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A hypothesis-generating analysis of the association between extreme weather events and untreated recreational water-associated outbreaks in the United States, 1978 – 2010

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Abstract

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By Kelly L Squires

Purpose: Acute gastrointestinal illness is the predominant illness in two-thirds of untreated recreational water-associated outbreaks in the United States. Survival and reproduction of waterborne pathogens has been shown to be influenced by both temperature and precipitation. The effects of extreme weather events on waterborne disease is of increasing concern due in part to global climate change and projections of an increase in average temperatures and an increase in severe rainfall events. Studies on a national scale have found positive associations between extreme weather events and waterborne disease outbreaks associated with drinking water. This study aimed to analyze the association between weather events and the incidence of waterborne outbreaks associated with untreated recreational venues in the United States.

Methods: Data on waterborne disease outbreaks were obtained from the Centers for Disease Control and Prevention's Waterborne Disease Outbreak Surveillance System and the National Outbreak Reporting System. Temperature and precipitation data were accessed from the National Oceanic and Atmospheric Administration's National Climatic Data Center. We used a time-stratified 2:1 matched case-crossover design and conditional logistic regression to analyze the relationship between weather and outbreak incidence.

Results: Average minimum temperature in the week preceding an outbreak was significantly associated with outbreak incidence (OR=1.162; 95% CI: 1.017-1.327), but not during other time periods. We also did not find an association between gastrointestinal outbreaks and average maximum temperatures or average precipitation over any time period. We found a stronger effect on *E. coli* during the 0-28 days preceding an outbreak compared to other pathogens.

Conclusions: The lack of an association in this study between average maximum temperatures and outbreak, as well as average precipitation and outbreaks, could be an indicator that current state and local regulations on beach closures are effective. Subsequent studies on the effects of temperature on gastrointestinal illness should study average minimum temperature as a separate predictor from maximum or average temperatures to further investigate its impact.

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I. BACKGROUND

Gastrointestinal Illness in the United States

Gastrointestinal illness is a significant and growing (1) burden on the United States healthcare system. In 2007, 15 million (12%) of the 122 million emergency department (ED) visits had a primary diagnosis of gastrointestinal illness (2). This represents \$27.9 billion in total charges (2). ED visits with a gastrointestinal diagnosis are more likely to result in subsequent hospitalization than ED visits with a non-gastrointestinal diagnosis (2). Abdominal pain is the most common symptom of gastrointestinal illness, followed by diarrhea, constipation, nausea, and vomiting (3). While most cases of gastrointestinal illness due to waterborne transmissions are self-limiting, illnesses can be severe and even fatal in the immunocompromised or other vulnerable populations including children, the elderly, and pregnant women (4). Acute gastrointestinal illness is the predominant illness in over half (54.3%) of recreational water-associated outbreaks in the United States and two-thirds of untreated recreational water-associated outbreaks (5).

Waterborne Disease in the United States

There are as many as 9 million waterborne illnesses in the United States each year (4). However, it is difficult to quantify the precise burden of waterborne disease in the United States. The illness type most commonly associated with waterborne disease is gastrointestinal illness, which often goes unreported (4). Individuals with gastrointestinal illness may not seek treatment, usually because symptoms are self-limiting in immunocompetent individuals (4). Those who do seek treatment often do not have their illness reported to the state or local health department. Finally, illnesses that are due to

waterborne transmission may be incorrectly classified as foodborne or person-to-person transmissions (4). While not all waterborne illnesses are gastrointestinal in nature, the majority of cases are. From 1978-2010, 49.8% of reported waterborne disease outbreaks were of acute gastrointestinal illness. Other waterborne outbreaks were skin ailments (33.2%), respiratory illnesses (9%), or other illnesses (8%) (5).

