WARMING OCEANS, COASTAL DISEASES, AND CLIMATE CHANGE PUBLIC HEALTH ADAPTATION

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I. INTRODUCTION

As is true for most of the world, increasing numbers of people in the United States live along the coast.[2] Indeed, although shoreline counties constitute less than 10% of the total land area of the United States (not including Alaska), they already account for 39% of the total population.[3] That percentage has been increasing since at least 1970, with no end in sight.[4] As a result, when things go wrong along the coast or in the ocean, risks to the American public are correspondingly large.

Unfortunately, things *are* going wrong in the ocean. Changing ocean conditions resulting from climate change pose considerable public health risks to coastal populations that are relevant to coastal adaptation planning. While some of these risks take the form of increasing severe "natural" disasters like hurricanes,[5] ocean-related disease is also an increasing risk.

This article posits that an increased focus on the increasing risk of ocean-related disease could benefit coastal climate change adaptation efforts in many ways. First, disease and public health risks have an immediate political salience that other coastal climate risks, such as sea-level rise, do not. In addition, in several vulnerable coastal states, especially in the southeastern United States, public cognizance of increasing coastal disease risk might productively short-circuit debates over climate change itself (whether it is real and whether humans

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[2] *What Percentage of the American population Lives Near the Coast?*, NAT'L OCEAN SERV., http://oceanservice.noaa.gov/facts/population.html (last visited Mar. 11, 2020).

[3] *Id.*

[4] *Id*.

[5] *See generally* Robin Kundis Craig, *Oceans and Coasts*, *in* CLIMATE CHANGE, PUBLIC HEALTH, AND THE LAW 204-240 (Michael Burger & Justin Gundlach, eds., 2018).

caused it) and coastal property rights in favor of actually dealing with these actual or potential public health problems.

Second, and relatedly, increasing coastal disease risk is a more immediate climate change impact than, say, coastal inundation. As the discussions below will make clear, diseases are already occurring as a result of the changing ocean, and many types of marine-related diseases have already increased their geographic ranges to invade previously "safe" coastal communities. As such, focusing public attention on this risk could increase public willingness to invest in coastal adaptation efforts immediately.

Finally, an increased focus on coastal disease risk could help to shift coastal planning from reactive to proactive adaptation efforts. Currently, most of the direct and physical threats to coasts from climate change prompt discussion about how to cope with those changes while largely preserving the status quo rather than true proactive adaptation efforts. For example, the risk of increasingly severe coastal storms tends to resonate in disaster preparedness frames, resulting in an inherently reactive mode of planning that focuses on being able to deal with such disasters as they occur. Identification of a disease risk, in contrast, generally shifts the conversation to prevention. In the coastal context, this shift in the discussion frame could in turn prompt increased attention to changing coastal ecosystems and habitats and provide impetus for thinking about coastal retreat and strategies to minimize disease-promoting habitat and human behaviors.

This Article proceeds in five parts. After this introduction, Part II will explore the disease risks that are increasing directly as a result of ocean warming, focusing on the spread of *Vibrio* bacteria and increased prevalence of harmful algal blooms, or HABs. Part III looks at increased disease risks from rising sea levels, generally in concert with increasing temperatures. It focuses on mosquito-borne diseases such as malaria and dengue fever. Part IV examines the most science-fiction-like potential for increased disease risk - melting ice around the world that exposes historical diseases, such as the 1918 pandemic flu virus. This Article concludes by summarizing the adaptation implications of these collective risks.

II. DISEASE RISK #1: OCEAN WARMING

Increasing ocean temperature is the most basic marine consequence of climate change. Ocean warming has a number of follow-on effects. In the ocean itself, warming waters alter currents and induce marine species to shift their ranges poleward, among other impacts. Warming ocean temperatures also change weather patterns worldwide and make hurricanes and typhoons more powerful.

Ocean warming also has a number of potential consequences in terms of marine-based disease. This Part will focus on two: the spread of marine *Vibrio* bacteria, including cholera; and the increase in harmful algal blooms (HABs).

A. Ocean Warming Because of Climate Change

In 2014, the Intergovernmental Panel on Climate Change (IPCC) published its Fifth Assessment Report on climate change.[6] The IPCC's reports are generally conservative, particularly where the ocean is concerned. Nevertheless, the Fifth Assessment Report provides a good starting assessment of the changes that have already occurred in the ocean, as well as projections for the future.

The world's ocean has been absorbing most - indeed, almost all - of the extra heat produced as a result of the increasing concentrations of greenhouse gases in the atmosphere, a function of the facts that water has a high heat capacity, the ocean has a large volume, and ocean currents can take heat to other places and deeper waters.[7] According to the IPCC:

> Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*), with only about 1% stored in the atmosphere. On a global scale, the ocean warming is largest near the surface, and the upper 75 m[eters] warmed by 0.11 [0.09 to 0.13]°C per decade over the period 1971 to 2010. It is virtually certain that the upper ocean (0−700

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[6] The IPCC's Fifth Assessment Report consists of four documents: INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS (2013), *available at* https://www.ipcc.ch/report/ar5/wg1/ (last visited Mar. 11, 2020); INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014: IMPACTS, ADAPTATION, AND VULNERABILITY (2014), *available at* https://www.ipcc.ch/report/ar5/wg2/ (last visited Mar. 11, 2020); INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE (2014), *available at* https://www.ipcc.ch/report/ar5/wg3/ (last visited Mar. 11, 2020); and INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2014: SYNTHESIS REPORT (2014), *available at* https://www.ipcc.ch/report/ar5/syr/ (last visited Mar. 11, 2020) [hereinafter 2014 IPCC SYNTHESIS REPORT].

[7] *Ocean Warming*, OCEAN SCIENTISTS FOR INFORMED POLICY, https://www.oceanscientists.org/index.php/topics/ocean-warming (last visited Mar. 11, 2020).

> m[eters]) warmed from 1971 to 2010, and it likely warmed between the 1870s and 1971.[8]

Ocean warming has continued to push deeper, and "[i]t is likely that the ocean warmed from 700 to 2000 m[eters] from 1957 to 2009 and from 3000 m[eters] to the bottom for the period 1992 to 2005."[9]

Importantly, ocean warming will continue for many decades. According to the IPCC, "[t]he global ocean will continue to warm during the 21st century, with the strongest warming projected for the surface in tropical and Northern Hemisphere subtropical regions . . . ."[10] However, "[a]t greater depth the warming will be most pronounced in the Southern Ocean (*high confidence*),"[11] meaning that Antarctica might experience the most profound changes. A study published in *Nature* on, appropriately, Halloween 2018 indicated that the ocean is warming even faster than the IPCC suggested.[12] While calculation errors immediately came to light that called into question the most extreme of the authors' estimations, the study's main conclusion - that the ocean is warming faster than the IPCC had indicated - remains valid.[13]

B. A Warming Ocean and *Vibrio* Bacteria

Among the beneficiaries of a warming ocean are several species of *Vibrio*, which are "rod-shaped bacteria that are natural constituents of estuarine and marine environments."[14] The genus *Vibrio* contains over 100 species, about a dozen of which can cause human disease.[15] The most common ways of getting a vibriosis infection are either by eating contaminated seafood (usually shellfish) or

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[8] 2014 IPCC SYNTHESIS REPORT, *supra* note 5, at 4.
[9] *Id*. at 40.
[10] *Id*. at 11.
[11] *Id*. at 60.
[12] L. Resplandy et al., *Quantification of Ocean Heat Uptake from Changes in Atmospheric O_2 and CO_2 Composition*, 563 NATURE 105, 105-07 (2018), *available at* https://doi.org/10.1038/s41586-018-0651-8 (last visited Mar. 11, 2020).
[13] Christa Marshall, *High-profile Ocean Warming Paper to Get a Correction*," E&E NEWS, Nov. 14, 2018, *available at* https://www.sciencemag.org/news/2018/11/high-profile-ocean-warming-paper-get-correction (last visited Mar. 11, 2020).
[14] Craig Baker-Austin et al., *Non-Cholera Vibrios: The Microbial Barometer of Climate Change*, 25 TRENDS IN MICROBIOLOGY 76, 76 (2017), *available at* https://www.sciencedirect.com/science/article/pii/S0966842X16301408 (last visited Mar. 11, 2020).
[15] *Id*.

