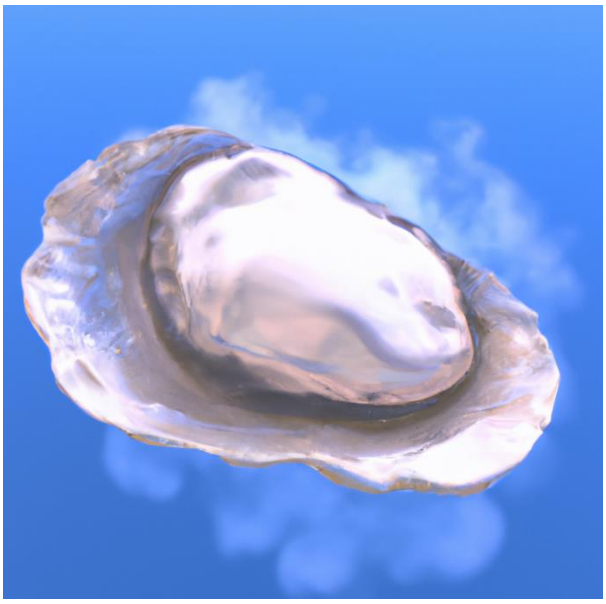
Tool kit 7. Climate Change, Anthropogenic activity, Micro-organisms and Oysters

Introduction



This report examines aspects of climate change, anthropogenic activities and their impacts on microbiological life and disease in oysters. Aquaculture and fisheries rely on the coastal environment and habitats that which are exposed to the affects of climate change. There is much media attention on global warming, focusing on our heating atmosphere and seas leading to extreme weather events, decreasing ice cover and rising sea levels. These environmental changes also alter the marine environment's fundamentals (physicochemical properties) and can lead to a less predictable or more chaotic natural environment where biological interactions are less certain and potentially profoundly affect our world. To better understand climate change, there is a need to improve our in situ monitoring of changes and, by doing so, develop better climate models and undertake appropriate management strategies for adaptation. While at the same time also mitigating our activities to reduce further global warming.

The STREAM initiative has secured funding amounting to €4.3 million over five years. This funding has been awarded by the European Regional Development Fund (ERDF) under the Ireland Wales 2014-2020 programme. The primary focus of this funding is on Priority 2, which involves adapting communities along the Irish Sea and its coastlines to the challenges posed by climate change. Guided and supported by the Welsh European Funding Office (WEFO) and the Southern Regional Assembly, the STREAM project is committed to evaluating the effects of climate change and gathering crucial data to safeguard the integrity of our coastal environments. Going beyond this, STREAM has developed some of its own specialised sensors and leveraged the capabilities of commercial water quality sensors. These sensors are strategically placed across nine different sites spanning the spanning the funded region within Ireland and Wales. In a concerted effort to comprehensively understand environmental shifts within the Irish Sea, the project has strategically deployed weather stations. These stations have provided essential temperature, wind patterns, and rainfall data. This collective dataset dramatically contributes to a thorough assessment of the evolving environment in the Irish Sea region. One of the noteworthy achievements of the STREAM project is the establishment of an innovative online portal. This portal has been designed to ensure easy and widespread access to the extensive data that has been amassed. Through this user-friendly platform, the STREAM team actively engages with various stakeholders, including coastal communities, researchers, governmental bodies, and other interested parties. The team effectively communicates and elucidates the significance of the environmental data that has been collected.

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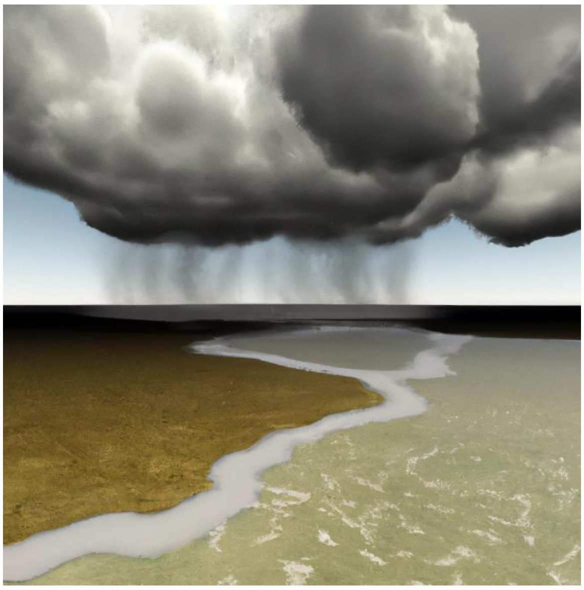
Through these collaborative endeavours, the STREAM project is dedicated to enhancing the adaptation and mitigation capabilities of both Ireland and Wales in the face of the complex challenges posed by climate change.



In 2012 (Callaway et al., 2012) found sparse evidence at the time to indicate that climate change is affecting aquaculture in the UK and Ireland. However in that paper they ouline a number of factors that could such as frequency and strength of storms, sea level rise and shifting of shoreline morphology. Rainfall pattern changes that increase turbidity, nutrient loads and trigger harmful algal blooms. However, some of the most significant effects of climate change may “relate to the emergence, translocation and virulence of disease, parasites and pathogens” along with the spread of nuisance and non-native species (Callaway et al., 2012).

According to the Intergovernmental Panel on Climate Change (IPCC 2021), global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (high confidence). This heating of the climate system has caused the global mean sea level to rise due to ice loss on land and thermal expansion from ocean warming. The IPCC report shows that emissions of greenhouse gases from human activities are responsible for approximately 1.1°C of warming since the period 1850 to 1900, and forecast that averaged over the next 20 years, global temperature is expected to reach or exceed 1.5°C of warming. However, it is essential to point out that substantial and sustained reductions in carbon dioxide emissions (CO_2) and other greenhouse gases would limit our climate change impact (IPCC 2020).

The Long Term Average period 1961 to 1990 (LTA 1961-1990) or ‘normal’ period is the WMO’s fixed reference period used for climate change and variability studies.The figure below shows the Irish air temperature anomalies from 1900 to 2021. The anomaly is the difference between the mean annual temperature and the mean annual LTA of 9.55 °C between 1961 and 1990. As can be seen, mean temperatures have varied considerably yearly. Warming periods occurred from the 1930s and 1940s and from the late 1980s to the present. Warming periods have been more extended and frequent since the end of the 20th century (https://www.met.ie/climate/what-we-measure/temperature).

