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Quantification of Climate Footprints of *Vibrio vulnificus* in Coastal Human Communities of the United States Gulf Coast

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Key Points:

- Likelihood of *Vibrio vulnificus* infections is influenced by elevated Sea Surface Temperature and chlorophyll of previous months
- Sea Surface Temperature, chlorophyll, and *V. vulnificus* cases occurrence showed increasing trends during the study period
- Statistically significant difference was observed between overall chlorophyll levels and the levels recorded during increased cases of *V. vulnificus*

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The incidence of vibriosis is rising globally with evidence of climate variability influencing environmental processes that support growth of pathogenic *Vibrio spp*. The waterborne pathogen, *Vibrio vulnificus* can invade wounds and has one of the highest case fatality rates in humans. The bacterium cannot be eradicated from the aquatic environment, hence climate driven environmental conditions enhancing growth and dissemination of *V. vulnificus* need to be understood to provide preemptive assessment of its presence and distribution in aquatic systems. To achieve this objective, satellite remote sensing was employed to quantify the association of sea surface temperature (SST) and chlorophyll-*a* (chl-*a*) in locations with reported *V. vulnificus* infections. Monthly analysis was done in two populated regions of the Gulf of Mexico—Tampa Bay, Florida, and Galveston Bay, Texas. Results indicate warm water, characterized by a 2-month lag in SST, high concentration of phytoplankton, proxied for zooplankton using 1 month lagged chl-*a* values, was statistically linked to higher odds of *V. vulnificus* infection in the human population. Identification of climate and ecological processes thresholds is concluded to be useful for development of an heuristic prediction system designed to determine risk of infection for coastal populations.

Plain Language Summary

Our study focused on *Vibrio spp*., a group of bacteria in warm, slightly salty water. One of these, *Vibrio vulnificus*, is especially dangerous and can cause severe illness with a high risk of death. The spread of this pathogen in humans is becoming more of a concern due to climate change. We aimed to understand what environmental conditions influence occurrence of the disease caused by this bacterium. The main factor linked to the rise of *V. vulnificus* is sea surface temperature (SST). However, other factors like chlorophyll also play a role. We used satellite data to monitor SST and chlorophyll levels and statistically associated this data with the number of people getting sick from *V. vulnificus*. Our findings indicate a pattern: when 2 months prior SST and 1-month prior chlorophyll levels are higher than their monthly average, the chance of *V. vulnificus* infections is higher. By using this pattern, we aim to predict better when and where infections might happen, helping identify at-risk areas and potentially stop outbreaks before they occur.

1. Introduction

The occurrence of *Vibrio spp.* in marine, estuarine, and riverine habitats of aquatic ecosystems has been extensively documented (Barbieri et al., 1999; Lipp et al., 2002; Miller et al., 2006) and widely accepted that they are autochthonous to the aquatic environment (Brumfield et al., 2021; Colwell, 1996; Johnson et al., 2012; Pfeffer et al., 2003; Vezzulli et al., 2013). Vibrios play an ecologically significant role in the environment, namely in carbon and nitrogen cycling and degradation of polymeric substances (Thompson & Polz, 2014). Their incidence is strongly influenced by climate and ecological processes, namely warm, productive and moderately saline water (Brumfield et al., 2021). *V. spp.* are commonly associated with aquatic invertebrates such as crustaceans, zooplankton and bivalves, all of which are known to enhance their occurrence in the water environment (Erken et al., 2015; Pardío Sedas, 2007; Rowley et al., 2014). Furthermore, *V. spp.* have been shown to concentrate in filter-feeding shellfish, notably oysters which are often consumed raw, thereby exposing individuals to large doses of the bacterium (Brumfield, Chen, et al., 2023; Lovelace et al., 1968). A few *V. spp.* are known to cause infections in humans, with *Vibrio cholerae* the causative agent of cholera and both *Vibrio parahaemolyticus* and *Vibrio vulnificus* historically also considered significant pathogens. *V. parahaemolyticus* is currently the leading cause of food-borne infections in the United States (Doyle et al., 2015; Letchumanan et al., 2019; Park

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et al., 2018) and *V. vulnificus*, first reported in the U.S. in 1976 (Oliver, 2014; Ratner, 1987), is also a common cause of foodborne illness associated with severe extraintestinal infection, necrotizing fasciitis, and septicemia (Hirai et al., 2015; Janda et al., 2015; Oliver, 2005). Importantly, *V. vulnificus* has one of the highest case fatality rates of any waterborne pathogen and is responsible for *ca*. 95% of all seafood-derived foodborne deaths in the U. S. (Brumfield, Usmani, et al., 2023; Brumfield et al., 2021).

Climate change has recently been associated with shifts in the geographical expansion of pathogenic non-cholera *V. spp*., an observation corroborated by increased incidence of vibriosis (Baker-Austin et al., 2017, 2018; Brumfield et al., 2021; Froelich & Daines, 2020; Martinez-Urtaza et al., 2010; Vezzulli et al., 2012, 2013, 2016, 2020). In the eastern U.S. between 1988 and 2018, *V. vulnificus* wound infections increased *ca*. 8-fold and the geographic case limit shifted significantly northwards (Archer et al., 2023). Those findings have since been supported by the long-term increase in *Vibrio spp*. infections reported by the State of Florida (FL) between 1992 and 2022 (Brumfield, Usmani, et al., 2023; Lobitz et al., 2000). The Gulf Coast of the U.S. has consistently reported human cases of vibriosis, with Florida and Texas having the highest number reported since 1981 (Florida CHARTS Reports, 2023). Several epidemiological studies (Hlady, 1997; Howard & Bennett, 1993; Motes et al., 1998; Weis et al., 2011) characterized infection risk in coastal estuarine and marine communities by association of the incidence of *V. spp*. with consumption of raw seafood or wound infection. It is worth noting that infections with *Vibrio spp*. carry a significantly higher risk for the elderly, children, and immune-compromised individuals with underlying health conditions (Brumfield et al., 2021; Desenclos et al., 1991). Florida demographics show that of the total population of 19.6 million (37% of which are older than 65), approximately 15 million live within 30 miles of the coast (Economics and Demographics, 2023). The aquatic environment of the Texas Mid-Coast, a distinctive area with a mix of fresh and saltwater wetlands and shallow bays, generally exhibits warm temperatures and low salinity (Bishop et al., 2017), suitable for growth of pathogenic *Vibrio spp*. (Brumfield et al., 2021). Other factors that should be noted is that the region is vulnerable due to the significant presence of an elderly population, a large number of mobile homes located along the coastal area, and a sizable number of residents with disabilities (Pathak & Fuller, 2021). Thus, these two coastal regions were identified as primary to study risk of *V. vulnificus* infections.

