BRIEF REPORT

Forecasted Impact of Climate Change on Infectious Disease and Health Security in Hawaii by 2050

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ABSTRACT

Objective: Climate change is expected to cause extensive shifts in the epidemiology of infectious and vector-borne diseases. Scenarios on the effects of climate change typically attribute altered distribution of communicable diseases to a rise in average temperature and altered incidence of infectious diseases to weather extremes.

Methods: Recent evaluations of the effects of climate change on Hawaii have not explored this link. It may be expected that Hawaii's natural geography and robust water, sanitation, and health care infrastructure renders residents less vulnerable to many threats that are the focus on smaller, lesser developed, and more vulnerable Pacific islands. In addition, Hawaii's communicable disease surveillance and response system can act rapidly to counter increases in any disease above baseline and to redirect resources to deal with changes, particularly outbreaks due to exotic pathogens.

Results: The evidence base examined in this article consistently revealed very low climate sensitivity with respect to infectious and mosquito-borne diseases.

Conclusions: A community resilience model is recommended to increase adaptive capacity for all possible climate change impacts rather an approach that focuses specifically on communicable diseases. (*Disaster Med Public Health Preparedness*. 2016;10:797-804)

Key Words: infectious disease medicine, emergency preparedness, disease outbreaks, disaster planning

Climate change is frequently associated with an increase in infectious disease through either increased abundance or enlarged distribution.[1] Climate change scenarios typically include a change in distribution of infectious diseases as average temperatures rise, while weather extremes modify the incidence of infectious diseases and outbreak frequency.[2] Climate change is therefore expected to cause widespread shifts in the pattern of a number of infectious diseases.[3] However, recent evaluations of the effects of climate change on Hawaii have not elaborated on this link.[4-6]

In considering the distribution and incidence of infectious diseases in Hawaii due to climate change, the capacity of the communicable disease surveillance system to detect diseases and respond rapidly and effectively must always be considered. Human populations are not passive when incidences increase. The State of Hawaii's communicable disease surveillance and response system has the capacity to redirect resources to deal with changes, particularly outbreaks due to exotic pathogens. For example, models may predict that a rise in temperature will make a population vulnerable to malaria, but in most developed country settings, malaria can be rapidly detected, outbreaks controlled, and the parasite eliminated.

In Hawaii for example, there are no endemic *Anopheles* spp., the vector of *Plasmodium*.[7] Constant monitoring of ships and ports detects anopheline importation events and deals with them so effectively that it is rare to find wild anophelines in Hawaii.[8] As a result of this surveillance and response, no population of *Anopheles* has successfully established in Hawaii.[7] Models may predict malaria being more likely to establish in Hawaii as warming progresses, but not only would the parasite need to be imported but a suitable vector mosquito as well. Hence, malaria is highly unlikely to establish in Hawaii.

Similarly, it is common to predict that cholera epidemics will result from rising temperatures. This will not occur in Hawaii since, owing to the high inoculating dose of *Vibrio cholerae* required to cause disease, cholera outbreaks occur only in communities in extreme poverty where chlorinated and reticulated water is unavailable. The typical event in developed country settings is that a case of cholera is imported and diagnosed and there is no secondary spread, as occurred in Hawaii in the 1990s.[9] Occasionally, more than one case is detected, again as in Hawaii,[10] but in developed country settings with appropriate responses, large cholera outbreaks will not occur.

The ability of Hawaiian public health systems to respond effectively to increases in infectious diseases highlights a significant difference between this potential impact of climate change and others, such as extreme weather events and sea-level rise. Communicable diseases can be controlled by current systems. The other impacts of climate change can at best be adapted to, not controlled. Hence, although climate change may tend to increase the incidence of a disease, humans have the tools to decrease incidence to an acceptable baseline or to eliminate it altogether. Infectious diseases are the better news story of climate change in developed country settings and Hawaii falls into this category.