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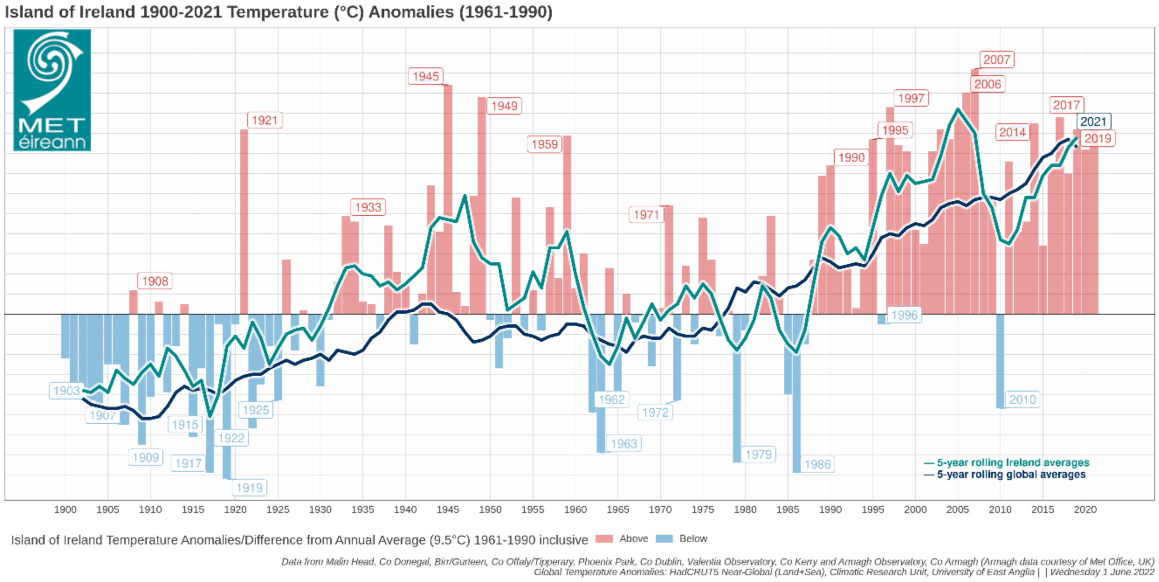
Figure 1. Island of Ireland 1900-2021 Temperature °C Anomalies (1961 to 1990) Met Eireann.



Representative Concentration Pathways (RCPs) are greenhouse gas (GHG) concentrations employed by the Intergovernmental Panel on Climate Change (AR5 Climate Change 2013: The Physical Science Basis) as a set of scenarios for the standardisation (intercomparison) of climate modelling and research. They are time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. Forthcoming mid-century climate change impacts for Ireland have been assessed using high-resolution modelling approaches based on medium-to-low (RCP 4.5) and high emission global warming scenarios (RCP 8.5). For Ireland, these projections forecast an increase of 1-1.2 C and 1.3-1.6°C in mean annual temperatures, respectively, with the most significant increases predicted for the country's east (Nolan & Flanagan, 2020). Nolan and Flanagen (2020) project substantial decreases in precipitation are for the summer months, with reductions ranging from ≈0% to 11% for the RCP4.5 scenario and from 2% to 17% for the RCP8.5 scenarios. However, they forecast more significant variability in mid-century precipitation with substantial projected increases in dry periods and heavy precipitation events. At the same time, mean 10-m wind speeds mid-century are projected to decrease for all seasons. Unfortunately

Cheng et al., 2022, examined a wide range of temperature observations held in the World Ocean Database (WOD) and found that the world oceans, in 2021, was the hottest ever recorded by humans. They report this long-term ocean warming is more significant in the Atlantic and Southern Oceans than in other regions. The North Atlantic Ocean warming trend was found throughout the instrumental records, with an escalating trend commencing in 2000. The most intense warming occurs in the Gulf Stream region. They also note that a "key feature of the North Atlantic Ocean is a cooling region south of Greenland (the so-called "warming hole")", which they ascribe to a slowdown of the Atlantic meridional overturning circulation described in other studies.

STREAM is an acronym for Sensor Technologies for Remote Aquatic Monitoring. It is an Interreg Ireland/ Wales funded project and a collaboration between the South East Technological University (SETU), Munster Technological University (MTU) and Swansea University (SU) which comprises the Weslsh Centre for Printing and Coating (WCPC) and the Centre for Substainable Aquatic Research (CSAR). The work STREAM is doing involves the use of commercial water quality sensors to monitor

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coastal and transitional waters. STREAM also is using weather stations to record climate - temperature, wind and rainfall. It has also worked on the development of novel sensors along with the study of the impact of change on selected species of fish and the modelling (the use of computers to simulate and study complex systems). The collection of data and information from which assessments of change can be undertaken and provide a valuable resource for planning and managing subsequent change.

Ireland's coastline is deeply indented; its length, including estuaries, is estimated to 5,630 km. These areas are recognised to be significant receiving waters as "80 per cent of the estimated waste loads from urban sewage and from industry enter tidal waters". Ireland's ten largest cities and towns are adjacent to estuaries or the coast (https://www.eea.europa.eu/publications/92-9167-001-4/page012.html). The discharge of wastewater around our coast also have significant environmental effects. These inputs into water bodies are also relevant to this report as discharges of nutrients and pathogens can directly impact aquaculture and coastal fishery activities. In 2020 the Environmental Protection Agency (EPA, 2020) showed a considerable improvement in urban wastewater treatment in aggregations of over 500 persons. However, the EPA 2020 also tabulated 35 areas around Ireland that released untreated wastewater (raw sewage) into the environment at the end of 2019. The percentage of unpolluted river water decreased from 77.3% in 1987-1990 to 66.2% in 2016-2018 (EPA, 2020).

Poloczanska et al., 2013 examined studies of the impact of climate change on marine organisms and observed that the general trends in marine species responses to climate change are consistent with "expectations". Including species shifts in distribution to higher latitudes and deeper locations. For example, on average, marine organisms have expanded the edges of their distributions by 72.0 ± 13.5 km per decade (typically polewards). At the same time, marine phenology adjustments in spring have advanced by 4.4 ± 1.1 days decade (Poloczanska et al., 2013). There has also been decreasing marine calcification resulting from anthropogenic CO_2 uptake by the oceans. Poloczanska et al., 2016 also noted and highlighted that most studies related to marine climate change impacts looked at changing temperature, with fewer investigations into the effects of varying oxygen levels, wave impact, precipitation (coastal waters), or ocean acidification.