To assess exposure risk and develop appropriate intervention strategies, climatic conditions were characterized in the context of growth and reproduction of *V. vulnificus* in its natural aquatic habitat. Four observations comprised the motivation to examine the climatic footprints of *V. vulnificus* in the human population: (a) increased frequency and magnitude of extreme weather events disturbing the ecology of coastal waters, namely seasonality (Baker-Austin et al., 2010, 2017; Brumfield, Chen, et al., 2023; Brumfield, Usmani, et al., 2023; Vezzulli et al., 2013); (b) rapid movement and settlement of human populations in warm coastal regions of the U.S. (Hauer et al., 2016; Neumann et al., 2015); (c) warming of the global oceans (Froelich & Daines, 2020; Levy, 2015; Vezzulli et al., 2015) influencing distribution of vibrios; and (d) an increasing trend in reported *V. vulnificus* cases along the Gulf of Mexico (Archer et al., 2023; Brumfield, Usmani, et al., 2023).

Plankton composition, especially the copepod population has been shown to be a critical factor driving *Vibrio* abundance in the estuarine environment (Turner et al., 2009), with *Vibrio spp*. shown to comprise the commensal flora of copepods and related organisms with chitinous exoskeletons (Gugliandolo et al., 2005, 2008; Kaneko & Colwell, 1975; Sochard et al., 1979). To obtain climatic thresholds related to vibriosis, environmental factors associated with reported cases of infection were estimated, in addition to determining the number of *V. vulnificus* cases. Thus, vibriosis can be regarded as related to specific climate influenced environmental conditions and thresholds can be related to risk of infection. While human behavior is undoubtedly an indispensable contributing factor for infection, environmental conditions (climate and ecological processes) are fundamental to location and timing of risk of potential infection. That is, climate and ecological processes influence conditions allowing growth and reproduction of the microorganism in the aquatic environment, by proxy useful for calculating risk of infection. Advancements in satellite remote sensing have facilitated retrieval of bulk climatic and ecological data, enabling researchers to overcome challenges previously encountered in field sampling studies, such as restricted spatial coverage and limited temporal resolution (A. Jutla et al., 2023; Usmani et al., 2022, 2023) The objectives of this study are to leverage earth observation data available in the public domain to establish thresholds for climate (SST) and ecological (abundance of plankton) processes related to *V. vulnificus* cases and explore the feasibility of an heuristic hypothesis that identified lead times and provided predictive intelligence with respect to likelihood of abundance of vibrios in coastal waters, hence human health risk.

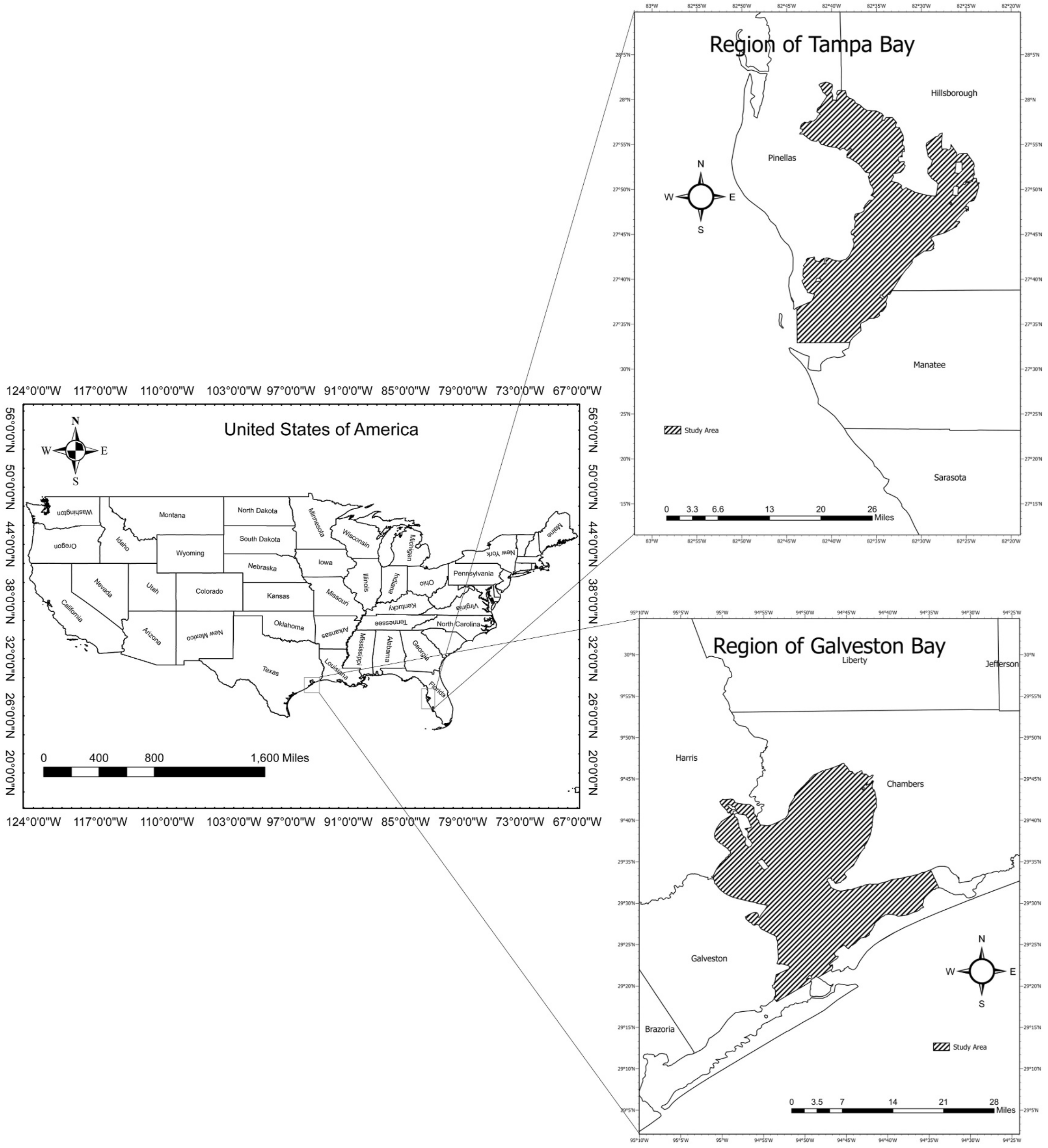


Figure 1. Tampa Bay, FL, and Galveston Bay, TX, regions of the study.