CHANGE IN DISTRIBUTION OF ENDEMIC PATHOGENS

Hawaii, owing to its small landmass and the mobility of its human population, has most likely a widespread distribution of currently endemic human pathogens. Even mosquito vectors of serious diseases such as dengue are spread across all islands. For example, *Aedes albopictus*, the vector of a major dengue outbreak in 2001-2002 and of a dengue epidemic on Oahu in 2012, is present on all islands.[7,11]

The Hawaiian Islands originally had no native mosquitoes, but 6 hematophagic species were accidentally introduced.[7] There are 4 diurnally active mosquito species in Hawaii: *Ae. albopictus* (Asian tiger mosquito), *Ae. aegypti* (yellow fever mosquito), *Ochlerotatus japonicas* (Japanese or rockpool mosquito), and *Wyeomyia mitchellii* (bromeliad or pineapple lily mosquito). They all breed in small containers and have a short flight range of only 100 to 150 yards. Currently, *Ae. aegypti* and *Ochlerotatus japonicus* are found only on the Big Island of Hawaii.[11] The 2 nocturnally active mosquito species are *Culex quinquefasciatus* (southern house mosquito), with a flight range of several miles, and *Ae. vexans nocturnus* (inland floodwater mosquito), which can fly 20 miles.[12] On Oahu, *Ae. aegypti*, the most efficient vector of dengue, chikungunya, and Zika viruses, is outcompeted by *Ae. albopictus*.[13]

The 2012 Pacific Islands Regional Climate Assessment report on key indicators of climate change stated that Hawaii would experience expanded ranges for pathogens and invasive species.[4] There are no endemic mosquito-borne pathogens in Hawaii and it is unlikely that variations in the distribution of vector-borne disease would be due to anything but human and vector factors.

INCREASED SUSCEPTIBILITY TO IMPORTATION OF EXOTIC PATHOGENS

Owing to its geographic isolation, Hawaii does not currently have some pathogens that if imported could establish and become endemic. Will climate change increase the risk of importation?

One of these is the tropical environmental bacterium *Burkholderia pseudomallei*, the cause of melioidosis.[14] Melioidosis is a potentially fatal disease. This bacterium can be imported into new locations by contaminated soil.[15] The current average temperature of Hawaii would permit *B. pseudomallei* to become established. However, since the incidence of melioidosis is related directly to rainfall,[16] if introduced, its epidemiology is unpredictable.

Another pathogen whose emergence was possibly driven by rising temperatures due to climate change in Canada is a genetic variant of the endemic Australian fungus, *Cryptococcus gattii* type VGIIa.[17] The VGIIa variant has increased virulence.[17] This environmental fungus causes pathogen pollution due to extensive contamination of the environment and causes serious infections (lungs and brain) in humans and animals.[18] The fungus has been progressing south from Canada and is now found in the Pacific Northwest states of Washington and Oregon.[19]

Comprehensive studies have identified a range of genetically distinct clusters in other US states.[19] *C. gattii* had been isolated from 2 clinical cases in Hawaii prior to genetic subtyping[20] and was recently detected in a wild dolphin in Hawaii, but this was not the VGIIa genotype.[21] This event illustrates that *C. gattii* VGIIa could establish in Hawaii. Introduction to Hawaii, if it occurs, will probably be via imported wood chips or crude wood products from Canada or the United States.[17]

Dengue cases are increasing yearly and dengue is endemic in much of Asia, including India and Southeast Asia, especially in popular tourist destinations, and in American Samoa, French Polynesia, Fiji, Kiribati, New Caledonia, Niue, Papua New Guinea, Samoa, and the Solomon Islands. Dengue is currently not endemic in Hawaii and outbreaks to date are considered to be intermittently imported from endemic areas by infected travelers. The current cluster of locally acquired dengue on the Big Island of Hawaii continues to be investigated, but was due to increased global movement of infected travelers, not climate change. The likelihood of the disease becoming endemic to Hawaii remains low because it was spread by a highly localized population of *Ae. aegypti* and this species does not exist on the other islands.[22] *Ae. aegypti* does not disperse more than several hundred meters from its hatching site and is not expected to fly inter-island. Its establishment on other islands is quite possible but would only be attributable to the transportation of human goods containing larvae, not to climate change.