The average monthly sea temperature recorded at Malin Head compared with the thirty year average for 1961 to 1990 is shown in Figure 2 (https://www.met.ie/climate/average-monthly-sea-temperature-at-malin-head/). As can be seen, there is a significant and uniform increase in the average monthly seawater temperatures throughout the year.

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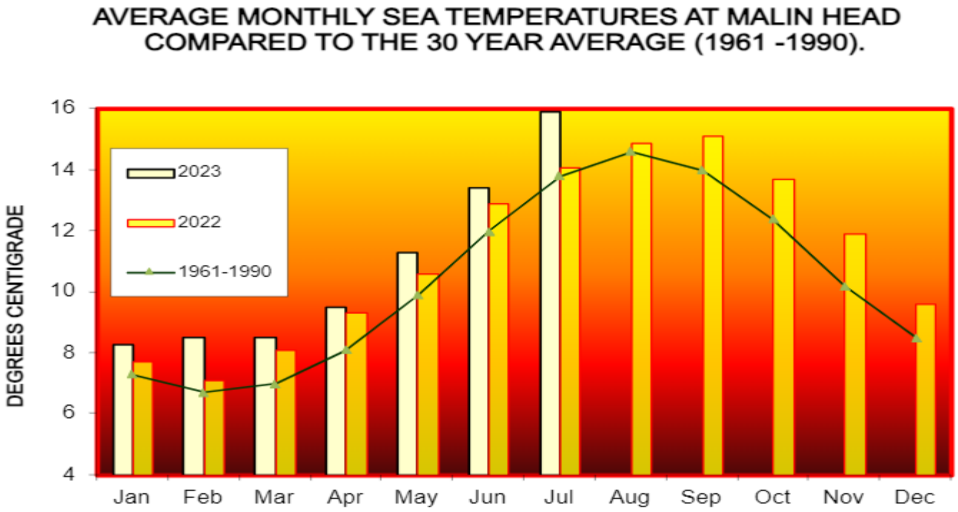
Figure 2 Average Monthly Seawater Temperature at Malin Head compared to the 30 year average (1961-1990) Met Eireann.



Disclaimer: the above figure for 2023 are provisional and may be subject to change after quality control and before official Met Eireann release.

To assess and plan for environmental changes it nessary to establish structured monitoring programmes such as the Water Framework Directive (WFD). Frequently sampled or monitored parameters for seawater quality under the WFD include temperature, conductivity/ salinity, dissolved oxygen, pH, turbidity and total algae. Other common measurements may also include ammonia, nitrate, BOD and TOC. However, the location, depth and time at which a sample is taken must also be recorded, as there may be significant discrepancies in the findings temporally, spatially and geographically. Another important consideration is the method used to measure a sample, whether it is where a water sample is taken to a laboratory for analysis or assessed electronically in situ.

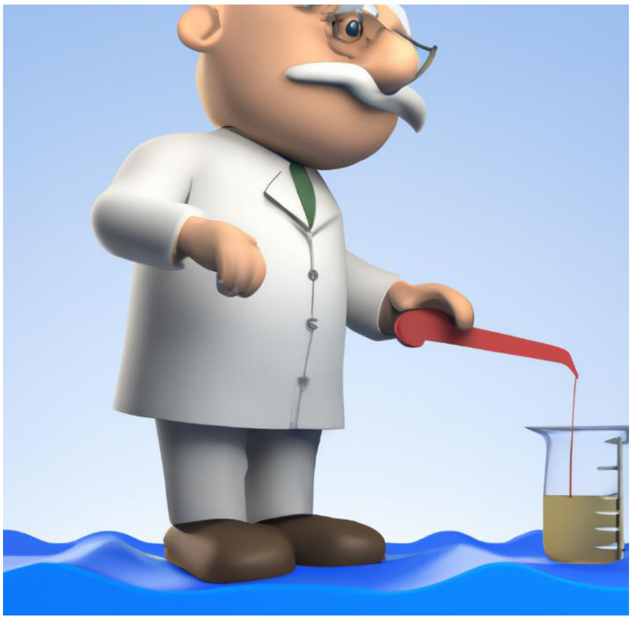
Fisheries and Aquaculture

Seafood consumption is recommended as part of a balanced diet due to its nutritional and health benefits. Consumption is growing, and demand increases with the world's population and improvements in living standards. However, there has been a continued decline based on the FAO's long-term monitoring of assessed marine fish stocks (FAO 2020). In 2018 global capture fisheries reached 96.4 million tonnes while world aquaculture fish production reached 82.1 million tonnes (FAO, 2018). The Food and Agriculture Organisation (FAO) reports that climate change threatens our ability to ensure global food security, eradicate poverty, and achieve sustainable development (FAO, 2018). There are also concerns that diseases may limit future food supply from the global crustacean fishery and aquaculture sectors (Stentiford et al., 2012).

There is also a concern that as our oceans and climate are inextricably linked even subtle changes in the marine ecosystem, such as increased temperature and lower pH, could significantly affect our fisheries, aquaculture, economy, and coastal environment (Barange et al., 2018). To improve our understanding of any change, we must refine our ability in measuring them, develop how we interpret the information and act on that data appropriately.

Irish Aquaculture Production is export-driven and marine-based (BIM 2022). The total production volume of fish and shellfish has varied from around 30,000 to 50,000 tonnes in the last decade or so as harvests of salmon and bottom grown mussels have fluctuated. The Pacific oyster, *C. gigas*, is produced in many bays around Ireland, and this farming is important economically and provides many jobs in rural areas. In 2021, a *C. gigas* crop of 10,624 tonnes was valued at approximately €47.55 million (BIM National Seafood Survey Aquaculture Report 2022, Irish Sea Fisheries Board). *C. gigas* accounted for approximately 20% of the overall Irelands aquaculture output in that year. Their primary cultivation method is bag and trestle cultivation in intertidal areas. Periodically around Ireland and other countries, increased *C. gigas* mortalities have been recorded. Some of the critical factors associated with these events include the age of oysters, pathogens, the oyster's condition, temperature, and other environmental issues (Peeler et al., 2012) and will be explored in this report.