2. Methods

2.1. Study Area

The U.S. Gulf of Mexico was selected for this study since data were available on *V. vulnificus* infections in human population. Also, the geographical area has seen an increased intensity of extreme events, notably hurricanes and algal blooms (Anderson et al., 2015; Brumfield, Usmani, et al., 2023; Baumeister et al., 2014). The two study sites chosen for analysis were Tampa Bay, FL and Galveston Bay, TX (Figure 1). Two Gulf Coast counties of FL, Hillsborough and Pinellas have the highest population densities (U.S. Census Bureau QuickFacts, 2023b) and serve to represent Tampa Bay. Similarly for Texas, Harris and Galveston counties were chosen as representative of Galveston Bay. Both regions rank among counties with highest population densities (U.S. Census Bureau QuickFacts, 2023a), border on the ocean, and have recently reported an increase in *V. vulnificus* cases (Brumfield, Usmani, et al., 2023). These areas are prime locations of water-related recreational activities

(Froelich & Noble, 2016; Ramirez et al., 2009; Tomenchok et al., 2020), increasing the likelihood of human-pathogen interaction as well as concern for the seafood and tourism industries.

2.2. Environmental Data

Sea surface temperature (SST) (°C) and chlorophyll-*a* (chl-*a*) (mg/m^3) data were obtained from Level 3 browser of the National Aeronautics and Space Administration (NASA) ocean color products (NASA Ocean Color, 2023). Standard level 3 product of the Moderate Resolution Imaging Spectroradiometer (AQUA-MODIS) (MODIS | Aqua Project Science, 2023) instrument was used to extract SST and chl-*a*, with 8-daily files of 4 km spatial resolution data, spanning between 2003 and 2021 for Tampa Bay, FL, and Galveston Bay, TX. Data sets were obtained as NetCDF files and processed using the Matrix Laboratory (MATLAB) software package (R2019b) (MathWorks - Makers of MATLAB and Simulink, 2023) to extract time series for geographic coordinates bounding each location, respectively. The coordinates used were (−82.66, 27.93) and (−82.41, 27.83) for Tampa Bay, and (−95.00, 29.65) and (−94.65, 29.53) for Galveston Bay. Pixels for each location were averaged, excluding missing data. On occasion, no pixels within the defined area had a recorded value, hence the value for those respective 8-day periods were excluded from the analysis. To overcome issues associated with missing data, the 8-day time series obtained was transformed to a monthly scale to align with the resolution of *V. vulnificus* cases, also presented on a monthly scale.

2.3. Data on *V. vulnificus* Infections

Monthly *V. vulnificus* case data were obtained from the Community Health Assessment Resource Tool Set of the Florida Department of Health (Florida CHARTS Reports, 2023). Case data included both confirmed and probable cases for individuals of all age groups contracting the disease in FL. Monthly cases of *V. vulnificus* for Galveston Bay (Texas) were obtained on request from the Texas Department of State Health Services (Texas Health Data - Home, 2023). Unfortunately, case data for Texas were available only for the entire state and not for individual counties. Therefore, Galveston Bay was used as representative for *V. vulnificus* incidence across coastal TX, assuming a similar pattern of *V. vulnificus* incidence throughout coastal areas of the state, as the computation of odds ratios considered the binary nature of case occurrence or non-occurrence rather than actual number of cases. It should be noted that the time period for available *V. vulnificus* case data differed by location, whereby Tampa Bay included data between 2003 and 2021 and Galveston Bay between 2006 and 2021.

2.4. Statistical Analysis

Strength of the association of environmental variables (SST and chl-*a*) with *V. vulnificus* cases was determined using odds ratios (OR), a metric employed to measure association between exposure and outcome, where an OR value greater than one signifies significant association and less than one a non-significant association. In context of the present study, the odds ratio is defined as follows:

$$\textbf{Odds ratio}(\textbf{OR}) = \frac{\text{odds of observing infection if environmental variable exceeds a threshold}}{\text{odds of observing infection if environmental variable does not exceed a threshold}}.$$

To examine if a lagged relationship existed between environmental variables and *V. vulnificus* cases, the OR of cases with current (same as that of cases) and prior month environmental variables were estimated. This lagging ensured exposure preceded response and allowed assessment of a plausible delayed effect of the environmental variable. The likelihood of *V. vulnificus* cases, in the form of OR, was estimated to assess impact of monthly (defined as respective average of each of the 12 months) variation in SST and chl-*a*. For validation, the OR analysis conducted for Tampa Bay and Galveston Bay was also performed for Lee and Levy counties, located along the west coast of Florida. The coordinates used to obtain a time series of environmental variables were (−82.06, 26.46) and (−81.84, 26.33) for Lee County, and (−83.56, 29.44) and (−82.78,6 5, 28.95) for Levy County. Additionally, trends in environmental variables and *V. vulnificus* cases were determined using non-parametric Kendall's tau test (Gibbons, 1993).