Waterborne disease exposures can occur through ingestion, inhalation, dermal contact, or other routes. The Centers for Disease Control and Prevention (CDC) categorizes the transmission of waterborne disease into three types of water exposure: drinking water, recreational water, or other venues. Drinking water exposures include water systems that are intended for drinking, including distribution systems, wells, and bottled water. This also includes water used for showering or bathing, if it was part of a drinking water system. Recreational water exposures are divided into treated and untreated water venues. Other venues include water that is not intended for drinking, such as a wilderness creek used by a hiker, or if the water venue cannot be categorized as drinking or recreational. This may include cooling towers or decorative fountains (6).

Recreational water-associated disease

An exposure can be classified as recreational if the water associated with the illness was intended for recreational purposes (6). National reporting of recreational water-associated disease outbreaks began in 1978. Since that time there have been between six and 84 recreational water-associated outbreaks each year (5). Reporting has significantly increased ($p < 0.001$) since 1978 (5). In the 2009-2010 reporting period there were 81

recreational water-associated outbreaks, accounting for 1,326 illnesses and at least 62 (5%) hospitalizations (5). Recreational water exposure can be classified into two subgroups: treated and untreated venues. Treated recreational venues include swimming pools, whirlpools, hot tubs, spray pads, and kiddie pools. Untreated recreational venues include lakes, ponds, reservoirs, rivers, and beaches (6).

Untreated recreational water-associated disease

Untreated recreational water bodies become contaminated with pathogens from various sources. The farm environment is a particularly significant source of contamination. Cattle are the most important reservoir for *E. coli*, though other ruminants such as goats, sheep, and deer also carry the pathogen. Pigs, birds, rodents, fish, amphibians, and insects can all carry *E. coli* as well (7). Camps, where children may have contact with untreated water for recreational purposes, have been documented as the source of exposure in multiple outbreaks in the United States (8). Urban runoff is another common source of contamination of untreated recreational water bodies. This is because the impermeability of most urban surfaces, such as cement and asphalt, cause the majority of the microbial load to run off into the watershed. Another significant source of untreated surface water contamination is sewage effluent (9). It is not uncommon for municipalities in the United States to combine their sewer and storm water drainage systems; in the event of extreme precipitation such systems may be overwhelmed and incapable of handling the volume of incoming water. Raw sewage could subsequently bypass treatment and discharge into the local watershed (10).

Evidence suggests that untreated recreational venues are subject to incidental fecal contamination due to environmental conditions that enable the survival and growth of a variety pathogens (11), and infectious disease has been linked to fecally contaminated water. In 1996 almost 3,700 US beaches were closed or put on advisory, and 83% of the beach closures were due to excessive concentrations of bacteria (9). Nearby storm drains at ocean beaches have been shown to be a risk factor for increased illness in swimmers (12). A prospective cohort study conducted in three US cities found that as *E. coli* counts increased, so did the incidence of gastrointestinal illness among swimmers. The study also found an inverse relationship between the frequency of gastrointestinal symptoms and the distance from city wastewater outlets (13).

Outbreaks associated specifically with untreated venues have remained fairly steady since national surveillance began in 1978 (14). There were 24 outbreaks reported during the 2009-2010 reporting period, accounting for 30% of all recreational water-associated outbreaks (5). These 24 outbreaks resulted in 296 cases and 22 hospitalizations (5). Untreated recreational water-associated outbreaks had fewer average cases per outbreak than treated recreational water-associated outbreaks, but more average hospitalizations per outbreak (5). Of these outbreaks, 96% were associated with fresh water and 83% started in the three summer months of June, July, or August (5). *Cryptosporidium*, *E. coli*, *Giardia*, and *Shigella* were the etiologic agents in nearly half (49.9%) of all untreated recreational water outbreaks of gastrointestinal illness in the United States in the years 2009-2010 (5). Likewise, these four pathogens represented 49.3% of all such outbreaks in the decade 2001-2010 (5). Many parasitic and bacterial pathogens that cause

gastrointestinal illness show a marked increase in transmission during the summer months. This is due in part to increased participation in outdoor activities during this time, particularly recreational water activities that contribute to the transmission of gastrointestinal illness.