through infection of an open wound while swimming or wading in the ocean.[16] Pathogenic *Vibrio* species replicate in as little as eight or nine minutes, making them some of the most adaptable bacteria on the planet.[17]

Four disease-causing forms of *Vibrio* are considered most important from a public health perspective.[18] The first is *Vibrio vulnificus*, which "colonize[s] filter feeding animals such as oysters, crabs and mussels, but can also be found free-living in seawater."[19] In terms of human disease, *V. vulnificus* is mostly a food-borne pathogen. "Indeed, 95% of fatalities linked to seafood consumption in the USA are caused by this bacterium, underlying its importance as a key foodborne pathogen."[20] However, while "[m]ost people become infected with *V. vulnificus* through eating raw shellfish," the bacterium "can also cause wound infections where an open wound is exposed to seawater."[21] In addition to unpleasant but less serious effects, septicemia leading to amputation or death is one potential outcome from either route of infection.[22]

The disease potential of *Vibrio vulnificus* appears to be linked to sea temperature, and throughout the 20th century most identified infections occurred along the very warm Gulf of Mexico, especially in Florida. However, the emergence of *Vibrio vulnificus* disease in other parts of the world, notably Israel, has been linked to climate change and increasing temperatures.[23] Similarly, in the United States in the early 21st century, there has been an increase in the number of *Vibrio vulnificus* infections along the Atlantic coast, stretching as far north as Delaware, New Jersey, and Rhode Island, linked to increasing sea temperatures.[24]

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16 *Id*.
17 *Id.*
18 *Id*. at 77.
19 CARINA BLACKMORE, FLA. DIV. OF DISEASE CONTROL, VIBRIO VULNIFICUS 1 (1999), http://www.floridahealth.gov/diseases-and-conditions/vibrio-infections/_documents/Vibrio-vulnificus.pdf (last visited Mar. 11, 2020).
20 Baker-Austin et al., *supra* note 14, at 77.
21 BLACKMORE, *supra* note 18, at 1.
22 *Id*.
23 Shlomit Paz et al., *Climate Change and the Emergence of* Vibrio vulnificus *Disease in Israel*, 103 ENVTL. RES. 390, 390-91 (2007), https://doi.org/10.1016/j.envres.2006.07.002 (last visited Mar. 11, 2020).
24 Jessica Forres, *Vibrio Bacteria a Bigger Threat to Swimmers than Sharks as Northern Waters Warm*, FRIENDS OF THE IRISH ENVIRONMENT, May 30, 2008, https://www.friendsoftheirishenvironment.org/fie-work/27-papers-today/global-warming/11699- (last visited Mar. 11, 2020).

Another *Vibrio* species, *V. parahaemolyticus*, "is the most prevalent food-poisoning bacterium associated with seafood consumption and typically causes acute gastroenteritis."[25] Like *V. vulnificus*, this species appears to be spreading with warming seas - for example, it recently showed up for the first time along the northeast coast of the United States.[26] Public health officials around the world have reported large-scale outbreaks of *V. parahaemolyticus* infection over the last two decades, and "a highly pathogenic variant . . . emerged on the west coast of the United States during an unusually warm spring" and then migrated to the east coast and Europe in 2012.[27]

The third *Vibrio* species of concern in warming waters is *Vibrio alginolyticus*. "An often overlooked bacterium, *V. alginolyticus* is increasingly recognized as an emerging human pathogen, and as with other *vibrios* the incidence of infection significantly increases during summer months. *V. alginolyticus* is ubiquitous in sea water and tends to cause superficial wound and ear infections . . . ."[28] In Florida over the decade from 1998 to 2007, *V. alginolyticus* caused almost 20% of vibriosis infections, and these kinds of infections appear to be increasing in the United States.[29]

The most notorious disease-causing *Vibrio*, however, is *Vibrio cholerae*, which causes cholera. Cholera outbreaks are "associated with drinking or bathing in unpurified river or brackish water" but also appear to be linked to climate and temperature.[30] Moreover, *Vibrio cholerae* has a sea stage, during which copepods (a type of tiny animal, or zooplankton) act as host organisms. According to researchers investigating the link between climate change and cholera, "[c]limate, seasonal weather changes and seasonal changes in ocean currents affect the growth of copepods."[31] Thus, researchers hope that by measuring ocean parameters such as temperature and plankton blooms, they will be able to provide "an early warning system for cholera, enabling an effective deployment of resources to minimize or prevent cholera epidemics . . . ."[32]

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[25] Baker-Austin et al., *supra* note 14, at 78.
[26] *Id*. at 77.
[27] *Id*. at 78.
[28] *Id*. at 79 (citations omitted).
[29] *Id*.
[30] Brad Lobitz et al., *Climate and Infectious Disease: Use of Remote Sensing for Detection of Vibrio Cholerae by Indirect Measurement*, 97 PROC. NAT'L ACAD. SCI. 1438, 1438 (2000).
[31] Rita R. Colwell, *A Voyage of Discovery: Cholera, Climate, and Complexity*, 4 ENVTL. MICROBIOLOGY 67, 67 (2002).
[32] Lobitz et al., *supra* note 30, at 1438.

Cholera-carrying copepods "live[] in salt or brackish waters, including rivers and ponds, and travel[] with currents and tides. Copepods harbour both dormant, nutrient-deprived and culturable *Vibrio*. The bacteria can survive as an inactive sporelike form - dormant but still infectious - in the gut and on the surfaces of copepods in between epidemics."[33] Moreover, ships transport a very large number of these copepods in ballast water.[34]

Evidence indicates that "cholera outbreaks occur shortly after sea-surface temperature and sea-surface height are at their zenith."[35] Perhaps not coincidentally, therefore, within the same time frame that climate change has begun to affect ocean temperatures and ocean currents, cholera has re-emerged in epidemic form in the coastal areas of Southeast Asia, Central America, and South America.[36]

Indeed, there is considerable evidence that a warming ocean is increasing coastal populations' disease risk from all the *Vibrio* species. In 2016, for example, a team of researchers noted the:

> unprecedented number of domestically acquired human infections that occurred in Northern European countries and were associated with swimming/bathing in coastal waters. Most of these cases were reported during heat waves (e.g., 1994, 1997, 2003, 2006, 2010), and it is expected that, as global warming continues, such events are likely to increase in frequency and intensity. Besides human illnesses, evidence has also been gathered linking Vibrio infections to increasing mass mortality of marine life in the coastal marine environment.[37]

Vibriosis infections are also of increasing concern in the United States. As researchers summarized in 2017:

> Cases of *Vibrio* infections have a marked seasonal distribution - most occur during summer and early autumn, corresponding to the

[33] Colwell, *supra* note 31, at 68.
[34] *Id*.
[35] *Id*. at 67.
[36] *Id*.
[37] Luigi Vezzulli, et al., *Climate Influence on* Vibrio *and Associated Human Diseases During the Past Half-century in the Coastal North Atlantic*, 113 PROC. NAT'L ACAD. SCI. E5062, E5062 (2016), https://doi.org/10.1073/pnas.1609157113 (last visited Mar. 11, 2020).