Quality of shellfish waters



Directive 2006/113/EC establishes mandatory quality criteria for shellfish waters within European Union (EU) member countries. Its purpose is to protect shellfish from the harmful effects of sea pollution. The directive applies to coastal and brackish waters that need protection or improvement to support shellfish development and ensure high-quality products for human consumption. EU member states are responsible for designating these shellfish waters, with potential adjustments based on unforeseen factors. The directive sets parameters such as pH, temperature, colouration, suspended solids, salinity, dissolved oxygen, and the presence/concentration of specific substances. Member states can establish compliance values that are stricter than directive limits. The sampling frequency is defined in the document, and dispensations from compliance may be granted in cases of disasters or exceptional water quality. If non-compliance occurs, appropriate measures must be taken without increasing pollution. The directive replaced an earlier version, and its relevant aspects were integrated into the Water Framework Directive in 2013.

In order to ensure compliance with directive criteria, authorities in every EU country are required to sample their waters. These samples must align with established values, as outlined below:

• 100 % of the samples for the parameters 'organohalogenated substances' and 'metals';
• 95 % of the samples for the parameters 'salinity' and 'dissolved oxygen';
• 75 % of the samples for the other parameters.

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The STREAM project is developing sensors and monitoring for changes in water and weather to better assess the impacts of annual variability and climate change. When assessing water quality, different parameters such as chemical, physical, and biological properties can be tested to evaluate the status of a water body. The STREAM project investigates water temperature, dissolved oxygen, salinity (conductivity), pH, turbidity, chlorophyll, biotoxins, and nutrients.

The parameters STREAM is measuring include:

Temperature (^{O}C): is a critical factor that affects biological life as it impacts lifecycle and growth. Warmer waters also contain less dissolved oxygen than cool water, which can affect the survival and distribution of aquatic organisms. The water temperature regulates the rates of biological and chemical reactions, making some compounds may be more toxic at higher temperatures.

Dissolved oxygen (%): Marine plants, such as the microscopic phytoplankton and seaweeds, convert carbon dioxide into sugars and oxygen by photosynthesis. They produce over half of the oxygen in our atmosphere. While marine animals require dissolved oxygen through diffusion into their body tissue or gills.

Salinity (PSU): The salt concentration in seawater is measured in Practical Salinity Units (PSU). Around Ireland, in offshore waters, the salinity may reach levels approaching 35 PSU. In contrast, in estuaries, the levels may reduce to close to zero when there is a lot of freshwater inputs. The salinity affects the distribution of many plants and animals.

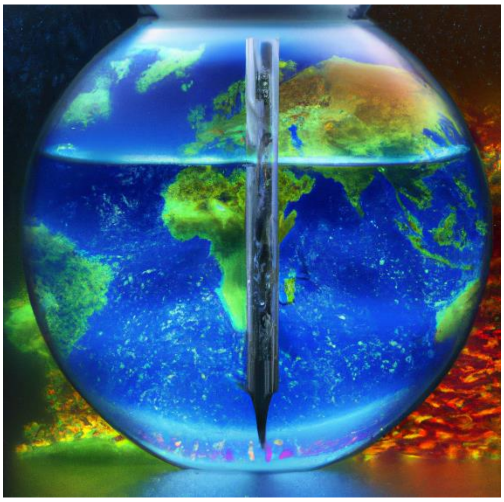
pH (0 to 14 scale): This measures how acid or alkaline the seawater is in coastal waters such as an estuary. This is strongly influenced by the area's geology, the river's source flows and biological activity.

Turbidity (NTU): Measures how clear or cloudy the seawater is. The clarity is affected by the amount of sediment silt particles and tiny marine organisms in the water column.

Chlorophyll (µg/L): Seawater contains microscopic organisms called phytoplankton and fragments of aquatic plants that use pigments such as chlorophyll-a to convert carbon dioxide into sugars and oxygen. By measuring chlorophyll, we can estimate these plants' biomass (amount), which tend to vary seasonally and follow nutrient levels in the water.

Nutrients – A vital property of seawater is the concentration of dissolved nutrients as they significantly influence the health of a waterbody and stimulate primary production by phytoplankton. The concentration of nutrients is measured by optical cells and a spectrophotometer tuned to defined wavelengths for nitrogen and phosphorous compounds.

See: https://www.marinestream.eu/tool-kit-monitoring-for-monitoring-for-coastal-and-marine-water-quality-physiochemical-parameters/



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A variety of other parameters that STREAM commercial water quality sensors are are shown in Table 1.

Table 1.Water Quality Parameters and the units they are measuring.

• fDOM_RFU: Fluorescent Dissolved Organic Matter that has been measured in Relative Fluorescent Units.
• fDOM_QSU: Fluorescent Dissolved Organic Matter that has been measured in Quinine Sulphate Units.
• Chlorophyll_ugl: Chlorophyll measured in micrograms per litre.
• Chlorophyll_RFU: Relative Fluorescent Units.
• BGAPE_ugl: Blue-Green Algae Phyco Erythrin (photosynthetic pigment associated with Marine Phytoplankton) measured in micrograms per litre.
• BGAPE_RFU: Blue-Green Algae Phyco Erythrin measured in Relative Fluorescent Units.
• NNO_3_mgl: Complete Nitrogen – Nitrate in milligrams per litre.
• NNO_2_mgl: Complete Nitrogen – Nitrite in milligrams per litre.
• TSSQeq: Total Suspended Solids as an equivalent. Parameters with the eq prefix are associated with the TriOS OPUS spectrometer, the company has developed a library of absorption spectra associated with the parameter.
• SAC254_lm: Spectral Absorption Coefficient at 254 nano metres, measures the dissolved organic material that absorbs UV light at a wavelength of 254 nm. It is usually used to monitor diffuse and point source pollution in water bodies.
• Abs360_AU: Light absorption at 360 nm measured in Absorbance Units.*
• ABS210_AU: Light absorption at 210 nm measured in Absorbance Units.*
• ABS254_AU: Light absorption at 254 nm measured in Absorbance Units.*
• NO3_mgl: measures the Nitrate in the water in milligrams per litre.

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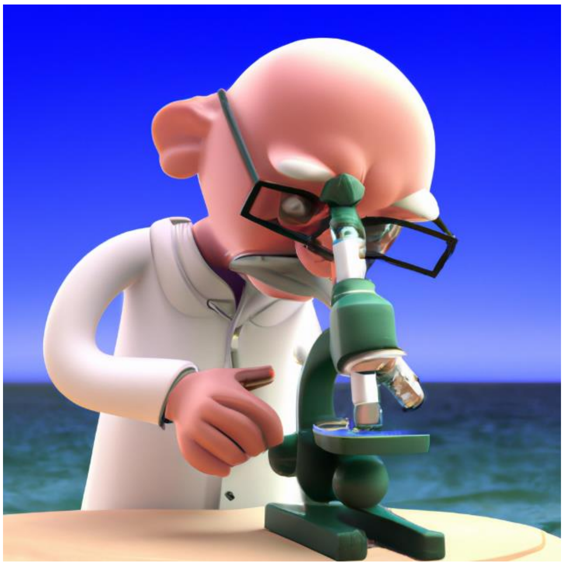
Climate change and micro-organisms.