Cryptosporidium

Cryptosporidium was responsible for approximately 15.9% of all untreated recreational water outbreaks of gastrointestinal illness in the United States in the years 2009-2010 (5). It is a highly chlorine-tolerant protozoa that causes the gastrointestinal illness cryptosporidiosis (15), a nationally-notifiable disease. *Cryptosporidium* is transmitted through the fecal-oral route via ingestion of contaminated food or water, or through person-to-person or animal-to-person contact (15). Cryptosporidiosis occurs most frequently in children ages 1-4 years (15). The use of recreational water is a risk factor for transmission of *Cryptosporidium*, reflected in the fact that peak illness occurs in children from summer through early fall (15). Illness is characterized by typically nonbloody and watery diarrhea, abdominal pain, weight loss, fatigue, headache, fever, and vomiting (16). Factors that aid in the transmission of *Cryptosporidium* include the low infectious dose (17), the large number of oocysts that can be shed by an individual (18), the extended length of time of shedding in an individual (19), and the pathogen's high chlorine tolerance. The rate of reported cryptosporidiosis illness in the United States is 2.9 per 100,000 people (15).

Escherichia coli (E. coli)

E. coli was responsible for approximately 15.9% of all untreated recreational water outbreaks of gastrointestinal illness in the United States in the years 2009-2010 (5). *E. coli* are a group of bacteria; some are harmless while others are pathogenic. The pathogenic Shiga toxin-producing *E. coli* (STEC) are nationally notifiable and cause infections with a range of illnesses, from mild diarrhea to potentially fatal hemolytic uremic syndrome (HUS) (20). *E. coli* is transmitted through the fecal-oral route via ingestion of contaminated food or water, or through person-to-person or animal-to-person contact (21). Animal reservoirs are ruminants, predominantly cattle (21). Infection occurs most frequently in children less than five years of age (20). The incidence of *E. coli* infections peaks in the summer months. Symptoms of infection can include abdominal cramps, diarrhea, bloody diarrhea, fever, and vomiting (21). Factors that aid in the transmission include the bacteria's ability to survive for extended periods of time in the environment, its ability to multiply in the environment, and its high prevalence in the environment (21,22) The rate of reported STEC infection in the United States is 2.1 per 100,000 people (20).

Giardia

Giardia intestinalis was responsible for approximately 3.2% of all untreated recreational water outbreaks of gastrointestinal illness in the United States in the years 2009-2010 (5). It is a protozoa that causes the gastrointestinal illness giardiasis, a nationally notifiable disease. *Giardia* is transmitted through the fecal-oral route via ingestion of cysts through contaminated food or water, or through person-to-person or animal-to-person contact. It is the most common human intestinal parasite identified in the United States. There were

nearly 20,000 reported cases of giardiasis per year in 2009 and 2010. Giardiasis occurs most frequently in children ages 1-9, and peak illness occurs from early summer through early fall. Illness is characterized by diarrhea, abdominal cramps, bloating, and weight loss. Both treated and untreated recreational water has been determined to be a vehicle of the transmission of *Giardia* cysts and subsequent infection. Specific risk factors for contracting giardiasis include swallowing water while swimming or other means of recreational contact with fresh water. Factors that aid in the transmission of *Giardia* cysts include the large number that can be shed by an individual, the extended length of time of shedding in an individual, the ability of the protozoa to survive in the environment (23), and the low infectious dose (24). The rate of reported giardiasis illness in the United States is 7.6 per 100,000 people.

Shigella

Shigella was responsible for approximately 14.3% of all untreated recreational water outbreaks of gastrointestinal illness in the United States in the years 2009-2010 (5). It is a genus of bacteria that causes the gastrointestinal illness shigellosis, a nationally notifiable disease. There are four species of *Shigella*, with *S. sonnei* causing approximately 75% of reported cases of shigellosis illness (25). *Shigella* is transmitted through person-to-person contact or through the ingestion of contaminated food or water (26). Shigellosis occurs most frequently in children under the age of 10 (20). While the largest percentage of reported cases occur between late summer and fall (26), *Shigella* infection does not demonstrate the marked seasonality typical of some of enteric diseases (20). This is likely due to the predominance of person-to-person transmission. Illness is characterized by

bloody diarrhea, fever, abdominal pain, and nausea (27). Factors that aid in the transmission of *Shigella* include the low infectious dose (28) and its effective spread through the person-to-person transmission route (26). Antibiotic resistance of *Shigella* species is an emerging threat and may lead to increased transmission and illness (20,29). The rate of reported shigellosis illness in the United States is 4.9 per 100,000 people (20).