Ae. albopictus mosquitoes demonstrate superior competence in the transmission of many viruses in laboratory settings, but they are a less important vector in the field owing to a lack of

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preference for human blood. They are already widespread throughout the Hawaiian Islands and climate change will have no perceptible impact on the current potential distribution of mosquito-borne diseases attributable to this species. Climate change will also have an insignificant impact on the extrinsic incubation cycle of pathogens since the temperatures in Hawaii are already high. Any introduction of a mosquito-borne disease in the islands will be due to travelers or migrants.

In 2007, the Zika virus emerged in the Pacific in the form of a major outbreak on Yap in the Federated States of Micronesia. By 2016, the virus has spread across the Pacific to the Marshall Islands, Tonga, Samoa, and American Samoa and has also been imported to Hawaii. It shares the same mosquito vectors as dengue, which prompted Hawaii to declare a state of emergency in 2016 for both diseases to help ensure against locally transmitted cases.[23] The movement of Zika across the globe is likewise due to increased movement of infected travelers, not to climate change, because all infection locations have always possessed the ingredients for transmission except for the virus.

Chikungunya is endemic to both French Polynesia and the Marshall Islands, which is a frequent destination for Hawaiians and US military personnel. This virus is spread by the same vectors as dengue and Zika. Cases have been imported to Hawaii by travel, but no locally acquired cases have been recorded. The movement of this virus between similar ecosystems is likewise due to increased movement of travelers and not to climate change.

While climate influences the geographical distribution of mosquitoes, other factors determine their suitability to the physical environment, which might otherwise be unsuitable based on climate factors alone.[24] These include the degree of required association with humans, the predilection for breeding sites in urbanized areas, the nature of water management, and the quality of public health services. The increased latitudinal distribution of *Ae. aegypti* was a factor in the spread of dengue and Zika to South America and Hawaii,[25] but this is not related to climate change because these areas have always had climates that could support this vector. The spread of vectors to locations that have always had the capacity to sustain them can never legitimately be related to climate change.

Hawaii has vector mosquitoes capable of transmitting dengue, West Nile, chikungunya, and Zika viruses. The question therefore becomes one of whether climate change will increase the likelihood of these viruses being imported. Since the Hawaiian Islands are remote from other landmasses, importation will require infected vectors to be imported or infected humans. Arguably, the likelihood of importation by infected mosquitoes in any climate scenario is extremely low, whereas the risk from climate-induced migrants will grow as migration increases as the result of rising seas. Given the small and localized populations of *Ae. aegypti* and the modern public health system, a shift from intermittent outbreaks originating from global travelers to endemicity is unlikely.

In the Marshall Islands, climate change impacts are expected to produce more frequent, longer, and unpredictable drought periods with further saltwater intrusion. Ahlgren and colleagues argued that the health impacts of the supplemental imported diet, combined with migration to population centers, may result in an even greater prevalence of chronic diseases and exert pressures that lead to more communicable disease.[26] The authors argue that the long-term militarization of the Marshalls has resulted in "large-scale ecologic, social and health consequences" and a state of "industrial capitalism" that has accelerated global warming.[27] Given the relatively insignificant carbon emissions from small Pacific Island states, this is an unreasonable and facetious argument. In 2015, 1 in 200 persons in the Marshall Islands had active tuberculosis and they increasingly look to Hawaii for treatment and migration. The movement of these cases has historically been due to the availability of services and not to climate change. The expected migration of populations that contain infectious persons as a result of sea-level rise is a different matter that is related to climate change. Existing public health policies and medical services are adequate to sufficiently cope with this level of influx and prevent significant outbreaks.

EFFECT OF TEMPERATURE RISE ON INCIDENCES OF COMMUNICABLE DISEASES

Although enteric diseases are predicted to increase in incidence with climate change, this is an oversimplification of diseases that have incidences determined by very complex and dynamic transmission webs.[28]

Salmonellosis is the enteric disease most sensitive to temperature rise.[28] Models in New Zealand, Europe, and Australia expect salmonellosis to increase with climate change.[28-31] Salmonellosis is the second leading cause of bacterial food-borne illness in the United States. Enteric salmonellosis typically has a seasonal pattern with incidences increasing in warm weather.[32,33] In developed societies like Hawaii, the source of salmonellosis is mainly in food and is particularly associated with poultry meat and eggs.