Climate change impacts warm the oceans, alters precipitation and salinity, changes seawater density, impacts circulation patterns. In addition, there is acidification of the seas, changed nutrient inputs and reduced oxygen levels. Micro-organisms (viruses, bacteria and pathogens) have a dominant role in global biogeochemical cycles, and they are highly dependent on their environment. Marine microbial communities change and adapt to environmental conditions and respond with "biogeographic range shifts, community structure modifications, and adaptive evolution" (Abirami et al., 2021). Temperature changes alone can affect these microbial community structures (Prog et al., 1983). It is also thought that the other environmental stressors mentioned may also interact with the health of organisms such as oysters, but not necessarily in fully additive or synergistic implications for disease (Reid et al., 2019). The seas around Ireland have warmed 0.3 to 0.4 °C per decade since the 1980s, and the most significant increase was the Irish Sea of 0.6 to 0.7 °C per decade (Dunne et al., 2008).

An example of a bacterial genus that impacts coastal regions are Vibrio. They are heterotrophic, are part of the marine ecology, and environmental cues are known to regulate their growth and distribution (Percival & Williams, 2013). This report focuses on Vibrio bacteria because certain species/strains can become pathogenic to shellfish under specific conditions (Bruto et al., 2016), and others have human health implications. Vibrio bacterial abundance is mainly associated with water temperature and salinity (Asplund, 2013). These bacteria are found in coastal waters where salinities are lower, and higher numbers often occur between May and October in the Northern Hemisphere when seawater temperatures are warm (Petton et al., 2021). Vezzulli et al., 2016 provided a chart (Figure) showing the calculated surface seawater temperature changes (red increased and blue decreased) in the North Atlantic between 1890-1958 and 2000-2011. They also examined bacterial levels in formalin preserved samples collected by Continuous Plankton Recorder surveys between 1958 to 2011 at various sites (marked as black dots and shown in Figure 3) to assess changes in the microbial population.

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Figure 3. Changes in the North Atlantic Sea Surface Temperature (SST °C) between 2000-2011 and 1890-1958. The red/orange/yellow colours show warming, green stability, and blue cooling. The areas sampled for Vibrio bacteria are depicted by black dots (Vezzulli et al., 2016)**.**

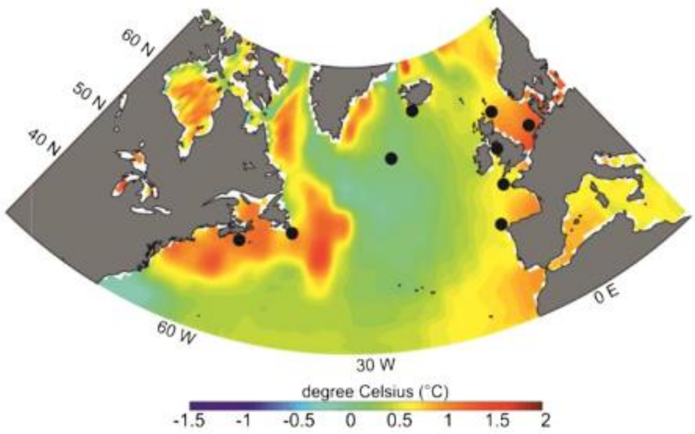
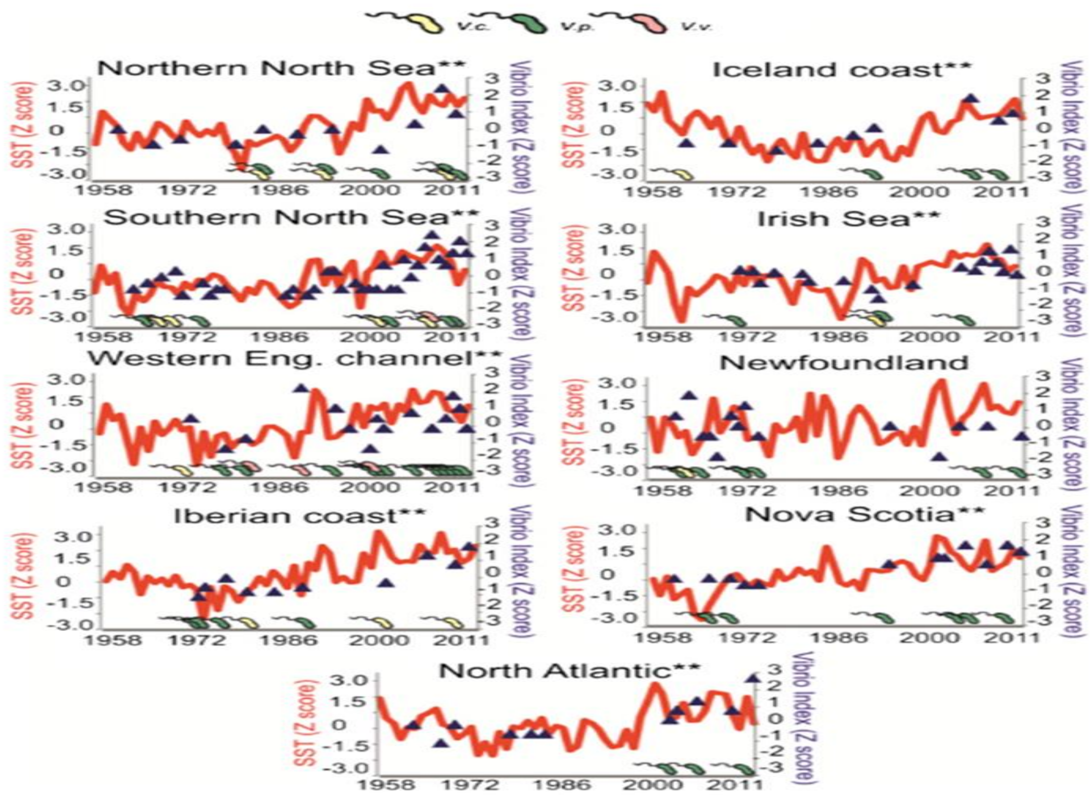


Figure 2. The relationship (1958 to 2011) between Vibrio bacterial abundance (blue triangles) and surface sea temperatures (red line) in the North Atlantic (Vezzulli et al., 2016). At the sites where temperature increases were recorded, there has typically been an increase in Vibrio abundance.