Extreme Weather Events

Temperatures may enhance the growth of certain pathogens or the nutrients on which they feed. Higher temperatures also lead to increased usage of recreational waters, further enhancing the possibility of exposure to pathogens. Increases in temperature also lead to increases in the capacity of the air to hold moisture.

Floods are the most common natural disasters and cause the greatest number of deaths of any type of natural disaster in the United States (30). In addition to the hazards that arise during a flood event, such as drowning and injury from debris, floods can lead to illness and infection for days after the event has ended. Extreme precipitation events cause large amounts of contaminated runoff from agriculture and livestock into surface waters, and high soil saturation can result in increased transport of pathogens (31). The overflow of sewage systems into natural water bodies can lead to an increase in the abundance of pathogenic organisms and subsequent waterborne disease transmission (30). As population grows and more people move into urban environments, the number of individuals that live in higher risk areas increases (32). This is particularly an issue in coasts and floodplains that are at highest risk of flooding (32). As more areas become

urbanized, the increase in impermeable surfaces leads to more runoff. The incidence of flooding can also increase due to deforestation and overgrazing as the lack of vegetation leads to a greater volume of runoff (32).

The effects of extreme weather events on waterborne disease is of increasing concern due in part to global climate change and projections of an increase in average temperatures and an increase in severe rainfall events (32). Average daily temperatures have risen by approximately 1°F in the continental United States over the past century (33). This is troubling not only because of the direct effect of increased temperature on pathogens, but also because warmer air can hold more moisture and lead to increases in precipitation (34). Additionally, precipitation events have become more extreme than in the past, with extreme events defined as >2 inches of rain per day (34-36). This can have serious implications for waterborne disease in the United States. Outbreaks of *Cryptosporidium* have previously been associated with both extreme and irregular precipitation events, irrespective of treatment (37).

The Effect of Weather on Waterborne Disease

The US National Assessment on the Potential Consequences of Climate Variability and Change has identified public health priorities for the United States. One such priority is to increase research on the effect of weather on the incidence of waterborne disease outbreaks (31). Rainfall and subsequent runoff have already been recognized as the driver of multiple outbreaks in the United States, but the true burden of disease due to these environmental events is unknown.

Studies on a national scale have found positive associations between extreme weather events and waterborne disease outbreaks in both the United States and The Netherlands. The study in the United States, analyzing the association between extreme precipitation events and drinking water-associated disease outbreaks, found that 51% of such outbreaks followed a precipitation events above the 90th percentile ($p=0.002$) (38). Additionally, 68% followed a precipitation events above the 80th percentile, ($p=0.001$) (38). Outbreaks associated with surface water contamination showed a stronger association with extreme precipitation than outbreaks associated with groundwater contamination. This suggests that untreated recreational water, which is by nature surface water, may also exhibit a similar trend. This study excluded all recreational outbreaks, analyzing only the relationship between precipitation and drinking water outbreaks. An analysis of the incidence of waterborne outbreaks associated with untreated recreational venues and extreme precipitation in the United States has not been done (38).

A nationwide study in The Netherlands investigated the relationship between untreated recreational water-associated disease outbreaks and extreme precipitation and temperature events. This study analyzed 742 outbreaks that occurred between the years 1991 and 2007. Gastrointestinal illness represented 31% of the illnesses in this study, while the majority (48%) were dermal conditions. The authors found that the number of outbreaks during each summer swimming season was associated with the number of warm days in a summer season, defined as one with a maximum of ≥ 25 °C (11).