A continuous point source epidemic due to *Sal. enteritidis* phage type 4 in Hawaii was a contaminated chicken farm, which was only stopped by depopulating stock.[34] Pork is also a source of salmonellas in developed countries.[33,35] The incidence of salmonellosis is likely to rise as temperatures increase with more frequent food-borne outbreaks.[28,29] However, because the drivers of incidence are complex and are related more to human behaviors than to the prevalence in the source animals,[26] if behaviors change, the incidence

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may not be predictable. Awareness of this association with ambient temperature, however, can alert disease control interventions.

Two parasitic causes of enteric disease may be influenced by climate change. *Cryptosporidium* is responsible for approximately 9% of pediatric diarrhea cases in developed countries and *Giardia* is responsible for 2% to 7% of cases in developed countries.[36] The incidence of cryptosporidiosis, caused by *Cryptosporidium parvum* and *C. hominis*, is inversely related to temperature.[37] However, its incidence is positively correlated with rainfall.[28] *Cryptosporidium* infects via the fecal-oral route through various pathways (direct, food, water, swimming), but of greatest concern, owing to potential numbers of cases, is transmission via reticulated water supplies.[38]

Parasites in water and incidence of disease are higher in rural areas in the United States.[38] Incidence of cryptosporidiosis and giardiasis were both positively correlated with urban area, population size, and population density in the United States.[38] Giardiasis differs from cryptosporidiosis in that its incidence is positively correlated with both rainfall and temperature.[37] As temperature rises and rainfall declines in Hawaii, cryptosporidiosis should decline while the direction of change in giardiasis is unpredictable.

EFFECT OF FLOODING ON INCIDENCE OF INFECTIOUS DISEASES

Flooding will increase the incidence of a number of communicable diseases, particularly in societies with poor public health infrastructure.[39] Increase in rain intensity with resultant inundation, flooding, and contamination of surface waters is a well-recognized climatic risk factor for transmission of *Leptospira* spp.[40] Overall, the Hawaiian archipelago has experienced significant trends in increasing temperatures,[41] decreasing rainfall,[42] and decreasing rain intensity over the past 30 years.[43] However, there is variation with some areas receiving higher rainfall.[43] Infection from exposure through recreational or occupational water activities, such as swimming or taro farming, was thus posited to be of concern.[4,44]

Despite these trends, island distribution of leptospirosis cases remained virtually unchanged from 1974 to 2011.[44,45] However, the peak of incidence shifted from summer to winter from 1999 to 2008, and the major serogroup and sources of infection also changed. Sources in Hawaii changed from recreational to occupational, which is a different trend from that seen in most developed countries.[44,46]

Globally the incidence of leptospirosis after flooding has increased, particularly becoming an issue in urban areas in developing countries.[47] This is less of a problem in developed countries, but is being seen.[48] One leptospirosis outbreak was due to flooding on Big Island.[49] The incidence of leptospirosis is determined by a complex web of interactions that involve human hosts as the endpoint, animal reservoirs and victims, the environment, weather, and climate.[50] Human behavior is central, but climate and extreme weather events are playing an increasingly important determinant role.[51] How the pattern of leptospirosis will change on Hawaii cannot be predicted, but it will change.

WATER CONTAMINATION WITH HARMFUL PATHOGENS AND CHEMICALS

Changes in precipitation and warming may affect water supplies indirectly by salt water intrusion following rising sea levels or directly by increased flash flooding of streams, marshes, and urban areas leading to a greater incidence of fecal-oral diseases. Areas with poor sanitation infrastructure and high burdens of infectious disease often experience increased rates of diarrheal illness due to cholera, cryptosporidiosis, and typhoid fever after flood events.[52] Water-related illness in Hawaii, which has adequate infrastructure, is more likely to be due to infection and contamination.