Figure 2. The relationship (1958 to 2011) between Vibrio bacterial abundance (blue triangles) and surface sea temperatures (red line) in the North Atlantic (Vezzulli et al., 2016)**.**



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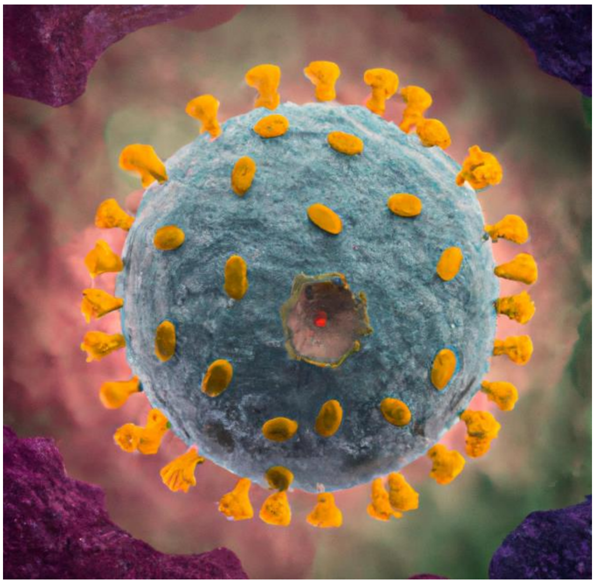
Oysters mortalities

Different species of oysters have been cultured around Europe and over the years become adversely affected by disease. Documented oyster farming in Europe began in the seventeenth century with the indigenous species *Ostrea edulis* (Buestel et al., 2009). But there were significant declines in its stocks in the nineteenth century due to overfishing, infection by *Marteilia refringens* and *Bonamia ostreae*. In the 1920s, the Portuguese oyster *Crassostrea angulata* was introduced into France to boost oyster production, but this species perished because of iridovirus around 1970. Consequently, the Pacific oyster *Crassostrea gigas* was brought to Europe in the 1960s and 1970s (as cited in Buestel et al., 2009).

Globally, *C. gigas* populations have experienced significant mortality, and the seriousness of these events has increased dramatically since 2008 (Petton et al., 2021a). These cases have been referred to as Pacific oyster mortality syndrome (POMS). The combination of environmental and host factors "(e.g. oyster genetics, growth and age, temperature, food availability, and microbiota)" have been shown to influence POMS permissiveness" (as cited in Petton et al., 2021). Vibrio bacteria are often implicated, but it is not fully understood if they are the causative agent or secondary opportunistic colonisers. As disease results in a progressive replacement of nonvirulent vibrios by genetically related virulent strains (Lemire et al., 2015). de Lorgeril et al., 2018 found a consortium of micro-organisms that induce pathogenesis. They studied intra-host interactions underlying juvenile oyster mortalities. They demonstrated the primary infection was by Ostreid herpesvirus (OsHV-1), followed by repression of antibacterial defences and significant changes in associated microbiota. They then found that bacterial colonisation was the secondary event completing the infectious process and leading to mortality (de Lorgeril et al., 2018).



Damage to the gills, infection by ostreid herpesvirus (OsHV-1-mvar), and colonisation of the gill tissues by bacteria have been described for oysters that succumb to disease (Gutierrez et al., 2018). Other factors contributing to mortalities include specific Vibrio bacterial infection and raised temperature (Malham et al., 2008; Petton et al., 2021b). Bruto et al. 2016 showed Vibrio population structure to be seasonal and varied in oysters affected by POMS. From the studies read the indications are that the causes of oyster mortalities are often multifactorial.

Petton et al., 2021a write “progression from a healthy state to systemic infection in oysters” about POMS being a polymicrobial disease induced by a primary infection altering hemocyte physiology, followed by secondary bacteremia leading to oyster death. In their report they describe the progression of an oyster in a healthy state (Immune Homeostasis), where the bacteria are controlled by healthy hemocytes, to how immune suppression can occur with exposure and infection of the hemocytes by OsHV-1. Once this has occurred and the OsHV-1 alters the hemocyte physiology, dysbiosis can result in a proliferation of opportunistic bacteria and colonisation of deeper cell tissue in the oyster; systemic infection results in bacteria-induced hemocyte lysis.

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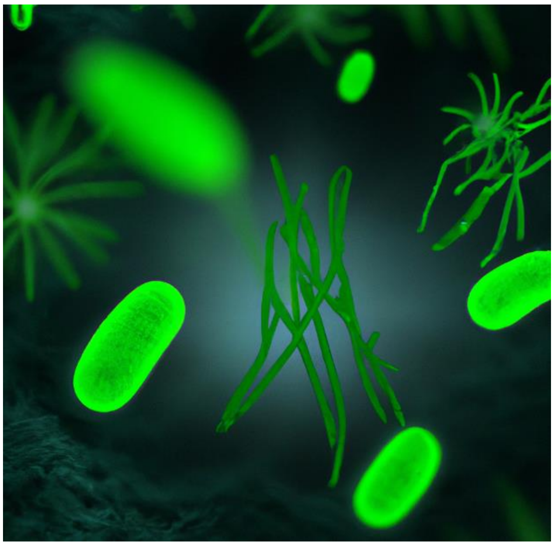
Petton et al., 2021 reported that POMS is a multifactorial polymicrobial disease and their paper focused on five environmental and host-associated factors with disease expression shown. With (vi) husbandry, (vii) plankton and (viii) nutrients and (ix) other physiochemical issues included by the author for discussion purposes. Pernet et al., 2016 point out that the development of protective measures for bivalve farming is presently held back by the lack of crucial scientific knowledge and explore an integrated approach to managing bivalve disease.