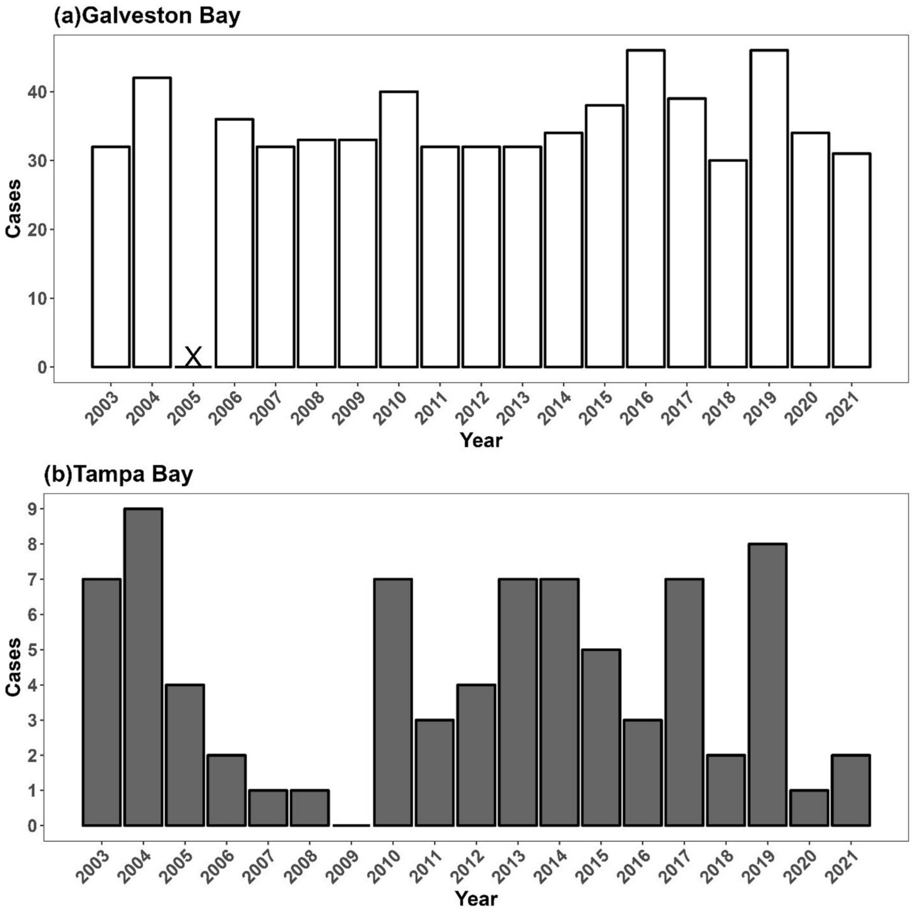


Figure 2. Total number of yearly *Vibrio vulnificus* cases reported for (a) Galveston Bay and (b) Tampa Bay between 2003 and 2021. The symbol "X" for Galveston Bay for the year 2005 denotes data were unavailable.

3. Results

3.1. Disease Surveillance and Environmental Variables

Annual cases of *V. vulnificus* in the human population in Tampa Bay and Galveston Bay are shown in Figure 2. Although a definitive trend was not observed, sporadic high-case occurrences were noted for specific years. Galveston Bay case occurrence data for 2005 were not available. Interannual case variability for Galveston Bay (coefficient of variation = 0.14) was less than that observed for Tampa Bay (coefficient of variation = 0.67). Seasonality analysis (Figures 3a and 3b) showed cases occurred more frequently during summer months (May–October) compared to the rest of the year. On average, SST was significantly higher ($p < 0.001$) in Tampa Bay (25.42°C ± 5.22°C) than in Galveston Bay (23.39°C ± 6.43°C). Similarly, chl-*a* concentrations were also significantly higher ($p < 0.001$) in Tampa Bay (18.01 ± 7.36 mg/m^3) than in Galveston Bay (15.72 ± 5.31 mg/m^3). The complete time series for SST and chl-a for the two study locations are presented in Figures S1 and S2 in Supporting Information S1.

3.2. Association Between Environmental Variables and *V. vulnificus* Cases

To capture the effect of SST, those months where SST exceeded the average value (AVG) over the entire data collection (19 years for Tampa Bay and 16 years for Galveston Bay) were included in the analysis. Figure 4 shows the monthly average SST for the two study regions. For summer months, the proportion of cases occurring when SST exceeded the monthly average *ca*. 50%, whereas during colder months it was close to 100%. This finding underscores the primary role of SST, with incidence of cases highest when SST surpassed the monthly average, even during colder months of the year.

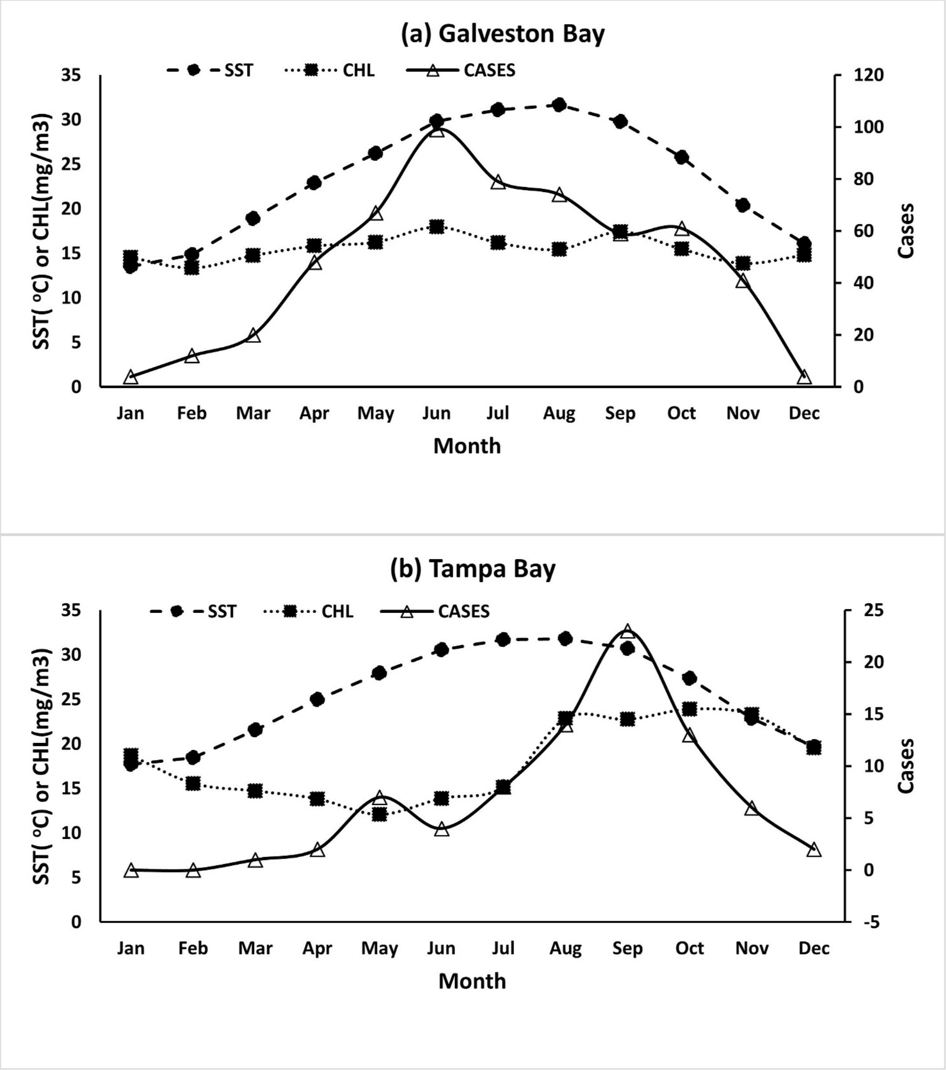


Figure 3. Seasonality of SST, Chlorophyll-*a* (CHL), and number of reported *Vibrio vulnificus* cases for (a) Galveston Bay between 2006 and 2021 and (b) Tampa Bay between 2003 and 2021. Values are shown as long-term monthly averages for each month.