The State of Hawaii has 487 km of marine recreational shoreline, 575 marine water bodies, 5353 km of rivers and streams, 60 km^2 of bays and harbors, and 8 km^2 of lakes and reservoirs.[53] In their most recent report, the Clean Water Branch assessed 160 marine water bodies and found that 136 failed state water quality criteria for at least one or more conventional pollutants or enterococci.[53] Two inland freshwater bodies were tested and failed with excessive phosphorous and nitrogen. According to this report, the status of inland (streams) and marine water at 825 assessment sites was as follows: Kauai (141 assessment sites, 47 rated low, 4 medium concern), Oahu (275 sites, 91 low, 14 medium, and 15 high concern), Molokai (43 sites, 4 low concern), Lanai (17 sites, 7 low concern), Maui (185 sites, 57 low, 30 medium, and 1 high concern), and Hawaii (164 sites, 75 low, 3 medium, and 2 high concern). This amount of runoff contamination suggests moderate susceptibility to factors that increase runoff, such as increased storm activity and flooding.

In a study of the distribution of 5 bacterial pathogens in Oahu coastal streams, *Salmonella*, *Campylobacter*, *Staphylococcus aureus*, *Vibrio vulnificus*, and *V. parahaemolyticus* were widespread in 12 of 22 streams.[54] Furthermore, all streams had detectable concentrations of 4 fecal indicators: enterococci, *Escherichia coli*, *Clostridium perfringens*, and coliphages. *Salmonella* was more common in agricultural and forested areas, whereas *S. aureus* was associated with urban and agricultural land. The prevalence of these pathogens is unlikely to increase due to climate change, but flash flooding will spread them into areas where human contact is more likely.

Four enteric viruses (adenovirus, enterovirus, norovirus GI, and norovirus GII) were also detected and quantified in Oahu coastal streams during dry weather.[55] A model calculated the risk of gastroenteritis for a person swimming in the ocean near

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the stream outfall and showed on average it was 0.01% and that adenoviruses and noroviruses contributed most to risk. No estimates of risk in wet weather were provided. Hence, predicting the effect of climate change on risk of gastroenteric infection while swimming near stream runoff is not possible.

More frequent flooding may impact the amount and distribution of heavy metals and agricultural chemicals entering the marine environment.[56] These pollutants can cause many health effects including neurological and developmental effects. Inorganic arsenic, a potent human carcinogen and poison, is of particular concern because it alters the immune system. Low levels of arsenic are found in native soils in Hawaii, but elevated levels have been found in former pesticide storage areas associated with old sugar cane mills.[57] Inorganic arsenic binds to iron, which makes it fairly stable in soil and less toxic to people who may come in contact.

Inundation and flooding has led to contamination of surface water and groundwater on some Pacific islands.[58] While the Hawaiian Islands are very large compared to many small fragile Pacific islands and have better protected underground freshwater reserves, surface water is a problem. Polluted runoff associated with excessive storm water or commercial and industrial chemicals result in beach closures every year.[59]

Seafood organisms provide a major source of protein to global populations and are particularly susceptible to contamination from these runoff pollutants. Furthermore, ciguatera and other marine pathogens may extend their range as a result of warming oceans, resulting in more toxins in seafood.[5] Ciguatera is common in Hawaii, with approximately 20% of reef fish testing positive for ciguatoxin. These results correlate with the reported incidents from the Department of Health of actual ciguatera poisoning in the State of Hawaii.[60] Climate change and warming oceans may result in a spread of ciguatera to colder areas that do not currently experience it, but the impact on Hawaii, which already has warm waters, will most likely be negligible.

Increased exposure could result in seafood exceeding safety guidelines and increasing the risk of morbidity and developmental changes. Immune system effects during development can remain throughout life and result in reduced capacity to fight serious infection and an increased risk of several other diseases including cancer.[61] Acute poisoning following the ingestion of biotoxin-contaminated fish and shellfish has been reported throughout the world. Approximately 40 species, of 5000 known marine phytoplankton species, produce potent biotoxins that enter the food chain via clams and mussels.[62] Human morbidity caused by toxin-contaminated seafood is

TABLE 1

Infectious Pathogens, Agents, and Diseases Matched With Current Status in Hawaii With Forecasted Vulnerability by 2050