> period of warmer temperatures. Several reports have recently indicated that human *Vibrio* illnesses are increasing worldwide, including fatal acute diarrheal diseases, such as gastroenteritis, and wound infections and septicemia. A number of significant factors underpin the need for a greater understanding of these food borne pathogens within an international context: compared to other major food borne pathogens, the number of *Vibrio* infections is steadily increasing. Indeed, the Centers for Disease Control and Prevention (CDC) estimates that the average annual incidence of all Vibrio infections increased by 41% between 1996 and 2005 in the USA.[38]

In addition, *Vibrio* infections are now occurring in new locations suggestive of a warmth-driven expansion in range,[39] and climate change projections indicate that the risk of *Vibrio* infection will continue to increase because of a longer transmission season and an expanding geographical range as the ocean continues to warm.[40]

C. A Warming Ocean and Harmful Algal Blooms

A warming ocean also promotes harmful algal blooms, or HABs. Algae are marine plants, many of which are beneficial to marine food webs.[41] Marine algae include both the large marine seaweeds and kelp and the nearly microscopic algal forms of marine phytoplankton.[42] The small phytoplanktonic forms of algae can create an "algal bloom," which "is a rapid increase in the population of algae in an aquatic system. . . . Typically only one or a few phytoplankton species are involved and some blooms may be recognized by discoloration of the water resulting from the high density of pigmented cells."[43] This discoloration can give

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[38] Baker-Austin et al., *supra* note 14, at 76 (citations omitted).
[39] *Id*. at 76-77.
[40] Jan C. Semenza, *Environmental Suitability of* Vibrio *Infections in a Warming Climate: An Early Warning System*, 125(10) ENVTL. HEALTH PERSPECTIVES 1, 5 (2017), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5933323/ (last visited Mar. 11, 2020).
[41] *What Is a Harmful Algal Bloom?*, NAT'L OCEANOGRAPHIC & ATMOSPHERIC ADMIN., https://www.noaa.gov/what-is-harmful-algal-bloom (last visited Mar. 11, 2020).
[42] *Id*.
[43] *Reference Terms: Algal Bloom*, SCIENCEDAILY, https://www.sciencedaily.com/terms/algal_bloom.htm (last visited Mar. 11, 2020).

algal blooms common names, such as "red tides."[44] Increasing nutrient concentrations are the usual cause of algal blooms.[45]

A HAB, in turn, is a bloom of a species of algae phytoplankton that is harmful in some way.[46] With respect to human health, the most important HABs are those that "produce toxins that can kill fish, mammals and birds, and may cause human illness or even death in extreme cases."[47] For example, sea lions in California have died when blooms of certain marine algae produce domoic acid.[48]

Public health officials most commonly recognize five HAB-related human illnesses.[49] First, "[i]t is generally well-accepted that ciguatera fish poisoning (CFP) is the most frequently reported seafood-related disease in the United States and most common foodborne illness related to finfish consumption in the world."[50] CFP occurs when people consume fish - generally tropical reef species - "that have accumulated potent neurotoxins (ciguatoxin) in their flesh and viscera. The toxins are produced by the marine dinoflagellate *Gambierdiscus spp*.," which live in coral reef ecosystems.[51] "More than 400 fish species are thought to have the potential for ciguatera toxicity."[52] Herbivorous fish eat the dinoflagellates (a form of algal phytoplankton[53]), and the ciguatoxin accumulates in their flesh, concentrating up the food web to apex-level predators.[54] As a result, "[t]he risk is greatest for carnivorous, predatory fish, such as barracuda (of which >70% may be toxic). Other high risk fish include snapper, grouper, and amberjack."[55] CFP generally causes severe gastrointestinal problems that abate within twenty-four hours, but it can also cause cardiovascular and neurological issues, sometimes leading to respiratory distress, coma, and death.[56]

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[44] DANIELLE HALL, SMITHSONIAN OCEAN WHAT EXACTLY IS A RED TIDE?, (2018), *available at* https://ocean.si.edu/ocean-life/plants-algae/what-exactly-red-tide (last visited Mar. 16, 2020).
[45] *Id*.
[46] *What Is a Harmful Algal Bloom*?, *supra* note 41.
[47] *Id*.
[48] *The Rising Tide of Ocean Plagues: How Humans are Changing the Dynamics of Disease,* EUREKALERT!, Feb. 17, 2006 [hereinafter EUREKALERT], http://www.eurekalert.org/pub_releases/2006-02/s-trt021206.php (last visited Mar. 11, 2020).
[49] Lynn M. Grattan et al., *Harmful Algal Blooms and Public Health*, 57 HARMFUL ALGAE 2, 3 (2016), *available at* http://dx.doi.org/10.1016/j.hal.2016.05.003 (last visited Mar. 11, 2020).
[50] *Id*. (citations omitted).
[51] *Id*.
[52] *Id*. (citations omitted).
[53] *What Is a Harmful Algal Bloom?*, *supra* note 41.
[54] Grattan et al., *supra* note 49, at 3.
[55] *Id*. (citations omitted).
[56] *Id*. (citations omitted).

Second, Paralytic Shellfish Poisoning (PSP) results from "eating bivalve mollusks (mussels, scallops, clams) contaminated with a group of structurally related marine toxins collectively referred to as saxitoxins."[57] Mollusks consume the various dinoflagellates that produce these toxins during red tides, concentrating the saxitoxins in their flesh.[58] As a result, mollusk predators like lobsters can also convey the toxins to humans.[59]

> Geographically, the most risky regions for PSP are temperate and tropical marine coasts. In North America, this includes Alaska, the Pacific Northwest, and the St. Lawrence region of Canada; however, incidents of PSP regularly occur in the Philippines and other tropical regions. Toxic shellfish have also been found in temperate regions of southern Chile, England, Japan, and the North Sea.[60]

PSP symptoms start with numbness or tingling around the mouth, which in more severe cases can "spread to the neck and face, and may be accompanied by headache, abdominal pain, nausea, vomiting, diarrhea, and a wide range of neurologic symptoms. These neurologic symptoms may include weakness, dizziness, dysarthria, paresthesia, double vision, loss of coordination, vertigo or dizziness, and/or a 'floating' sensation."[61]

Third, another red tide shellfish risk is Neurotoxic Shellfish Poisoning (NSP).[62] People typically get NSP "by ingesting bivalve shellfish (e.g., clams, oysters and mussels) that are contaminated with brevetoxins."[63] In the United States, strict prohibitions on commercial shellfish harvests during and after red tides mean that most NSP cases come from recreational harvesters, although NSP risks are increasing as the brevetoxin-generating HABs migrate to new coastlines.[64] "In fact, the largest number of reported U.S. cases came from a single outbreak of forty-eight persons in North Carolina as a result of the

[57] *Id*. (citations omitted).
[58] *Id*. (citations omitted).
[59] *Id*. (citation omitted).
[60] *Id*.
[61] *Id*.
[62] *Id*. at 5 (citations omitted).
[63] *Id*.
[64] *Id*.

transportation of brevetoxin-producing organisms up the eastern seaboard."[65] NSP symptoms include both gastrointestinal and neurological problems.[66] The latter are of more concern and can "include paresthesia of the mouth, lips, and tongue; peripheral tingling, partial limb paralysis, slurred speech, dizziness, ataxia, and a general loss of coordination."[67] In 2018, Florida's southwest coast experienced a nine-month-long, 100-mile-long, brevetoxin-producing red tide in which the brevetoxins aerosolized, causing more health problems.[68] This HAB "caused the death of thousands of marine animals, *induced respiratory issues in six Florida counties near the Gulf of Mexico*, forced the closure of several beaches, and negatively affected tourism across the southwest Florida coast."[69]