Table 1 provides OR for the association between SST > AVG_{SST} and corresponding cases with respect to various lag times. Here, OR exhibited significant association (>1) of elevated SST up to 3 months lag with occurrence of human cases. Overall, the impact of SST on cases decreased with lag time. In Galveston Bay, a significant association with SST was observed for up to 2-month lag. By comparison, SST of Tampa Bay showed a more delayed impact, with significant association observed for up to 3 months. Since no association was found for lags more than 3 months, it was concluded that *V. vulnificus* cases were influenced by SST of the preceding 3 months, in agreement with other studies reporting elevated SST a primary factor linked to *Vibrio* abundance (Brumfield, Chen, et al., 2023; Paz et al., 2007; Wright et al., 1996). As shown in Figure 4, thresholds of SST > AVG_{SST} for January through December were between 17.68 and 31.79°C (Tampa Bay) and 13.47 and 31.64°C (Galveston Bay). Whereas, for warmer months (May to October), thresholds of SST > AVG_{SST} were between 27.32 and 31.79°C (Tampa Bay) and 25.74 and 31.64°C (Galveston Bay). This corroborates observations of Brumfield et al. (Brumfield, Chen, et al., 2023) who reported thresholds above 15°C and 25°C associated with increased *V.*

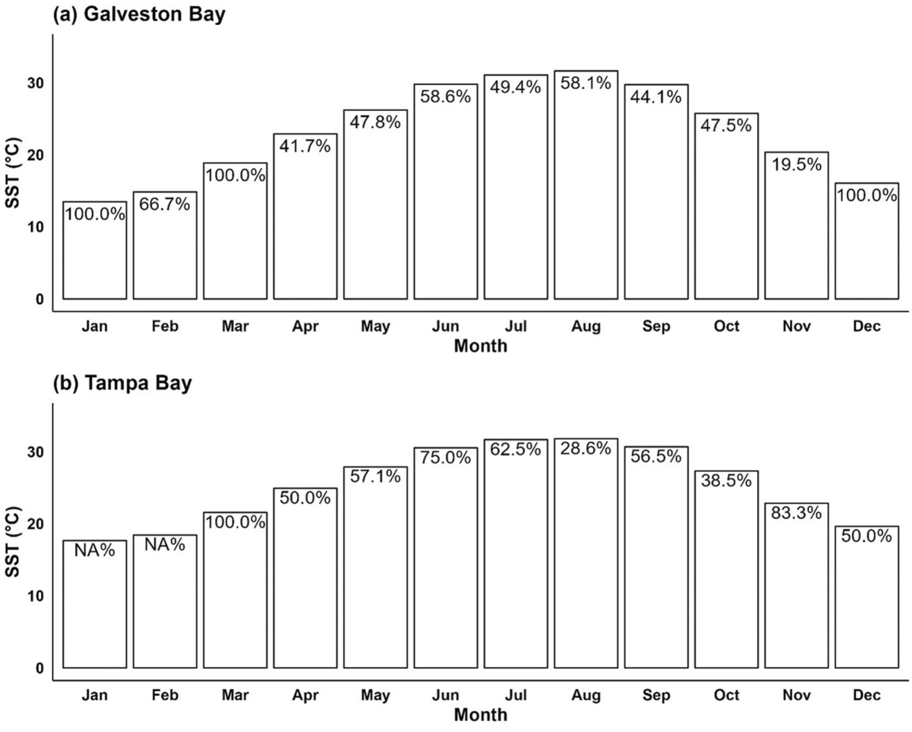


Figure 4. Monthly average sea surface temperature (SST) for (a) Galveston Bay, TX, and (b) Tampa Bay, FL. Percentages represent the proportion of *Vibrio vulnificus* cases observed during each month when SST > AVG for the given month. "NA %" represents no cases were recorded during January and February in Tampa Bay across all years included in the analysis.

vulnificus abundance in Chesapeake Bay and Sheahan et al. (2022) also reported SST thresholds >20°C for *V. vulnificus*.

While SST is concluded to be a necessary condition for increased incidence of *V. vulnificus* cases, it is not sufficient to singularly predict risk (Johnson et al., 2010), since other parameters have been reported to be significant, for example, salinity and plankton (Baker-Austin et al., 2010; Colwell, 1996; Gugliandolo et al., 2005; A. S. Jutla et al., 2012; Lipp et al., 2002). Chlorophyll serves as estimate of phytoplankton, allowing chl-*a* measured by satellite sensors to provide a measure of the phytoplankton population. The phytoplankton population precedes the zooplankton bloom with its commensal vibrios. To quantify the association of chl-*a* and elevated monthly SST with *V. vulnificus* cases, OR for monthly chl-*a* were estimated for two categories of elevated monthly SST: (a) $SST > AVG_{SST}$ and (b) $SST > AVG_{SST} + STD_{SST}$. Key statistics for chl-*a* time series of the regions under study were 18.01 (AVG) mg/m^3 ±7.36 (STD) mg/m^3 for Tampa Bay and 15.72 (AVG) mg/m^3 ±5.31 (STD) mg/m^3 for Galveston Bay.

Table 1
OR for Sea Surface Temperature (SST) Higher Than (>) Monthly Average (AVG), With Respect to Lag Time

	$SST > AVG_{SST}$	$SST > AVG_{SST} + STD_{SST}$
Galveston Bay		
No lag	1.37	1.44
Lag 1 month	1.29	1.19
Lag 2 months	1.18	1.20
Lag 3 months	0.97	0.97
Tampa Bay		
No lag	1.24	1.58
Lag 1 month	1.36	1.24
Lag 2 months	1.30	1.41
Lag 3 months	1.17	1.11

Table 2 shows that lags up to 3 months, inclusive of concurrent months, were significant and fit the expectation that the phytoplankton bloom would precede that of zooplankton, followed by increased *V. spp.* populations. OR exceeding one were observed only when chl-*a* levels were above the respective threshold, underscoring significance of chl-*a*, in addition to favorable SST, for occurrence of *V. vulnificus* cases. Since elevated SST (Table 1) forms the necessary condition for higher odds of *V. vulnificus* cases, it implies that the OR for chl-*a* in Galveston Bay should be interpreted primarily up to a lag of 2 months, where both SST and chl-*a* show significant influence. Results of Tables 1 and 2 support the hypothesis that both abiotic and ecological factors are essential parameters associated with *V. vulnificus* with a lag up to 2 months.