Table 1. A summary of environmental and host-associated factors for consideration with disease expression (Petton et al., 2021a)**. With (vi) husbandry, (vii) plankton and (viii) nutrients and (ix) other physiochemical issues included by the author for discussion purposes.**

i)	Temperature – Changing sea surface temperature (SST) is one of the significant physical impacts of climate change. It also influences all biological organisms' metabolism, growth, abundance, distribution, and phenology. Temperature increases associated with the warming of the climate are a substantial driver of disease outbreaks (Harvell et al., 2002).
ii)	Oyster genetics - Some oysters, particularly those able to limit infection by OsHV-1, are resistant to POMS.
iii)	Oyster age - A series of studies have reported that POMS-induced mortality rates are lower in adult oysters than in spat and juvenile oysters (13,20,79).
iv)	Oyster energetic status – (e.g. food availability, growth, and energy reserves) - Food availability can influence disease risk positively or negatively. (A) food availability improves the physiological condition and lowers susceptibility to infectious disease. (B) food scarcity limits resources available to the pathogen as it slows the growth and metabolism of the oyster, which the pathogen depends on.
	v) Plankton – There is a positive correlation between plankton species and vibrios abundance. For example, *V. crassostreae* is associated with temperature and plankton composition. In contrast, *V. tasmaniensis* was correlated with planktonic composition only.
	vi) Microbiota – Potential shifts in the composition of the microbiota community (dysbiosis) associated with POMS. "Global change has caused a worldwide increase in reports of Vibrio-associated diseases with ecosystem-wide impacts on humans and marine animals" (LeRoux et al., 2015).
	vii) Husbandry – stress in stocks increases the potential for an animal to succumb to pathogens present in the environment, resulting in disease outbreaks.
viii)	Nutrients – Malham et al., 2009 found experimentally that the addition of inorganic nutrients at field-measured concentrations (15 µM phosphate, 278 µM nitrate, 5.14 µM nitrite) caused significant oyster mortality at a temperature of 21 °C but not at 12 °C.
ix)	Physiochemical properties – such as oxygen, salinity, pH and turbidity
x)	Relative sea-level rise (RSLR), the rate of sea-level rise adjusted to include the impact of isostatic change and associated shoreline morphology changes.

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xi)	Precipitation events, cahnhges in rainfall amounts and the periods in which theuy occur.
xii)	Storm damage resulting in damage to infrastructure, communications, erosion and deposition.

Anthropogenic activities and the warming world are changing the properties of the aquatic environment. Their knock-on effects result in abundance, population constituents, distribution, and phenology adjustments in macro and micro-organisms.

1. The rise in sea surface temperatures (SST) is a significant impact of climate change. Changes in temperature can affect the abundance of plants and animals, alter their lifecycles, and change water circulation patterns that distribute nutrients. According to Reid et al., 2011 European coastal seas temperatures have risen four to seven times faster over the past few decades than global oceans. Marine pathogens are responsive to temperature change creating synergisms that could affect biodiversity (Harvell et al., 2002). "Global change has caused a worldwide increase in reports of Vibrio-associated diseases with ecosystem-wide impacts on humans and marine animals (LeRoux et al., 2015). Harvell et al. 2002 wrote, "climate warming can increase pathogen development and survival rates, disease transmission, and host susceptibility" and cited changes in El Nino events regarding how climate can influence marine pathogen success. A permissive temperature range for POMS has been identified, specifically, 16°C to 24°C (as cited in Petton et al., 2021). It is known that mortality can increase in the oysters exposed to hypoxia and elevated temperature indicating acute thermal stress (Bruhns et al., 2022).

Using the model "ShellSim", Hawkins et al. (2002) predicted that an increase in water temperature would reduce aquaculture productivity and decrease the mean weight and length of both oysters and mussels. These decreases would dramatically affect the blue mussel and have lesser consequences for the Pacific oyster population. They projected that an increase of 1°C in the water temperature would lead to a reduction of about 50% in mussel production and less than 8% in Pacific oyster production. An increase of 4 C would result in a decrease of 70% in mussel production and less than 8% in Pacific oyster production.

2. Unfortunately, as molluscs lack an immunological memory, exposure of oysters to disease agents does not result in specific immune responses. But there can be an innate immunity to diseases by oysters that have survived a mortality event being naturally selected for resistance to disease (Gestal et al., 2008; Renault, 2008). Dégremont et 352al., 2010; Pernet et al., 2012). Gutierrez et al. (2018) studied genetic parameters for resistance to OsHV and found "significant but low heritability for the binary trait of survival and viral load measures (h2 0.12 – 0.25)." Their genome-wide association study highlighted a region of linkage group 6 containing a significant QTL affecting host resistance. This finding they believe is a step toward applying genomic data to enhance selective breeding for disease resistance in oysters.

Around Ireland in 2019, 8,460 tonnes of *C. gigas* output was triploid stock, and 2,000 tonnes of diploids were produced (BIM National Seafood Survey Aquaculture Report 2020). A study by Clegg et al., 2014 which investigated oyster mortalities between 2012 and 2013, found a univariable association between ploidy and diploid stock at a higher risk. In 2021 the farmed C. gigas tonnage output profile of 10,624 tonnes was composed of 5% diploid, and approximately 85% triploid (BIM 2023).

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3. Some studies have shown that POMS mortalities are higher in spat and juvenile oysters than adults (Petton et al., 2015, Clegg et al., 2014). It is known that the susceptibility of Pacific oysters to OsHV-1 decreases with age (Berg et al., 2015).

4. Food availability may have positive and negative influences on the impacts of infectious disease. Food availability influences the risk of disease and its severity in two ways, according to (Pernet et al., 2019). It can improve the host's physiological condition, lowering their susceptibility to infectious disease, “reflecting a trade-off between immunity and other fitness-related functions”. Restricted food decreases the physiological condition of the host, making them more susceptible to disease as they lack the resources for an appropriate immune response. While food scarcity may also reduce the resources available to a pathogen while also slowing the host's growth and metabolism on which the pathogen depends to proliferate (Pernet et al., 2019).

5. In addition to pathogens that affect shellfish, there are concerns that non-native bacteria that could pose some human health issues might migrate into Irish water.

6. The BIM BIM/IFA/MI Best Practice Guidelines for Pacific Oyster Producers for 2021 highlights many issues for consideration in culturing and biosecurity that need to be considered when rearing oysters. These encompass bag and site stocking density, biofouling, stock handling, and biosecurity. It is essential to follow good husbandry practices to keep farmed animals healthy. As practices that cause stress in animals can increase the risk of infection from environmental pathogens, leading to the outbreak of diseases. To prevent this, good husbandry practices should aim to reduce stress levels in animals.he development of disease outbreaks. Good husbandry practices should therefore aim to minimise stress.

(Berg et al., 2015) recount that following an epidemiological examination of the detection of OsHV-1 µVar in a site subject to the Irish surveillance programme. That reported the most likely source of infection was movement of mussels into a depuration plant in the bay of concern from OsHV-1 µVar infected bays. And that therefore the treatment of water from depuration plants should be considered.