Fourth, HABs that produce domoic acid can lead to Amnesic Shellfish Poisoning (ASP).[70] Researchers first discovered this HAB risk to human health in 1987 in eastern Canada, where the people who ate contaminated blue mussels from Prince Edward Island suffered gastrointestinal distress and, in a few cases, death.[71] Some of the survivors, however, suffered from the memory disorder that gives ASP its name.[72] New regulations require shellfish beds to be closed when domoic acid levels reach twenty parts per million, but domoic acid levels have been increasing in many places, including along the United States' Pacific coast.[73] Blooms of *Pseudonitzschia* produce the domoic acid, which shellfish then concentrate in their tissues. In late 2018, Dungeness crab fishermen in California and Oregon sued thirty fossil-fuel energy companies over the increasing domoic acid problem, blaming the companies for their role in promoting climate change, which is in turn promoting these HABs.[74] However, the bigger seafood problem may be razor clams, because "they can hold the toxin for up to one year in the natural environment, or several years after being processed, canned, or frozen."[75]

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[65] *Id*. (citation omitted).
[66] *Id*.
[67] *Id*.
[68] Priya Shukla, *Why Is Florida Experiencing Its Most Toxic Algae Bloom In a Decade*?, FORBES, Aug. 10, 2018, https://www.forbes.com/sites/priyashukla/2018/08/10/why-is-florida-experiencing-its-most-toxic-algae-bloom-in-a-decade/#fe7aa28587e1 (last visited Mar. 11, 2020).
[69] *Id*. (emphasis added).
[70] Grattan et al., *supra* note 49, at 5.
[71] *Id*.
[72] *Id*.
[73] *Id*.
[74] Jason Daley, *Crab Fishermen Sue Energy Companies Over Climate Change*, SMITHSONIAN SMART NEWS, Dec. 5, 2018, https://www.smithsonianmag.com/smart-news/crab-fishermen-sue-energy-companies-over-climate-change-180970957/ (last visited Mar. 11, 2020).
[75] Grattan et al., *supra* note 49, at 5.

Finally, Diarrhetic Shellfish Poisoning (DSP) is caused by okadaic acid and related toxins that a variety of dinoflagellates produce when they bloom, "most notably, *Dinophysis* spp and *Prorocentrum* spp."[76] "Mussels, clams, scallops and oysters are the most common vectors for the DSP toxins," and "[o]utbreaks of DSP have been reported in the U.S., Japan, France and other parts of Europe, Canada, New Zealand, United Kingdom, and South America."[77] The first confirmed case of DSP in the United States was in 2011 from mussels harvested in Sequim Bay, Washington, but cases have since arisen in Texas and New York, "suggesting that a 'tipping point' was exceeded across the U.S., allowing these toxins to affect several coastal regions that historically have not been impacted by them."[78] As the name suggests, the main symptom of DSP "is incapacitating diarrhea, followed by nausea, vomiting, and abdominal cramps"; the disease can lead to dehydration, and the toxins may cause longer-term health problems.[79]

"Every U.S. coastal and Great Lakes state experiences HABs."[80] Two of the biggest promoters of HABs are warm ocean temperatures and nutrient concentrations.[81] Climate researchers expect coastal HABs to increase in both frequency and intensity, both because ocean temperatures are increasing and because higher levels of nutrient pollution are entering the marine system.[82] As one group of researchers summarized in 2016, "With the dramatic increase in the number of harmful algal blooms, as well as their frequency and intensity in coastal regions throughout the world, there are more toxic algal species, more algal toxins, and more geographic areas affected than ever before."[83] Exposure risks are also increasing: "The risk of HAB-related illnesses is further amplified

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[76] *Id*. (citations omitted).
[77] *Id*. at 5-6 (citations omitted).
[78] *Id*. at 6 (citations omitted).
[79] *Id*. (citations omitted).
[80] *What Is a Harmful Algal Bloom?*, *supra* note 41.
[81] *Id*.; EUREKALERT, *supra* note 48.
[82] MICHAEL N. MOORE ET AL., LINKING OCEANS AND HUMAN HEALTH: A STRATEGIC RESEARCH PRIORITY FOR EUROPE (POSITION PAPER 19 OF THE EUROPEAN MARINE BOARD) 25 (2013), *available at* http://marineboard.eu/sites/marineboard.eu/files/public/publication/Oceans%20and%20Human%20Health-214.pdf (last visited Mar. 11, 2020); Ana C. Dvorak et al., *Possible Impacts of Sea Level Rise on Disease Transmission and Potential Adaptation Strategies, a Review*, 217 J. ENVTL. MGMT. 951, 955 (2018), *available at* https://www.sciencedirect.com/science/article/pii/S0301479718303359?via%3Dihub (last visited Mar. 11, 2020).
[83] Grattan et al., *supra* note 49, at 2.

by shifting preferences to heart healthy diets, increased travel to coastal destinations, increased consumption of imported fish, the growth of coastal urban communities, and growing segments of the population involved in marine recreation."[84] As a result of both sets of factors, environmental and exposure, "it is anticipated that the number of cases of HAB-related illnesses will continue to rise over the next decade."[85]

III. DISEASE RISK #2: SEA-LEVEL RISE

Sea-level rise presents a number of risks to coastal communities, including inundation of farmland and water supplies with salt water and increased storm surge.[86] In terms of disease, however, sea-level rise is important mainly because it expands the habitat available to pathogens or disease-carrying vectors. For example, global sea level rise is projected to flood lower-elevation coastal areas, expanding the estuarine and brackish environments that provide ideal habitat for the pathogenic *Vibrio* species discussed in Part I.[87] This Part, however, focuses on mosquito-borne diseases.

A. Climate Change and Sea-Level Rise

While local conditions can vary considerably, global average sea levels are clearly rising. According to the IPCC in 2014, "Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m[eters]."[88] The ocean has been rising faster since the mid-19th century than it had risen over the previous 2000 years,[89] and "[i]t is *likely* that extreme sea levels (for example, as experienced in storm surges) have increased since 1970, being mainly a result of rising mean sea level."[90] The IPCC also concluded that:

> It is *very likely* that the mean rate of global averaged sea level rise was 1.7 [1.5 to 1.9] mm/yr between 1901 and 2010 and 3.2 [2.8 to 3.6] mm/yr between 1993 and 2010. Tide gauge and satellite altimeter data are consistent regarding the higher rate during the

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[84] *Id.* (citation omitted).
[85] *Id*. at 3.
[86] Craig, *supra* note 5, at 208-10, 222-29.
[87] Semenza, *supra* note 40, at 6.
[88] *Id*. at 4.
[89] *Id*. at 4.
[90] *Id*. at 8.

> latter period. It is *likely* that similarly high rates occurred between 1920 and 1950.[91]

Sea-level rise has two main components: melting land-based ice (glaciers and ice shelves) and expanding volume as the ocean warms. The two contributors to sea level rise have been roughly equal until recently, although melting ice and disintegrating ice shelves are becoming more important contributors.[92] According to the IPCC,

> Since the early 1970s, glacier mass loss and ocean thermal expansion from warming together explain about 75% of the observed global mean sea level rise (*high confidence*). Over the period 1993–2010, global mean sea level rise is, with *high confidence*, consistent with the sum of the observed contributions from ocean thermal expansion, due to warming, from changes in glaciers, the Greenland ice sheet, the Antarctic ice sheet and land water storage . . . .[93]

Sea-level rise will continue to accelerate through the 21st century and beyond.[94] According to the IPCC, "For the period 2081–2100 relative to 1986–2005," global average sea level will rise somewhere between one-quarter and four-fifths of a meter.[95] Moreover, "[b]y the end of the 21st century, it is very likely that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience a sea level change within ±20% of the global mean."[96] However, sea-level rise will not be uniform across regions. For example, "[s]ince 1993, the regional rates for the Western Pacific are up to three times larger than the global mean, while those for much of the Eastern Pacific are near zero or negative."[97]

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[91] *Id*. at 42.
[92] Mark F. Meier et al., *Glaciers Dominate Eustatic Sea-Level Rise in the 21st Century*, 317 SCIENCE 1064, 1065 (2007) (arguing that glaciers and ice caps "contribute about 60% of the eustatic, new-water component of sea-level rise").
[93] 2014 IPCC SYNTHESIS REPORT, *supra* note 6, at 42.
[94] *Id*. at 13.
[95] *Id*. at 13.
[96] *Id*.
[97] *Id*. at 42.