Table 2
OR When Chlorophyll-a (chl-a) > Monthly AVG Under Elevated SST (> Monthly AVG) for Various Lag Times

Galveston bay		
SST > AVG	chl-*a* > $\text{AVG}_{\text{chl-}a}$	chl-*a* > $\text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	0.94	1.15
Lag 1 month	1.39	1.00
Lag 2 months	1.50	1.05
Lag 3 months	1.24	0.96
SST > AVG + STD	chl-*a* > $\text{AVG}_{\text{chl-}a}$	chl-*a* > $\text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	1.20	0.58
Lag 1 month	3.50	1.14
Lag 2 months	2.13	0.38
Lag 3 months	1.03	0.40
Tampa Bay		
SST > AVG	chl-*a* > $\text{AVG}_{\text{chl-}a}$	chl-*a* > $\text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	0.90	0.63
Lag 1 month	1.25	1.10
Lag 2 months	1.25	0.82
Lag 3 months	1.63	1.36
SST > AVG + STD	chl-*a* > $\text{AVG}_{\text{chl-}a}$	chl-*a* > $\text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	0.81	0.00
Lag 1 month	1.50	2.33
Lag 2 months	0.89	1.04
Lag 3 months	3.08	1.15

3.3. Validation on Lee and Levy Counties

Similar analyses for Lee and Levy counties, both located along the FL West Coast, were conducted (Tables 3 and 4) and it was observed that OR for a lag of 1 month for Lee and Levy counties were highest, with a mild effect of chl-*a* continuing to a lag of 3 months for Levy county and 2 months for Lee county. However, for SST > AVG + STD, the OR was less than one at a lag time of 3 months; therefore, lag 3 months results for chl-*a* can be neglected because the necessary condition (OR > 1 for SST > AVG + STD) was not satisfied. Similar to Tampa Bay and Galveston Bay, the effect of SST diminished as lag time increased (Table 3).

4. Discussion and Conclusion

With increasing incidence of infection caused by *Vibrio spp*. globally (Brumfield et al., 2021; Janda et al., 1988; Martinez-Urtaza et al., 2010; Trinanes & Martinez-Urtaza, 2021), *V. vulnificus*, a bacterium with a high rate of mortality (Learn how to prevent a Vibrio wound infection, 2022), is emerging as an important environmental pathogen especially because it occurs naturally in aquatic ecosystems. The recent upsurge in human cases of vibriosis following Hurricane Ian in Florida is testament to the severity of infection and its impact on human well-being. It is critical that precautionary measures be devised to reduce risk of exposure to *V. spp*. to limit infections. Previous research clearly indicated that environmental parameters, namely SST and chlorophyll, influence occurrence of pathogenic vibrios (Baker-Austin et al., 2010; Brumfield et al., 2021; Huq et al., 2005, 2013; Johnson et al., 2010; Julie et al., 2010; Lobitz et al., 2000; Martinez-Urtaza et al., 2008). Both SST and salinity are also dominant variables in determining incidence and distribution of this pathogen (Brumfield, Chen, et al., 2023; Heng et al., 2017; Høi et al., 1998; Pfeffer et al., 2003). Laboratory-based studies and environmental surveillance have provided data showing the bacterium thrives in warm waters of low to moderate salinity (Baker-Austin et al., 2018; Brumfield, Chen, et al., 2023; Diner et al., 2021; Hsieh et al., 2007; Singleton et al., 1982; Wetz et al., 2014), with variations in numerical estimates of optimal range and thresholds (Brumfield et al., 2021). Published data on environmental parameters linked to *V. vulnificus* focused primarily on SST and salinity. However, initially, Lobitz et al. (2000) and subsequently several other studies reported significant association with chlorophyll concentration (Brumfield, Chen, et al., 2023; Deter et al., 2010; Diner et al., 2021; Johnson et al., 2010, 2012).

Table 3
OR When SST > Monthly Average for Various Lag Times for Lee and Levy County

Lee		
	SST > AVG_{SST}	SST > $\text{AVG}_{\text{SST}} + \text{STD}_{\text{SST}}$
No lag	1.08	0.99
Lag 1 month	1.11	0.87
Lag 2 months	1.02	1.68
Lag 3 months	0.96	0.87
Levy		
	SST > AVG_{SST}	SST > $\text{AVG}_{\text{SST}} + \text{STD}_{\text{SST}}$
No lag	1.15	1.00
Lag 1 month	1.10	1.03
Lag 2 months	1.11	1.08
Lag 3 months	1.03	0.99

The objective of the work presented here was to determine if incidence of *V. vulnificus* cases is associated with modalities of SST and chl-*a* concentration, obtained using remote sensing sensors. The results of this study indicate these environmental variables significantly influence case numbers, predominantly within a preceding 3 month time period.

The observed positive association of chlorophyll with *V. vulnificus* cases is fully consistent with previous studies (Johnson et al., 2010; Lobitz et al., 2000; Oberbeckmann et al., 2012; Potdukhe et al., 2021), namely that chlorophyll serves as an indicator of subsequent zooplankton abundance and correlates with zooplankton population increases following a phytoplankton bloom, which can be calculated (Colwell, 1996). Also phytoplankton blooms are an indicator of nutrient, namely increased organic matter, a factor linked to proliferation of the bacteria (Colwell, 1996; Hsieh et al., 2007; Lucas et al., 2010; Main et al., 2015; Paerl et al., 2001; Sison-Mangus et al., 2016). Furthermore, quantitatively, it can be hypothesized that elevated SST,

Table 4
OR for Chlorophyll-a (chl-a) Under Elevated SST for Various Lag Times

Lee		
SST > AVG	$\text{chl-}a > \text{AVG}_{\text{chl-}a}$	$\text{chl-}a > \text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	1.07	0.90
Lag 1 month	1.38	1.40
Lag 2 months	1.38	1.40
Lag 3 months	0.54	0.41
SST > AVG + STD	$\text{chl-}a > \text{AVG}_{\text{chl-}a}$	$\text{chl-}a > \text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	0.92	1.63
Lag 1 month	0.00	0.00
Lag 2 months	Undefined	2.67
Lag 3 months	0.69	1.22
Levy		
SST > AVG	$\text{chl-}a > \text{AVG}_{\text{chl-}a}$	$\text{chl-}a > \text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	1.12	0.00
Lag 1 month	1.54	3.18
Lag 2 months	0.74	0.85
Lag 3 months	1.27	0.70
SST > AVG + STD	$\text{chl-}a > \text{AVG}_{\text{chl-}a}$	$\text{chl-}a > \text{AVG}_{\text{chl-}a} + \text{STD}_{\text{chl-}a}$
No lag	1.00	1.00
Lag 1 month	2.30	5.60
Lag 2 months	0.00	0.00
Lag 3 months	0.80	1.81

characterized by magnitudes greater than the monthly average along the Gulf Coast, provides a favorable condition for *V. vulnificus* growth, along with chlorophyll and subsequent increased zooplankton populations and *V. vulnificus* in the environment (through pathways likely different from upwelling and/or may include terrestrial nutrient runoff) and human exposure (Figure 5).