Weather events can affect waterborne disease incidence both directly and indirectly. They can cause direct effects by affecting the survivability and reproduceability of a pathogen (39). Increased temperatures can affect pathogenic waterborne organisms by extending an organism's replication cycle (37). It is well established that *E. coli* is temperature-dependent, though ideal temperatures vary depending on whether the outcome is survival or growth (40). They can cause indirect effects by changing human behavior. For instance, most regions in the United States are not suitable for swimming outdoors in the winter months; therefore, untreated recreational water-associated disease outbreaks are incredibly rare during this time because human exposure to waterborne pathogens is not occurring, regardless of whether or not pathogens are prevalent (39).

Field studies have found that *E. coli* concentrations in surface waters increase after severe precipitation events (41). A 2009 study of eight beaches in Wisconsin found that after a 5mm rainfall event, five of these beaches had a significantly higher *E. coli* concentration than the seasonal mean (42). The three beaches that did not show elevated *E. coli* concentrations had minimal agricultural animal populations. Increased precipitation has been associated with an increased presence of *Giardia* cysts in California (43) and has been acknowledged as a cause of outbreaks of Giardiasis in the United States (4). Increased precipitation has been associated with the incidence of severe illness from *Shigella* infection in China (44). The incidence of Shigellosis increases with increasing temperatures and increasing precipitation. Ma et al calculated a risk ratio for developing shigellosis of 1.1 for every 1°C increase in temperature between 12°C and 22°C (45).

Xiao et al calculated that there is a 0.5% increase in the incidence of shigellosis for every 1 mm increase in precipitation (46).

Lag Periods

After an extreme temperature or precipitation event, health effects are not experienced immediately. The period between a weather event and the time of exposure is known as the lag period. The length of a given lag period, which can be anywhere from hours to months, depends on a variety of factors including the type of weather event and the pathogen of interest (39). If the outcome of interest is the time of incidence of disease, as opposed to time exposure, then the incubation period of the pathogen must be considered as well.

The four pathogens of interest in this analysis, *Cryptosporidium*, *E. coli*, *Giardia*, and *Shigella*, have varying incubation periods. The time between exposure and infection with *Cryptosporidium* oocysts and development of cryptosporidiosis is generally 1-12 days (47) but is typically 7 days (48). The incubation time of *E. coli* infection is generally 1-3 days after exposure (49) but can be up to 4 days (48). The incubation time of giardiasis is generally 1-14 days after one is exposed (50). The incubation time of shigellosis infection is generally 1-3 days after exposure (48).

An analysis of temperature and all forms of gastrointestinal illness in the Mekong Delta found a four-week lag time between high temperature and the incidence of disease (51). However, the four pathogens of interest do not all have equivalent lag times between an

environmental event and exposure or disease incidence. Naumova et al analyzed the distribution of ambient air temperatures over a ten-year period in Massachusetts against the distribution in the incidence of a variety of gastrointestinal illnesses in order to determine the probable lag period between temperature and disease incidence. The authors found that the peak incidence of cryptosporidiosis and shigellosis is approximately 5 weeks after the peak ambient air temperature. The peak incidence of giardiasis is approximately 6 weeks after peak ambient air temperature (51). This is consistent with the incubation time of giardiasis possibly being longer than that of the other two pathogens (51-53).

Lag periods between precipitation events and the incidence of waterborne illness are generally shorter. A Massachusetts study found that a flooding event, as defined by the National Oceanic and Atmospheric Administration (NOAA) was associated with an increased risk for emergency room visits for gastrointestinal illness in the 0-4 days following the event (53). An outbreak of *E. coli* O157:H7 in Ontario, Canada was preceded by severe rainfall event 5-10 days earlier (54). A seven-day lag period has been used to calculate the effect of extreme precipitation events on the incidence of shigellosis in Taiwan (55).