B. Sea-Level Rise and Mosquito-Borne Disease in the United States

Humans suffer from a variety of vector-borne diseases - this is, diseases that require contact with an animal or insect for human infection to occur. Climate change affects most vector-borne diseases, and in a number of ways. The most certain of these impacts include the geographic shift of both vectors and reservoirs as a result of temperature change; the alteration of development, survival, and reproduction rates of vectors, reservoirs, and pathogens; and the inducement of changes in human behavior that amplify the risk of infection.[98] For example, in terrestrial northern latitudes, warming temperatures are allowing animal and insect disease vectors to shift north, effectively expanding their ranges and increasing the chances that humans will be infected[99] with diseases such as West Nile Virus.[100]

Mosquitoes are common transmitters of vector-borne diseases, "including malaria, lymphatic filariasis and dengue with recently estimated prevalence of 247, 120 and 50 million cases worldwide respectively."[101] In general, with respect to insect vectors such as ticks and mosquitoes, a warmer climate provides more favorable conditions for both vector and pathogen survival.[102] Indeed, warmer temperatures can actually speed up ticks' and mosquitoes' life cycles[103] and can lengthen the season in which mosquitoes are active.[104] In some places, warming

[98] Audrey Waits et al., *Human Infectious Diseases and the Changing Climate in the Arctic*, 121 ENVTL. INT'L 703, 705 (2018), *available at* https://www.sciencedirect.com/science/article/pii/S0160412018312005 (last visited Mar. 11, 2020); Jonathan A. Patz et al., *Climate Change Challenges and Opportunities for Global Health*, 312 J. AMER. MED. ASS'N 1565, 1572 (2014), *available at* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6108836/ (last visited Mar. 11, 2020); Tony McMichael et al., *Health Risks, Present and Future, From Global Climate Change*, BMJ 2 (2012), *available at* https://www.bmj.com/content/344/bmj.e1359 (last visited Mar. 11, 2020).
[99] Waits et al., *supra* note 98, at 705.
[100] Scott C. Weaver & William K. Reisen, *Present and Future Arboviral Threats*, 85 ANTIVIRAL RES. 328, 331 (2010), *available at* https://www.sciencedirect.com/science/article/pii/S0166354209004951 (last visited Mar. 11, 2020).
[101] Ranjan Ramasamy & Sinnathamby N. Surendran, *Possible Impact of Rising Sea Levels on Vector-borne Infectious Diseases*, 11 BMC INFECTIOUS DISEASES 1, 1 (2011), *available at* https://bmcinfectdis.biomedcentral.com/track/pdf/10.1186/1471-2334-11-18 (last visited Mar. 11, 2020).
[102] *Id.*
[103] *Id.*; *see also* Waits et al., *supra* note 98, at 705.
[104] Dvorak et al., *supra* note 82, at 955.

temperatures now allow mosquitoes to survive the winter.[105] A 2018 Climate Central study of 244 U.S. cities found that 229 of them - 94% - already faced increased risks of mosquito-borne diseases simply as a result of having more warm days each year.[106] Few of the top ten cities are coastal - San Francisco, California, is the notable exception - but the report also notes that "[a]s climate change increases temperatures during winter months, transmission could become possible year-round in some places across the continental U.S., beginning with South Florida."[107] The report further notes that "[t]he land area of the U.S. most suitable for *Aedes albopictus* mosquitoes is projected to increase from 5 percent to about 50 percent by 2100, putting 60 percent of the northeastern U.S. population at risk for the diseases carried by this mosquito, including West Nile virus, dengue and Zika."[108]

Heat is not the only factor influencing the spread of mosquito-borne disease, however. Unlike ticks, mosquitoes require water to breed, and some species of disease-bringing mosquitoes already prefer brackish or saline water.[109] In addition, non-vector freshwater mosquito species have developed tolerances for brackish water in India, Sri Lanka, and western Australia, causing concern that their disease-bearing relatives could do the same.[110] Together, these factors mean that sea-level rise is also a factor in mosquito-borne disease risk - a factor that differentially impacts coastal communities.

"Rising sea levels will affect the extent of saline (>30 parts per thousand or ppt salt) or brackish (0.5-30 ppt salt) water bodies in coastal areas."[111] As James Titus has noted, "[b]y deepening shallow bodies of water, a sea level rise could cause them to stagnate."[112] Warm, stagnant bodies of brackish water are perfect breeding grounds for disease-bearing mosquitoes. As a result, and

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[105] Waits et al., *supra* note 98, at 705.
[106] JULIA LANGER, ABBEY DUFOE, & JEN BRADY, CLIMATE CENTRAL, U.S. FACES A RISE IN MOSQUITO 'DISEASE DANGER DAYS' 2 (2018), *available at* http://assets.climatecentral.org/pdfs/August2018_CMN_Mosquitoes.pdf?pdf=Mosquitoes-Report (last visited Mar. 11, 2020). Interestingly, many of the cities that are becoming *less* risky for mosquito-borne disease, like Phoenix, Arizona, are shedding risk days because they are becoming *too hot* for mosquitoes, *id*. at 3, leading to other health concerns.
[107] *Id*. at 4 & tbl. 1.
[108] *Id.* at 5.
[109] Ramasamy & Surendran, *supra* note 101, at 2.
[110] *Id*. at 2-3.
[111] *Id*. at 2.
[112] James G. Titus, *Greenhouse Effect, Sea Level Rise, and Land Use*, 7 LAND USE POL'Y 138, 145 (1990).

especially in combination with higher temperatures, sea-level rise in coastal areas will contribute to the expected resurgence of mosquito-borne diseases such as malaria and the introduction of new mosquito-borne diseases, such as dengue fever.

Worldwide, both malaria and dengue fever are spreading, both by emerging into new areas and by returning to areas where the diseases had been under control. For example, the World Health Organization (WHO) reported in December 2016 that "[i]n 2015, there were roughly 212 million malaria cases and an estimated 429 000 malaria deaths" worldwide.[113] Moreover, malaria has returned to countries like Peru, largely as a result of climate change and deforestation.[114] Peru almost eradicated malaria forty years ago, but in 2008 64,000 cases were registered in the country, half in the Amazon region.[115] Public health officials believe that there were many more unregistered cases deep within the massive and humid rainforest, where health authorities find it almost impossible to gain access.[116]

Malaria is also endemic in the United States, if currently essentially eradicated.[117] According to the Centers for Disease Control (CDC), "About 1,700 cases of malaria are diagnosed in the United States each year. The vast majority of cases in the United States are in travelers and immigrants returning from countries where malaria transmission occurs, many from sub-Saharan Africa and South Asia."[118] In contrast, "Outbreaks of locally transmitted cases of malaria in the United States have been small and relatively isolated," generally resulting from "airport malaria," where mosquitoes unintentionally flown to the United States on planes from malaria-endemic countries infect people here; congenital malaria, where an infected mother transmits the malaria parasite to a fetus during pregnancy; and the rare case of malaria transmission through a blood transfusion,

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[113] *Malaria*, WORLD HEALTH ORG., https://www.who.int/features/factfiles/malaria/en/ (last visited Mar. 11, 2020).
[114] Andrés Schipani & John Vidal, *Malaria Moves in Behind the Loggers*, THE GUARDIAN, Oct. 30, 2007, http://www.guardian.co.uk/world/2007/oct/30/environment.climatechange (last visited Mar. 11, 2020).
[115] *Id.*
[116] *Id.*
[117] *The History of Malaria, an Ancient Disease*, CTR. FOR DISEASE CONTROL AND PREVENTION, http://www.cdc.gov/malaria/history/eradication_us.htm (last visited Mar. 11, 2020).
[118] *About Malaria*, CTR. FOR DISEASE CONTROL AND PREVENTION https://www.cdc.gov/malaria/about/ (last visited Mar. 11, 2020).

which occurs about once every two years.[119] Even so, the CDC warns that "the potential risk for the disease to re-emerge is present due to the abundance of competent vectors, especially in the southern states,"[120] and the resurgence of malaria in Peru provides a cautionary note for the United States.