Prior studies have shown the importance of chlorophyll as an estimator of phytoplankton and predictor of zooplankton and positive relationship with *V. vulnificus*, establishing that bacterium as a determinant (Deter et al., 2010; Johnson et al., 2010, 2012; Randa et al., 2004; Wright et al., 1996). Because previous comparative studies were conducted in different geographical locations than the Gulf Coast, there are variations in the range of chlorophyll reported. Johnson et al. (2010) documented 1–275 µg/L and a recent study (Brumfield, Chen, et al., 2023) conducted in the Chesapeake Bay reported 5–25 µg/L as optimal chl-*a* for *V. vulnificus* abundance. In the study reported here, chl-*a* (2003–2021 for Tampa Bay and 2006–2021 for Galveston Bay) ranged from 5.75 to 45.17 µg/L (Tampa Bay) and 7.01 to 32.00 µg/L (Galveston Bay). In May 2015, an anomalously high chlorophyll concentration of 62.76 µg/L was observed for Galveston Bay. This value was discarded following an outlier test (Methods and formulas for Outlier Test, 2023) and was not included in any of the chlorophyll ranges. During a period of increased occurrence of cases (May–July for Galveston Bay and August–October for Tampa Bay), the chlorophyll range was 9.97–45.17 µg/L in Tampa Bay and 9.80–32.00 µg/L in Galveston Bay. A statistically significant difference ($p < 0.05$) was observed between overall chlorophyll range and time of increased incidence of cases, with 23.17 and 16.79 µg/L average chlorophyll concentrations during the increased risk period compared to overall average of 18.01 and 15.72 µg/L, for Tampa Bay and Galveston Bay, respectively.

In the context of a changing climate characterized by rising sea level and SST, the implication for *V. vulnificus* is a significant concern (Semenza et al., 2017). A warmer aquatic system provides an environment favorable for growth and proliferation of *V. vulnificus*, with the bacterium increasingly detected in regions where previously not, especially geographically closer to the poles (Baker-Austin et al., 2013, 2017, 2018; Colwell, 1996; Froelich & Daines, 2020; Vezzulli, 2023; Vezzulli et al., 2012, 2013, 2016). Increased populations of *V. vulnificus* enhance the threat of exposure and increases the risk of infection of those individuals coming into contact with the bacterium. Consequently, infections are projected to increase in every coastal state of the US East Coast, under current future warming scenarios, by the end of the 21st century (Archer et al., 2023; Harvell et al., 2002; Semenza et al., 2017).

The SST data indicating increased risk of *V. vulnificus* cases presented in this study shows a positive trend (Kendall's tau) for Tampa Bay (FL), and Galveston Bay (TX), as illustrated in Figure 7. The trend for chl-*a* shown in Figure 8, is also positive for both regions. Combined, these data present an alarming prognosis since, parallel with the increasing trend in SST and chl-*a*, the trend in cases is also positive for both the TX and FL West Coast (Figure 6). The FL coasts have experienced changes in climate over the past several decades, detailed in a 2016 report by the United States Environmental Protection agency (Epa & Change Division, 2023) showing the FL peninsula having warmed by more than a degree (F) during the last century. Similarly, the coastal regions of FL are experiencing a rise in sea surface height, with sea levels rising *ca.* 1 inch every 3 years (Palm & Bolsen, 2020), along with the potential of intensification of Atlantic hurricanes (Balaguru et al., 2016; Emanuel, 1987; Garner et al., 2017; Global Warming and Hurricanes – Geophysical Fluid Dynamics Laboratory, 2021; Lin et al., 2012) and

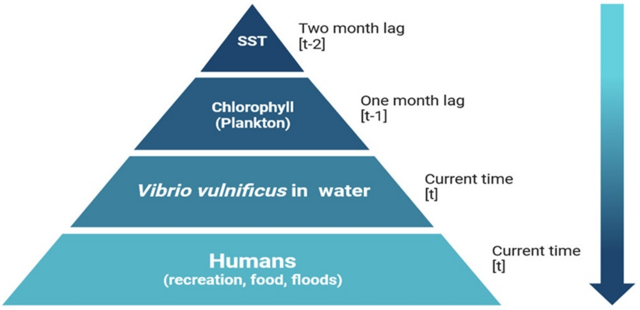


Figure 5. Hypothesis linking sea surface temperature (SST) and chlorophyll concentration with odds of *Vibrio vulnificus* infection.

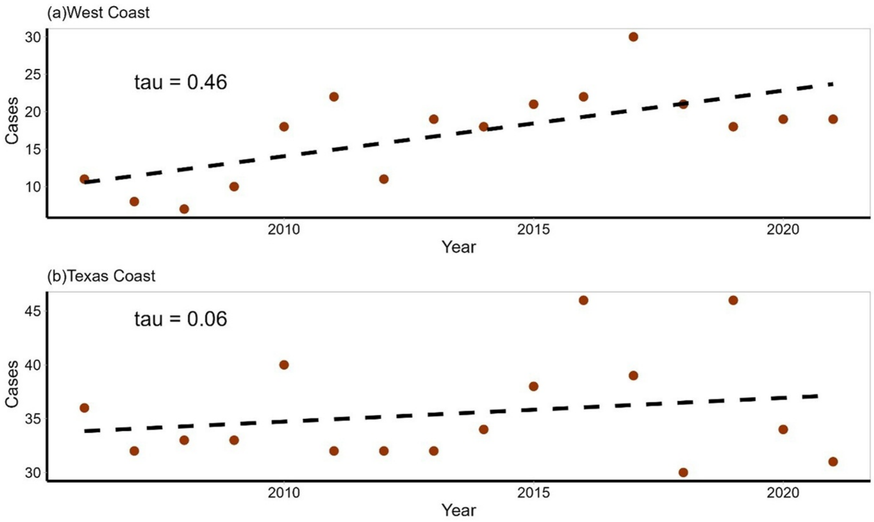


Figure 6. Observed trends for *Vibrio vulnificus* cases along (a) the FL West Coast, and (b) the Texas Coast.