Infection	Current Status and Forecasted Vulnerability by 2050
Mosquitoes	*Aedes albopictus, Ae. aegypti, Ochlerotatus japonicas, Wyeomyia mitchellii, Culex quinquefasciatus, Ae. vexans nocturnus* present. Climate change is not expected to change vector composition or distribution
Dengue	Disease intermittent. Vectors present. May become intermittent due to increased travel
Chikungunya	Disease not present. Vectors present. May become intermittent due to increased travel
Zika	Disease not present. Vectors present. May become intermittent due to increased travel
Malaria	Disease not present. Vectors not present. Likelihood not expected to change
West Nile virus	Disease not present. Vectors present. Likelihood not expected to change
Cholera *Vibrio vulnificus* and *V. parahaemolyticus*	Disease not present and not expected to change due to climate change
Melioidosis	Pathogen not present. Effects of climate change are unpredictable
Cryptococcus gattii	Pathogen not present, but likely to increase if introduced. Introduction and spread will not be due to climate change
Salmonellosis	Pathogen present but seasonal and effects of climate are unpredictable
Cryptosporidiosis	Pathogen present but should decline
Giardiasis	Pathogen present but effects of climate change are unpredictable
Leptospirosis	Effects of climate change will likely change pattern of incidence
Campylobacter	Unlikely to increase due to climate change
Staphylococcus aureus	Unlikely to increase due to climate change
Gastroenteritis: adenovirus, enterovirus, norovirus GI/GII	Effects of climate change on abundance or distribution are unpredictable; insufficient data
Arsenic	Highly localized and not expected to change due to climate change
Polluted runoff	Common and not expected to change due to climate change
Ciguatera	Common and unlikely to increase because seas here are already warm
Paralytic and diarrheic shellfish poisoning	Associated with temperate climates and colder coastal waters and are not a concern in Hawaii
Toxic algal blooms	Nontoxic blooms exist in Hawaii and the introduction of toxic varieties would not be associated with climate change

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referred to as paralytic, neurotoxic, amnesic, diarrhetic shellfish and ciguatera fish poisonings depending on patient symptoms.[63] One human case of paralytic poisoning in Hawaii was noted in 1986 that was attributed to the consumption of smoked mackerel.[64] Paralytic shellfish poisoning and diarrheic shellfish poisoning involving biotoxins that are associated with temperate climates and colder coastal waters and are not a concern in Hawaii.

Algal proliferation associated with ocean currents, winds, sea surface temperature, pH, sunlight, and runoff can cause blooms. Some algae produce harmful toxins in seafood, such as ciguatera, that cause illness or death in humans, whereas others are nontoxic but may degrade ecosystems by adversely affecting corals, sea grasses, and other organisms. Nontoxic microalgae blooms are a recurring problem along the Kihei coast in Maui.[65] They adversely impact coral reefs and local aesthetics and are expected to cause losses of $16 million annually over several decades. Their impact is on reductions in real estate value and hotel business as well as increased cleanup costs, but not health thus far.[66]

FORECASTED CLIMATE CHANGE IMPACTS ON INFECTIOUS DISEASES IN HAWAII

A summary of the previously discussed infectious diseases and the likelihood and nature of their response to climate change are presented in Table 1.

In summary, infectious-disease-related health issues that can be associated with climate changes and their current and potential impact on Hawaii have been delineated here. There are no priority areas of high health concern that will not be able to be managed by existing services. Health department efforts need to remain focused on controlling existing pathogens and preventing the entry of novel infectious disease agents via infectious travelers and migrants.

Hawaii's robust sanitation and health care infrastructure can be expected to render residents less vulnerable to many potential climate change impacts on health. Notably, both international and US organizations have argued for improvements in health system and sanitation infrastructure as part of the process of building resilience in vulnerable nations.[67-69] The critical responsive system that counteracts health impacts is the public health surveillance and response system. A society can mitigate against threats if it has an efficient system. The question is, should we be directly focusing valuable and limited resources on these areas of very low climate sensitivity as part of our climate change preparedness efforts?

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