Case-Crossover Analysis

Case-crossover studies have been used in the assessment of the effect of meteorological events on waterborne disease (56-58). The case-crossover design is most often used in epidemiologic investigations in which exposure to a risk factor is short-term and the

adverse health outcome is acute (59). As Maclure and Mittleman explain, this design is particularly useful at answering the question, “Was this event triggered by something unusual that happened just before?” (60). The study population consists only of cases; these cases serve as their own controls, and the exposure periods are chosen from each case’s history (60,61). The set of event and control periods within each case’s exposure history is the reference window (61). Because a case-crossover study employs self-matching, the design allows for the control of confounders that do not vary with respect time (61). There are some terms in relation to case-crossover studies are important to define. The induction time is the time between the component cause, or event of study, and the initiation of disease (60,62). The latent period, which can be called the incubation period in infectious processes, is the time between the initiation of disease and the detection of disease (60,62). The effect period in a case-crossover study is the time between the minimum and maximum induction period and incubation periods (60). The hazard period includes the effect period as well as the duration of exposure (60). Exposure windows are arbitrary units of observation (60). This can be useful to use when estimates of the effect period or the hazard period are imprecise or unknown (60). These estimates in the study of the effect of weather on gastrointestinal illness can be difficult to ascertain due to varying lengths of induction times, incubation periods, and gaps in research.

II. Manuscript Introduction

Gastrointestinal illness is a significant and growing (1) burden on the United States healthcare system. While most cases of gastrointestinal illness are self-limiting, illnesses can be severe and even fatal in the immunocompromised or other vulnerable populations (4). Acute gastrointestinal illness is the predominant illness in over half of all recreational water-associated outbreaks in the United States and two-thirds of untreated recreational water-associated outbreaks (5). *Cryptosporidium*, *E. coli*, *Giardia*, and *Shigella* were the etiologic agents in nearly half 49.3% of all untreated recreational water outbreaks of gastrointestinal illness in the United States in the first decade of the 21st century (5).

The Centers for Disease Control and Prevention (CDC) categorizes the transmission of waterborne disease as drinking water, recreational water, or other. Recreational water exposures are divided into treated and untreated water venues. Untreated recreational water venues include lakes, ponds, reservoirs, rivers, and beaches (6). Evidence suggests that untreated recreational venues are indeed subject to incidental fecal contamination due to environmental conditions (11) and infectious disease has been linked to fecally contaminated water.

The US National Assessment on the Potential Consequences of Climate Variability and Change has identified increased research on the effect of weather on the incidence of waterborne disease as a public health priorities for the United States (31). Weather events that may affect the incidence of waterborne disease outbreaks are increases in temperature or precipitation. Temperatures may enhance the growth of certain pathogens

or the nutrients on which they feed. Higher temperatures lead to increased usage of recreational waters. Increases in temperature also lead to increases in the capacity of the air to hold moisture. Extreme precipitation events cause large amounts of contaminated runoff from agriculture and livestock into surface waters (31). The overflow of sewage systems into natural water bodies can lead to an increase in the abundance of pathogenic organisms and subsequent waterborne disease transmission (30). The effects of extreme weather events on waterborne disease is of increasing concern due in part to global climate change and projections of an increase in average temperatures and an increase in severe rainfall events (32).

Studies on a national scale have found positive associations between extreme precipitation events and increases in drinking water outbreaks in the United States (38) and extreme precipitation and temperature events and untreated recreational water outbreaks in The Netherlands (11). An analysis of these weather events with untreated recreational water outbreaks in the United States has not been done previously. The purpose of this study is to investigate the relationship between precipitation and temperature and untreated recreational waterborne disease outbreaks using the Waterborne Disease Outbreak Surveillance System and the National Outbreak Reporting Systems of reported waterborne disease outbreaks in the United States from 1978 to 2010.