Public health officials generally consider dengue fever the most important mosquito-borne disease.[121] It has no treatment, can be deadly, and according to the WHO, "[d]uring the past five decades, the incidence of dengue has increased 30-fold. Some 50–100 million new infections are estimated to occur annually in more than 100 endemic countries, with a documented further spread to previously unaffected areas; every year hundreds of thousands of severe cases arise, including 20,000 deaths."[122] Dengue fever epidemics are currently spreading through South America.[123] A study published in June 2019 in *Nature Microbiology*:

> estimated that more than two billion additional people could be at risk for dengue in 2080 compared with 2015 under a warming scenario roughly representative of the world's current emissions trajectory. That increase largely comes from population growth in areas already at high risk for the disease, as well as the expansion of dengue's range.[124]

[119] *Malaria Transmission in the United States*, CTR. FOR DISEASE CONTROL AND PREVENTION, https://www.cdc.gov/malaria/about/us_transmission.html (last visited Mar. 11, 2020).
[120] *Id*.
[121] Natasha Evelyn Anne Murray et al., *Epidemiology of Dengue: Past, Present and Future Prospects*, 5 CLINICAL EPIDEMIOLOGY 299, 303–04 (2013), *available at* https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3753061/ (last visited Mar. 11, 2020).
[122] WORLD HEALTH ORG., GLOBAL STRATEGY FOR DENGUE PREVENTION AND CONTROL 2012-2020 1 (2012) (citations omitted), https://apps.who.int/iris/bitstream/handle/10665/75303/9789241504034_eng.pdf;jsessionid=7E2153F3CC6B299C4FCE4E3EFBB7F7A4?sequence=1 (last visited Mar. 12, 2020).
[123] Marcela Valente, *South America: Climate Change Fuels Spread of Dengue Fever,* INTER PRESS SERVICE, Mar. 19, 2007, http://www.ipsnews.net/2007/03/south-america-climate-change-fuels-spread-of-dengue-fever/ (last visited Mar. 12, 2020).
[124] Kendra Pierre-Louis & Nadja Popovich, *How Dengue, a Deadly Mosquito-Borne Disease, Could Spread in a Warming World*, THE NEW YORK TIMES, June 10, 2019, https://www.nytimes.com/interactive/2019/06/10/climate/dengue-mosquito-spread-map.html (last visited Mar. 12, 2020). The study discussed in the article is: Moritz U. G. Kraemer et al., *Past and Future Spread of the Arbovirus Vectors* Aedes aegypti *and* Aedes albopictus, 4 Nature MICROBIOLOGY 854, 854-63 (2019), *available at* https://doi.org/10.1038/s41564-019-0376-y (last visited Mar. 12, 2020).

Those at risk now include some residents of the United States. As with malaria, currently most U.S. residents who contract dengue fever were infected somewhere else,[125] although the CDC notes that "[d]engue is common in the US territories of Puerto Rico, the US Virgin Islands, and American Samoa."[126] Increasing incidents of native infection cases are also occurring in the states - namely, Hawai'i, Texas, and Florida. Dengue was present in Hawai'i until 1944, but no locally transmitted outbreaks occurred between 1944 and 2001.[127] In 2001-2002, however, 122 people on Maui, Oahu, and Kauai became infected with the dengue virus, followed by outbreaks in 2011 on Oahu and 2015-2016 on the Big Island, in which 256 people contracted dengue fever.[128] In Texas, "Sporadic outbreaks have occurred in the Gulf coastal area and in extreme south Texas."[129] These include cases in 2005 and an outbreak of eighteen cases in 2013, both in the southernmost counties of Texas.[130] As in Hawai'i, dengue had been present in Florida into the 20th century, but public health officials eliminated it by 1934.[131] However:

> In 2009-2010, an outbreak of dengue was identified in Key West. A total 22 persons were identified with dengue fever in Key West during the summer and fall of 2009. In 2010, 66 cases of locally acquired dengue associated with Key West were reported in Florida with onset dates between March and November 2010.[132]

In 2013, twenty-eight residents of Martin County, Florida, were infected with the dengue virus, twenty-four of whom developed dengue fever symptoms and six of

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[125] *Dengue Fever*, FLA. DEPT. OF HEALTH, http://www.floridahealth.gov/diseases-and-conditions/dengue/ (last visited Mar. 12, 2020); *Dengue Fever FAQs*, TEX. DEP'T OF HEALTH & HUMAN SERV., https://www.dshs.texas.gov/idcu/disease/dengue/information/faqs/ (last visited Mar. 12, 2020).
[126] *Dengue in the US States and Territories*, CTR. FOR DISEASE CONTROL, https://www.cdc.gov/dengue/areaswithrisk/in-the-us.html (last visited Mar. 12, 2020).
[127] Robert Herriman, *Hawaii Dengue Outbreak Tops 2001 Outbreak*, OUTBREAK NEWS TODAY, Dec. 5, 2015, http://outbreaknewstoday.com/hawaii-dengue-outbreak-tops-2001-outbreak-36619/ (last visited Mar. 12, 2020).
[128] Meghan Ross, *6 Facts to Know About Hawaii's Dengue Fever Outbreak*, PHARMACY TIMES, Feb. 16, 2016, https://www.pharmacytimes.com/news/6-facts-to-know-about-hawaiis-dengue-fever-outbreak (last visited Mar. 12, 2020).
[129] *Dengue Fever FAQs*, *supra* note 126.
[130] Dine Fine Maron, *Dengue Fever Reemerges in Texas*, SCIENTIFIC AMERICAN, Nov. 18, 2013, *available at* https://blogs.scientificamerican.com/observations/dengue-fever-reemerges-in-texas/ (last visited Mar. 12, 2020).
[131] *Dengue Fever*, *supra* note 126.
[132] *Id*.

whom had to be hospitalized.[133] Miami-Dade County has reported twenty-one cases of dengue fever in the last decade, including in November 2018, while Broward County has had four cases.[134]

Thus, dengue fever is an existing and probably expanding risk in the United States. Indeed, the June 2019 study predicted that dengue fever would spread along the Gulf and Atlantic coasts of the United States by 2080.[135]

IV. DISEASE RISK #3: ICE MELTING

As Planet Earth warms, ice is melting. The loss of land-based ice in Greenland and Antarctica and various coastal glaciers are contributing to global sea-level rise, and that contribution is likely to increase as this century progresses. The melting ice also poses a disease risk, however - one that may be particularly important to coastal communities.

A. Climate Change and Ice Melt

A warming atmosphere and ocean are accelerating ice melt - but exactly how badly remains climate change's greatest uncertainty. For example, the unexpectedly increasing pace of polar ice melt has added significant volatility to the art of sea level rise prediction.[136] Studies repeatedly indicate that the Greenland ice sheet and Antarctic ice are melting faster than expected,[137] and an August 2007 study published in *Science* suggested "that future sea-level rise may be larger than anticipated and that the component due to GIC [glaciers and ice caps] will continue to be substantial."[138] The IPCC noted in 2014 that "[o]ver the period 1992 to 2011, the Greenland and Antarctic ice sheets have been losing

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[133] FLA. DEPT. OF HEALTH, MARTIN COUNTY DENGUE OUTBREAK AND SEROSURVEY 1 (2013), *available at* http://www.floridahealth.gov/diseases-and-conditions/dengue/_documents/mc-dengue-survey-summary-june2014.pdf (last visited Mar. 12, 2020).