7. Malham et al., 2009 found experimentally that the addition of inorganic nutrients at field-measured concentrations (15 µM phosphate, 278 µM nitrate, 5.14 µM nitrite) caused significant oyster mortality at a temperature of 21 °C but not at 12 °C.

8. The EPA (2023) report that “81% of monitored coastal water bodies and 36% of monitored transitional waters are at ‘high’ or ‘good’ ecological status. There has been a decline in the quality of our estuaries and coastal waters, particularly in the south and southeast of the country where high nutrient levels in the water are damaging their ecology” (see - https://www.epa.ie/our-services/monitoring--assessment/freshwater--marine/estuaries-and-coastal/).

9. Seawater's physical and chemical properties vary considerably according to latitude, season, depth, vicinity of land and freshwater inputs. Approximately 3.5 per cent of oceanic seawater is made from dissolved compounds, and the remainder is pure water. The chemical composition of seawater is influenced by dissolved rock and sediments, gas exchange with the atmosphere, the metabolism and decomposition of organisms, volcanic activity and freshwater. There is also carbon, nitrogen, and phosphorous, limiting factors for organic cycles in the sea (Marine Ecosystem - Physical and Chemical Properties of Seawater | Britannica, 2022).

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Changes in salinity changes can affect biological communities and their distribution. The adaptation by an organism to changes in salinity also has an energetic cost which may have resultant impacts on organisms (Smyth & Elliott, 2016).

The level of salinity in the environment has been shown to affect Vibrio's abundance, as Hsieh et al. stated in 2008. However, compared to seawater temperature, the impact of salinity on *V. aestuarianus* is believed to be less significant, according to Vezzulli et al. in 2014. *Vibrio vulnificus* is a type of Gram-negative bacterium found in estuaries during the warmer summer months in the United States; where virtually all oysters contain this organism. It is also found in shellfish and fish in South America, Asia, and Europe. Though in Northern Europe (including the Baltic Sea) the number of reported Vibrio infections is approximately an order of magnitude less than that reported along the US Atlantic Coast (Vezzulli et al., 2016).

Another Gram-negative bacterium, *Vibrio parahaemolyticus*, exists in estuarine, marine, and coastal environments in North America and parts of Europe. This bacterium is also a cause of acute human gastroenteritis from consuming raw, undercooked, or mishandled marine products. In rare cases, individuals with pre-existing medical conditions may develop wound infections, ear infections, or septicaemia due to *V. parahaemolyticus*. But it can be depurated and removed from bivalve molluscs in the depuration process.

Nutrient mitigation

Mitigation tools are needed to reduce the impacts of nutrients on coastal ecosystems, and shellfish aquaculture is a potential tool for helping remove nitrogen from estuaries and bays (Ar Kormas et al., 2021). Bivalve shellfish such as oysters and mussels are filter-feeders. They feed on plankton and detritus (broken-up algae), converting those nutrients into shellfish biomass. Therefore, their harvesting can benefit nitrogen removal, called "bio-extraction", but this needs to be assessed for the different species and cultivation methodologies. (An, R. 2015) found in a study that oysters incorporate about 40% of nitrogen inputs into their tissues and decrease the relative amount of nitrogen that ends up in sediments by over 50%.

Planning for change

It has been predicted that by the end of the 21st century, there will be a further rise in the global mean sea level due to the increasing warming of the oceans. This may lead to worsening issues related to coastal erosion and flooding.

It is expected that sea level alterations will expand estuaries' horizontal and vertical dimensions, causing tides to reach further upstream. This could significantly impact Ireland's coastal habitations and ecosystems and could be compounded by increased surface water runoff at times. Moreover, rising sea levels could submerge freshwater ecosystems and affect nearshore groundwater quality. All of these scenarios require assessment and planning by the oyster industry around Ireland,

Currently, decisions regarding the planning and development of coastal regions can be made in separate sectors and the potential for missed opportunities for adapting coastal areas to climate change. Therefore, systems like Marine Spatial Planning and Integrated Coastal Zone Management (ICZM) advocate for a strategic approach to planning within coastal zones.

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Conclusion

The potential impact of climate change on shellfish (bivalve molluscs) health is a matter of concern, as evidenced by the findings presented in the IPCC Report 2021 and information from the CDC and Frontiers regarding Vibrio species. Below is a synthesis of some of the critical points from sources to draw a conclusion:

1. Climate Change Overview: Climate change is a pervasive and rapidly intensifying global phenomenon. The IPCC Report 2021 underscores that changes have been observed in every region and across various climate system parameters, such as temperature, sea level, and atmospheric gas concentrations. These changes are unprecedented in recent geological history, with CO_2, CH_4, and N_2O levels reaching levels not seen in millions of years.

2. Temperature and Sea Level Rise: The IPCC Report highlights that global surface temperatures have risen alarmingly, surpassing temperatures of the last several millennia. Furthermore, the global mean sea level has surged unprecedentedly, primarily driven by ice loss and thermal expansion from ocean warming.

3. Water Cycle and Precipitation Changes: Climate change has intensified the water cycle, leading to extreme rainfall, floods, and droughts in various regions. Shifts in precipitation patterns are expected, including increased rain in high latitudes and decreased precipitation in subtropical areas.

4. Coastal Vulnerability: Coastal areas are particularly vulnerable, with continued sea level rise anticipated to result in more frequent and severe coastal flooding and erosion. Extreme sea level events may become annual occurrences by the end of the century.

5. Ocean Changes: The ocean is undergoing significant transformations, including warming, frequent marine heat waves, ocean acidification, and reduced oxygen levels. These changes are linked to human influence and have far-reaching consequences for ocean ecosystems.

6. Vibrio Species and Shellfish: Shellfish, such as bivalve molluscs, face a dual threat from climate change and Vibrio species infections. Vibrio parahaemolyticus and Vibrio vulnificus infections are known to be associated with raw or undercooked seafood consumption, with infections being more common in warmer waters.

In conclusion, climate change poses a multifaceted and escalating risk to the health of shellfish, particularly bivalve molluscs. Rising temperatures, sea levels, and changing ocean conditions can directly impact shellfish populations by affecting their habitats and food sources. Moreover, the increased prevalence of Vibrio species in warmer waters threatens human health and the shellfish industry. It is imperative to recognize the urgency of addressing climate change through mitigation and adaptation strategies to safeguard the health of shellfish populations and maintain food security in the face of a changing climate.

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Report

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