of these emergent risks. Such approaches are a useful blueprint, particularly in global countries and regions where the gathering of such data is fragmentary and not overseen by a legal framework for capturing reported infections. In countries with a longstanding history of vibriosis (eg, USA, Japan, China), improvements in clinical diagnosis and outreach are particularly important at reducing risks.[48] Finally, improvements in the isolation, identification, and characterisation of strains that cause human infections have improved immeasurably in the past decade. In particular, the unparalleled resolution of whole genome sequencing methods has enormous practical applications such as inferring mechanisms of transmission, unravelling the evolution of strains, and pinpointing outbreaks for risk management purposes.[49]

Conclusion and future directions

Various factors point to an alarming global increase in *Vibrio* diseases, particularly those caused by non-cholera *Vibrio* bacteria. Climate change and the rapid warming of coastal regions, coupled with extreme weather events such as heatwaves, marine heatwaves, and hurricanes, will undoubtedly provide the environmental ignition for an increase in risk exposure to these environmentally ubiquitous pathogens. Demographic and behavioural factors as well as the recent and ongoing increase in global seafood consumption, the globalisation of seafood trade, the more frequent use of coastal waters for recreational activities, and an increasingly susceptible population to more serious infections will greatly increase the risk of both contracting vibriosis and its effect on human health. *Vibrio* diseases also represent some of the most costly bacterial infections to treat, and studies suggest that the economic and clinical costs are likely to increase substantially in the future.[50] What can be done? Many of the available tools and mitigation strategies that currently exist have been embedded in countries with longstanding issues with *Vibrio* bacteria. However, greater international collaboration is clearly required to help develop effective transnational management of these pathogens. Where hotspots of these bacteria are emerging (eg, the Baltic Sea) transdisciplinary and cross-sectorial collaborations are required to mitigate these emerging risks. An international framework for data sharing—including epidemiological, clinical, and environmental datasets—led by an overarching international entity such as a reference laboratory or central network for *Vibrio* pathogens is now urgently required. An agreed and defined case definition regarding vibriosis is required and, perhaps more importantly, a legal framework to gather epidemiological data, such as that adopted in the USA, is now crucial in many regions. If *Vibrio* infections became reportable, trends over time could be monitored, outbreaks better detected, and prevention and control programmes could be fully evaluated. This global effort would enhance the understanding and analysis of factors that contribute to the emergence, maintenance, and spread of *Vibrio* diseases, provide assistance and technical input into preventing the transboundary spread of infections, and guide international policies to reduce health effects associated with these bacteria.

Contributors

CB-A, RH, and JM-U: conceptualisation of the article, writing original draft, writing various drafts and data visualisation. IL and EA: writing original draft and data visualisation. JT: data visualisation and re-editing of figures.

Declaration of interests

We declare no competing interests.

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