[134] *Florida's First Case of Dengue Fever in 2018 Confirmed*, NEWS@THEU, Nov. 20, 2018, https://news.miami.edu/stories/2018/11/floridas-first-case-of-dengue-fever-in-2018-confirmed.html (last visited Mar. 12, 2020).

[135] Kendra Pierre-Louis & Nadja Popovich, *How Dengue, a Deadly Mosquito-Borne Disease, Could Spread in a Warming World*, THE NEW YORK TIMES, June 10, 2019, https://www.nytimes.com/interactive/2019/06/10/climate/dengue-mosquito-spread-map.html (last visited Mar. 12, 2020).

[136] Anny Cazenave, *How Fast Are the Ice Sheets Melting?*, 314 SCIENCE 1250, 1250-51 (2006).

[137] *Id.* at 1251; J.L. Chen, et al., *Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet*, 313 SCIENCE 1958, 1958 (2006).

[138] Meier et al., *supra* note 92, at 1066.

mass (*high confidence*), likely at a larger rate over 2002 to 2011. Glaciers have continued to shrink almost worldwide (*high confidence*)."[139] It projects that these ice sheets and glaciers will continue to decrease throughout the 21st century, shrinking by 15% to 85% by 2100.[140] Beyond this century:

> The threshold for the loss of the Greenland ice sheet over a millennium or more, and an associated sea level rise of up to 7 m[eters], is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) of global warming with respect to pre-industrial temperatures. Abrupt and irreversible ice loss from the Antarctic ice sheet is possible, but current evidence and understanding is insufficient to make a quantitative assessment.[141]

NASA confirms that the planet is losing ice at an increasing rate: "Data from NASA's GRACE satellites show that the land ice sheets in both Antarctica . . . and Greenland . . . have been losing mass since 2002. Both ice sheets have seen an acceleration of ice mass loss since 2009."[142] Indeed, Antarctica's melting has been accelerating, with a melt rate as much as 280% greater in 2019 than in 1979.[143]

If the Greenland ice sheet melts entirely, sea level will rise up to seven meters (twenty-three feet).[144] The West Antarctic Ice Sheet contains enough ice to raise sea level by five to seven meters (17-23 feet).[145] If all of Antarctica melts, sea level will rise approximately sixty meters, or almost 200 feet.[146] If both

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[139] 2014 IPCC SYNTHESIS REPORT, *supra* note 6, at 4.
[140] *Id*. at 12.
[141] *Id*. at 16.
[142] *Vital Signs of the Planet: Facts*, NAT'L AERONAUTICS AND SPACE ADMIN., https://climate.nasa.gov/vital-signs/ice-sheets/ (last visited Mar. 12, 2020).
[143] Brandon Miller, *Antarctica Ice Melt has Accelerated 280% in Last 4 Decades*, CNN, Jan. 14, 2019, https://www.cnn.com/2019/01/14/world/climate-change-antarctica-ice-melt-twin-studies/index.html (last visited Mar. 12, 2020).
[144] VIVIAN GORNITZ, GODDARD INSTITUTE FOR SPACE STUDIES, NAT'L AERONAUTICS AND SPACE ADMIN., SEA LEVEL RISE, AFTER THE ICE MELTED AND TODAY (2007), *available at* http://www.giss.nasa.gov/research/briefs/gornitz_09/ (last visited Mar. 12, 2020).
[145] *Id*.; *see also* Daniel Glick, *The Big Thaw*, NAT'L GEOGRAPHIC, June 22, 2019, https://www.nationalgeographic.com/environment/global-warming/big-thaw/ (last visited Mar. 12, 2020) ("If the West Antarctic ice sheet were to break up, which scientists consider very unlikely this century, it alone contains enough ice to raise sea level by nearly 20 feet (6 meters)").
[146] ANTARCTIC TREATY CONSULTATIVE MEETING XXIX, THE ANTARCTIC AND CLIMATE CHANGE 3 (2006).

Greenland and Antarctica melt completely, sea level would rise about sixty-five meters,[147] or approximately 215 feet.

However, sea-level rise is not the only risk that melting ice may bring. Melting ice may also expose the world to old diseases.

B. It Sounds Like Science Fiction, But . . .

Melting ice could potentially expose people to long-forgotten diseases. In 2006, Dr. Scott Rogers, a Bowling Green State University biologist, reported "the potential for long-dormant strains of influenza, packed in ice in remote global outposts, to be unleashed by melting and migratory birds."[148] As a result, melting ice could expose human populations to strains of flu, such as the virus that caused the 1918 flu pandemic, against which human immunity has died out.[149] Dr. Rogers contends this "information could be used to help develop inoculation strategies for the future."[150]

This concern, it must be admitted, sounds like science fiction. However, ice-based disease transmission appears to have already occurred. In August 2016, a twelve-year-old boy died from and at least twenty other people living on the Yamal Peninsula, Siberia, were hospitalized with anthrax, infected when melting permafrost exposed an infected reindeer that had been frozen for about seventy-five years.[151]

If a melting Antarctica is the source of most concern for sea-level rise, a melting Arctic - where humans have been living for perhaps as long as 45,000

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[147] Cazenave, *supra* note 137, at 1250.
[148] *Flu Can Bide Time in Icy Limbo Before Re-Emerging*, *Biologist Believes*, SCIENCE DAILY, Nov. 28, 2006, http://www.sciencedaily.com/releases/2006/11/061127210430.htm (last visited Mar. 12, 2020).
[149] *Id*.
[150] *Id*.
[151] Jasmin Fox-Skelly, *Long-dormant Bacteria and Viruses, Trapped in Ice and Permafrost for Centuries, are Reviving as Earth's Climate Warms*, BBC EARTH, May 4, 2017, *available at* http://www.bbc.com/earth/story/20170504-there-are-diseases-hidden-in-ice-and-they-are-waking-up (last visited Mar. 12, 2020). *See also* Boris A. Revich & Marina A. Podolnaya, *Thawing of Permafrost May Disturb Historic Cattle Burial Grounds in East Siberia*, 4 GLOBAL HEALTH ACTION 1, 1-7 (detailing the increasing risk of anthrax infections in cattle and reindeer as a result of melting permafrost).

years[152] - is where the disease risk lies. Human remains in the Arctic can harbor diseases. As one example,

> in the 1890s there was a major epidemic of smallpox in Siberia. One town lost up to 40% of its population. Their bodies were buried under the upper layer of permafrost on the banks of the Kolyma River. 120 years later, Kolyma's floodwaters have started eroding the banks, and the melting of the permafrost has speeded up this erosion process.[153]

Moreover, permafrost can preserve those diseases for a *very* long time. "Frozen permafrost soil is the perfect place for bacteria to remain alive for very long periods of time, perhaps as long as a million years. That means melting ice could potentially open a Pandora's box of diseases."[154]

This assertion isn't just theory. As early as 1951, scientists found the 1918 H1N1 pandemic influenza virus in frozen corpses in Alaska, which they and later scientists could then study both *in vitro* and *in vivo*, including sequencing its genome in 2005.[155] In 2005, NASA scientists published the successful efforts to revive a 32,000-year old bacterium, *Carnobacterium pleistocenium*, that they found in permafrost in Fox Tunnel, Alaska.[156] *Carnobacterium* species are anaerobic and may help transform oxygenated aquatic environments to anaerobic conditions.[157] Some species can cause disease in fish.[158] Two years later, a different team of researchers published the report of their successful revival of bacteria found in Antarctic ice estimated to be 100,000 and *8 million* years old.[159]