III. Manuscript Methods

Outbreak Data

Data on all reported waterborne disease outbreaks, classified as untreated recreational water-associated, in the United States from 1978 to 2010 were obtained from the Centers for Disease Control and Prevention's Waterborne Disease Outbreak Surveillance System and the National Outbreak Reporting System. Included in this data set was a database identification number, state and county of exposure, etiologic agent(s), and the date the first case became ill. A waterborne disease outbreak was defined as an outbreak in which two or more cases of similar illness can be epidemiologically connected in place and time to a common water exposure (5). This data query returned 209 untreated recreational water-associated outbreaks. Outbreaks in which at least one etiologic agent was not a species of *Cryptosporidium*, *E. coli*, *Giardia*, or *Shigella* were excluded, resulting in 87 outbreaks. Of these 87 outbreaks, 14 did not include a county of exposure in the database. For these 14 outbreaks, a review of the original outbreak report located in the CDC's Waterborne Disease Prevention Branch in Atlanta, Georgia was completed. These reviews led to the discovery of the county of exposure in an additional 11 of the 14 outbreaks. The outbreak in which the county of exposure could not be determined was excluded, resulting in 84 outbreaks for analysis.

Weather Data

Temperature and precipitation data for the counties of interest were accessed from the National Oceanic and Atmospheric Administration's National Climatic Data Center. Daily maximum and minimum temperatures, measured in tenths of degrees Celsius, and total daily precipitation, measured in tenths of millimeters, were downloaded for the three-year strata in which each outbreak fell. When multiple weather stations were

present in each county, data were downloaded from the station closest to the centroid of the county that had complete data for daily maximum and minimum temperatures and total daily precipitation for the hazard periods of interest. When there was no station in a county with complete data for the parameters and years of interest, data from weather stations in adjacent counties were downloaded. The station closest to the centroid of the county of interest with complete data was used.

Case-Crossover Analysis

We used a time-stratified 2:1 matched case-crossover design. The years of analysis, 1978-2010, were divided into 3-year strata. Hazard periods in the analysis of the temperature were the five weeks prior to an outbreak of *Cryptosporidium*, *E. coli*, *Giardia*, or *Shigella*. Hazard periods in the analysis of the precipitation were the two weeks prior to an outbreak of *Cryptosporidium*, *E. coli*, *Giardia*, or *Shigella*.

Temperature and rainfall were measured as continuous variables. Control periods were the corresponding weeks in the years within each stratum that did not include an outbreak and could precede, follow, or both precede and follow the hazard period.

Estimates of effect periods were based on a usual incubation period of 1-12 days for cryptosporidiosis (47), 1-4 days for *E. coli* infection (48,49), 1-14 days for giardiasis (50), and 1-3 days for shigellosis (48). Odds ratios (ORs) for occurrence of outbreaks, based on temperature and rainfall effects, were estimated using conditional logistic regression.

IV. Manuscript Results

Outbreaks

From 1978-2010 there were 84 reported outbreaks of *Cryptosporidium*, *E. coli*, *Giardia*, and/or *Shigella* associated with untreated recreational water venues in the United States.

There were 74 outbreaks with one etiologic agent and ten outbreaks with two or more etiologic agents (Table 1). Six of the ten outbreaks with multiple etiologic agents had more than one etiologic agent of interest (*Cryptosporidium*, *E. coli*, *Giardia*, and *Shigella*; Table 1). *Shigella* was the etiologic agent in the most outbreaks (n=40, Table 1).

The 84 outbreaks analyzed in this study were located in 69 different counties across the United States, most of which (n=59) only had one outbreak (Table 2). 29 states had outbreaks included in the analysis. 28 of these states had between one and five outbreaks, while Minnesota had fourteen outbreaks. More outbreaks occurred in the month of July than any other month (n=4, Table 3). Figure 1 illustrates that the number of reported outbreaks grew steadily between the mid-1980s and early-1990s.

Hazard Periods

Univariate analyses of each predictor variable (average precipitation over two weeks, average maximum temperature over five weeks, and average minimum temperature over five weeks) evaluated in three separate models show that no variable is significantly associated with an outbreak individually (Table 4). When average precipitation for the two-week hazard period, average maximum temperature for the five-week hazard period, and average minimum temperature for the five-week hazard period were all included in the same model, the likelihood ratio for the model was not significant (p=0.165).