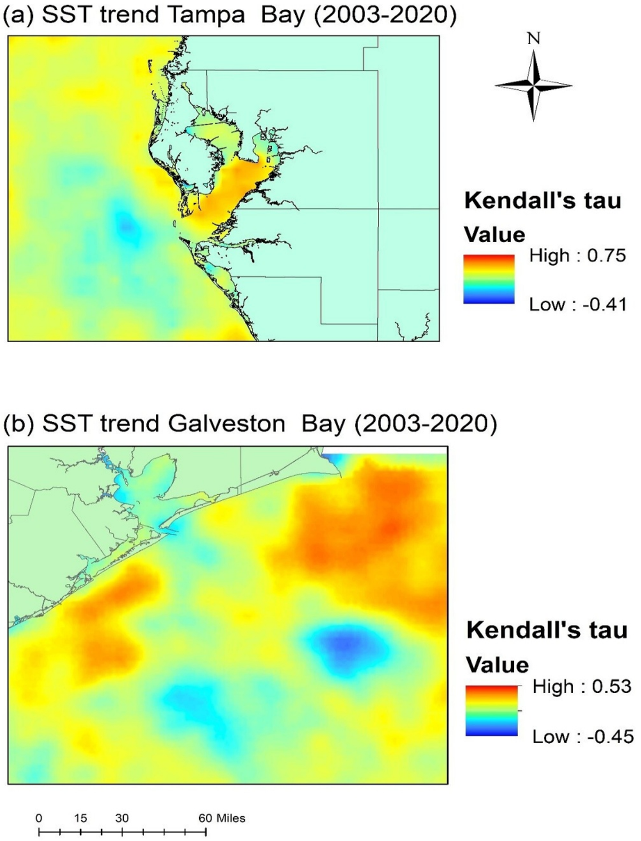
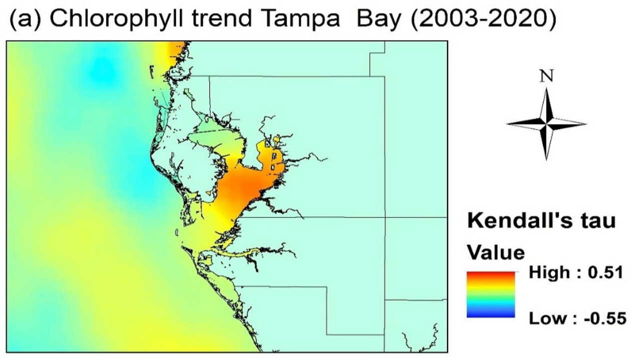


Figure 7. SST time trends (2003–2020) for (a) Tampa Bay, FL and (b) Galveston Bay, TX, based on data derived from Moderate Resolution Imaging Spectroradiometer (AQUA-MODIS).


(a) Chlorophyll trend Tampa Bay (2003-2020)

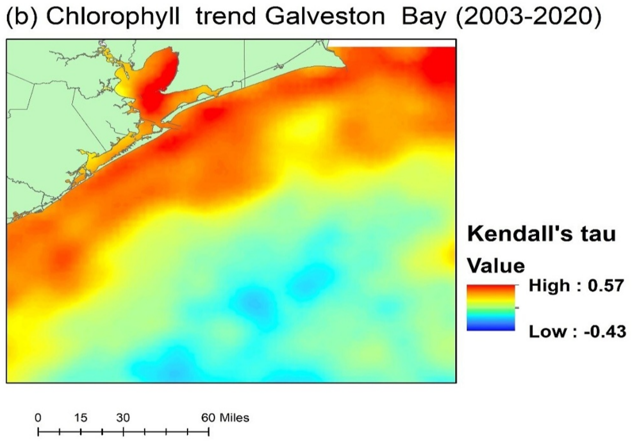

(b) Chlorophyll trend Galveston Bay (2003-2020)

Figure 8. Chlorophyll-*a* (mg/m^3) time trends along (a) Tampa Bay, FL and (b) Galveston Bay, TX, based on the data derived from Moderate Resolution Imaging Spectroradiometer (MODIS).

associated devastating floods. Floodwaters transmit potentially pathogenic agents, including *Vibrio spp*, and increase the likelihood of contact between the pathogens and human populations. In October 2022, a month after Hurricane Ian, a devastating category five hurricane made landfall in Lee County in September 2022, and 2028 cases of *V. vulnificus* were reported, the highest number ever recorded in that county (Sodders et al., 2023).

Figures 7 and 8 show annual SST and chlorophyll increasing with time and a rise in occurrence of *V. vulnificus* infections (Figure 6). With prediction models, public health authorities can thereby in identify high-risk areas and implement appropriate preventive measures.

The study reported here relied on availability of both satellite remote sensing and epidemiological data. Being able to incorporate salinity in the future as an additional important environmental variable in quantitative studies will yield greater precision. At the present time, obtaining salinity data in a gridded format presents challenges. Currently available salinity data, namely European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) (Barre et al., 2008), are in swath form and not amenable to mathematical treatment when integrated with MODIS data. Also, *V. vulnificus* cases reporting currently is limited and increased temporal and geographic resolution of the data are also needed. Age, ethnicity, and other social demographics for *Vibrio* risk prediction will enhance application of predictive risk models. In conclusion, the analysis provided in this report confirm the importance of environmental variables, namely SST and chlorophyll as drivers of *V. vulnificus* infections and offers the potential for significantly enhanced public health risk prediction models that incorporate salinity, SST,and chlorophyll data, and when coupled with improved resolution of clinical reporting, will establish threshold conditions for risk of *V. vulnificus* infection.

Tampa Bay and Galveston Bay were selected as study sites along the Gulf of Mexico region for reasons explained in Section 2.1 on the Study Area. This study can be extended to other sites sharing similar characteristics as Tampa Bay and Galveston Bay, which will provide robust support for the hypothesis presented here. As discussed above, underreporting of *V. vulnificus* cases can result in a site not being selected for study, despite its environmental similarity to the sites included in this analysis. Clearly, increased case surveillance will be advantageous. Moreover, an improved estimate of ecological parameters associated with growth and proliferation of vibrios in the environment will enhance understanding risks associated with incidence and severity of vibriosis.

This study used chlorophyll-a, estimated from remote sensing data estimate as proxy for plankton biomass. While this variable proved useful for our study, there was high variability in chlorophyll-a across the two sites. Capturing this variability accurately to establish a threshold for *V. vulnificus* is a complex task, as it can vary significantly across different spatial (e.g., coastal regions) and temporal (seasonal changes, short-term fluctuations). Thus, relative thresholds were determined using common statistical metrics (mean and STD) to establish association of chl-a with vibriosis cases. A more nuanced ecological explanation of this observed variability may well evolve that will provide deeper insight regarding the influence of plankton on *V. vulnificus* abundance and, consequently, number of vibriosis cases. The recently launched PACE (NASA PACE - Get to Know PACE, 2024) satellite is anticipated to extend and expand NASA's long-term observations with an enhanced ocean ecology.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All the data used in this research are available on Zenodo (Jamal et al., 2024).

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