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[152] Ann Gibbons, *Grisly Find Suggests Humans Inhabited Arctic 45,000 Years Ago*, SCIENCE, Jan. 14, 2016, https://www.sciencemag.org/news/2016/01/grisly-find-suggests-humans-inhabited-arctic-45000-years-ago (last visited Mar. 12, 2020).
[153] Fox-Skelly, *supra* note 152.
[154] *Id*.
[155] Jeffery K Taubenberger et al., *Discovery and Characterization of the 1918 Pandemic Influenza Virus in Historical Context*, 12 ANTIVIRUS THEORY 581, 581-91 (2007).
[156] Elena V. Pikuta et al., *Carnobacterium Pleistocenium Sp. Nov., a Novel Psychrotolerant, Facultative Anaerobe Isolated from Permafrost of the Fox Tunnel in Alaska*, 55 INTL. J. SYSTEMIC & EVOLUTIONARY MICROBIOLOGY 473, 473-78 (2005).
[157] *Id*. at 473.
[158] *Id*.
[159] Kay D. Bidle et al., *Fossil Genes and Microbes in the Oldest Ice on Earth*, 104 PROC. NATL. ACAD. SCI. 13455, 13455-60 (2007), https://doi.org/10.1073/pnas.0702196104 (last visited Mar. 12, 2020).

The authors speculated that such bacteria may have been important to the Earth's evolutionary history:

> The community DNA immobilized in Antarctic ice is essentially a ‘‘gene popsicle,’’ which can potentially be acquired by extant organisms upon thawing. Given the widespread influence of lateral gene transfer (LGT) within microbial populations and its putative influence on the tempo of microbial evolution, one can envision periods in Earth's history when large numbers of ancient genes became available as ice sheets melted. Indeed, the tempo of evolution after major global glaciations appears to have increased dramatically, although causal mechanisms have been poorly defined.[160]

While none of these revived ancient bacteria apparently pose any threat to humans, their revival does validate the hypothesis that old bacterial diseases could also emerge from the ice. The disease-causing bacteria most likely to survive in ice for lengthy times are those that form spores, like anthrax, "tetanus and *Clostridium botulinum*, the pathogen responsible for botulism . . . ."[161]

Viruses can also emerge from permafrost and become infectious. A 2014 study, for instance, reported that a French team of scientists had isolated a 30,000-year-old giant virus, *Pithovirus sibericum*, from Siberian permafrost.[162] The virus was still infectious - albeit only to amoeba.[163] Still, as the authors noted:

> Climate change in the Russian Arctic is more evident than in many other regions of the world. . .. This no doubt corresponded to a large release of micro-organisms from previously frozen soils, an unknown fraction of which was revived upon thawing. Indeed, pathogenic bacteria can survive under low temperatures recurrently causing diseases in circumpolar regions.[164]

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[160] *Id*. at 13458 (citations omitted).
[161] Fox-Skelly, *supra* note 152.
[162] Matthieu Legendrea et al., *Thirty-thousand-year-old Distant Relative of Giant Icosahedral DNA Viruses with a Pandoravirus Morphology*, 111 PROC. NATL. ACAD. SCI. 4274, 4274-79 (2007), *available at* www.pnas.org/cgi/doi/10.1073/pnas.1320670111 (last visited Mar. 12, 2020).
[163] *Id*. at 4278.
[164] *Id*. (citations omitted).

They further concluded that scientists and public health officials should be interested in exploring further what exactly is emerging from the permafrost.[165] As others have speculated, "We could even see viruses from long-extinct hominin species like Neanderthals and Denisovans, both of which settled in Siberia and were riddled with various viral diseases."[166]

A melting Arctic comes with other consequences relevant to disease risk, like increasing sea access and interest in Arctic trade and development, including commercial fishing,[167] oil and gas development,[168] and international shipping.[169] More people using the coasts of the Arctic region means increased human exposure to whatever pathogens emerge from Arctic ice, both because more people risk exposure in the Arctic itself and because more people will be traveling from the Arctic via the ocean to other coasts. Ships' ballast water and other features have long transported invasive species around the globe,[170] and if the Age of Discovery (or the contemporary COVID-19 pandemic) proved anything, it was that sailors (and cruise ship passengers) are excellent vectors for introducing new diseases to other parts of the planet.[171]

V. CONCLUSION

The disease risks to coastal communities from climate change are not trivial, and increasing numbers of these communities are likely to be coping with diseases that they've never seen before, or seen during only the warmest of El Niño or other ocean oscillation events. Whether communities are adequately monitoring and training for these emerging and resurging diseases is an open question, but there are reasons to doubt. With respect to mosquito-borne diseases,

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[165] *Id*. at 4278-79.
[166] Fox-Skelly, *supra* note 152.
[167] *E.g.*, Ivan Stupachenko, *Can Russia's Arctic Deliver on Big Fishing Promises?*, April 4, 2018, SEAFOODSOURCE, https://www.seafoodsource.com/features/can-russias-arctic-deliver-on-big-fishing-promises (last visited Mar. 12, 2020).
[168] For example, in 2017 President Trump attempted to open the United States' portion of the Arctic Ocean to oil and gas leasing, but in late March 2019, a federal judge ruled the Executive Order unlawful. League of Conservation Voters v. Trump, 363 F. Supp. 3d 1013, 1020-31 (D. Alas. 2019).
[169] Jessica Murphy, *Is the Arctic Set to Become a Main Shipping Route?*, BBC NEWS, Nov. 1, 2018, https://www.bbc.com/news/business-45527531 (last visited Mar. 12, 2020).
[170] *Ballast Water & Invasive Species*, ECOCHLOR, https://ecochlor.com/ballastWaterInvasiveSpecies.html (last visited Mar. 12, 2020).
[171] Nathan Nunn & Nancy Qian, *The Columbian Exchange: A History of Disease, Food, and Ideas*, 24 J. ECON. PERSPECTIVES 163, 163-64, 165-66 (2010).

for example, "[b]rackish/saline water bodies are frequently neglected in vector control programs."[172]

These new disease risks do give coastal communities reason to re-evaluate their approaches to climate change adaptation. For example, as sea-level rise creates new habitat for *Vibrios* and disease-bearing mosquitoes, coastal communities can take "steps to reduce the development of new coastal swamps and other potential brackish/saline water breeding sites, and tidal flows in estuaries."[173] Disease risk also means that climate change adaptation planning and implementation cannot rest solely in the hands of traditional coastal zone managers and land use planners or focus only on the *physical* impacts of climate change. Instead, adaptation efforts must include public health agencies, agriculturists and irrigators, livestock agencies and ranchers, and ecosystem stewards, among many others.[174]

Relatedly, increasing and changing coastal disease risk has the potential to make climate change real and adaptation strategies necessary in coastal communities that have largely ignored their climate change vulnerabilities. It also has the potential to shift adaptation focus and financing in communities that have been emphasizing physical impacts and strategies, such as seawalls to address sea-level rise. Indeed, increased cognizance of climate change coastal disease risk may ultimately aid coastal communities in seriously addressing coastal retreat strategies[175] earlier rather than later - after all, who wants to live next to a sea that can increasingly threaten your health, and in some particularly nasty ways?

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[172] Ramasamy & Surendran, *supra* note 101, at 4.
[173] *Id*.
[174] *Id*.
[175] *See generally* ANNE SIDER, MANAGED COASTAL RETREAT: A LEGAL HANDBOOK ON SHIFTING DEVELOPMENT AWAY FROM VULNERABLE AREAS (2013), *available at* http://columbiaclimatelaw.com/files/2016/11/Siders-2013-10-Managed-Coastal-Retreat.pdf (last visited Mar. 12, 2020).