However, average minimum temperature was significant in the model (OR=1.033; 95% CI: 1.003-1.063) (Table 5, Figure 2) (Table 5, Figure 2).

To analyze the suitability of including both average maximum temperature and average minimum temperature in the same model, partial correlation was calculated between the average maximum temperature for the five-week hazard period and the average minimum temperature for the five-week hazard period, controlling for strata. The two variables are strongly correlated $r(245)=0.834, p <0.001$ (Figure 3). Average maximum temperature and average minimum temperature were subsequently not included in the models simultaneously.

Stratification

Analyses of each predictor variable (average precipitation over two weeks, average maximum temperature over five weeks, and average minimum temperature over five weeks) in three separate models were conducted, stratified by pathogen. No predictor variable was significant for any pathogen when analyzed separately. ORs were also analyzed for each predictor variable stratified by type of organism (bacteria versus protozoa) and by US region (Northeast, Southeast, Midwest, West, Southwest). No predictor variable was significant for any variables for these stratifications (data not shown).

Weekly Hazard Periods

To analyze the possibility of temperature and precipitation effects at smaller scales, each two- and five-week hazard period was divided into one-week periods. No one-week hazard period for average maximum temperature or average precipitation was significantly associated with an outbreak (data not shown). However, the average minimum temperature in the week preceding an outbreak was significantly associated with outbreaks, with an OR=1.162 (95% CI: 1.017-1.327) (Table 6). This was the only predictor variable found to be individually associated with the incidence of a waterborne disease outbreak of gastrointestinal illness.

Average minimum temperatures were further analyzed to evaluate the association between the incidence of outbreaks and one-, two-, three-, and four-week hazard periods. Figures 4-6 show the ORs and confidence limits for the three models with a likelihood ratio test significant at $\alpha=0.05$. In every model that met this significance criteria, the average minimum temperature in the week preceding an outbreak was the only significant predictor variable analyzed. The most significant model (χ^2 (df=1) = 5.21, $p=0.023$), was that which only included average minimum temperature in the week preceding the outbreak.

Stratification by Pathogen

Analyses of each of the three models with a likelihood ratio test significant at $\alpha=0.05$ (Figures 4-6) was further stratified by pathogen. Only models for *E. coli* that included average minimum temperature in the one-four weeks prior to an outbreak were significant. Table 7 shows the model of average minimum temperature that depicted a

significant association with the incidence of an outbreak of *E. coli*. This could suggest that the effect of minimum temperatures is on pathogen survival or growth is stronger for *E. coli* than the other pathogens studied.

V. Manuscript Discussion

Using a national surveillance system for gastrointestinal outbreaks we observed an increased risk for untreated recreational water-associated GI outbreaks with increased average minimum temperatures in the 0-7 days preceding an outbreak, but not during other time periods. We also did not find an association between GI outbreaks and average maximum temperatures or average precipitation over any time period. We found a stronger effect on *E. coli* during the 0-28 days preceding an outbreak compared to the other three pathogens, whether or not precipitation was included in the model. Future studies could focus on this association with larger sample size to investigate if this association can be replicated in other scenarios.

By applying a case-crossover design, we controlled for differences in reporting between different counties and different states. We also controlled for factors that are not likely to change in the three-year strata between the control and case periods such as significant changes in county reporting requirements, health trends, age distributions, and socioeconomic stratification. Moreover, seasonal variation was controlled through time stratification and by matching case outbreak dates to corresponding dates in control years.

Previous analysis of the association between extreme precipitation events and drinking water-associated disease outbreaks in the United States found that 51% of such outbreaks followed a precipitation event above the 90th percentile ($p=0.002$) (38). Additionally, 68% followed a precipitation events above the 80th percentile, ($p=0.001$) (38). The results of our analysis do not necessarily contradict the results of this earlier study. Firstly, the authors analyzed drinking water-associated outbreaks and excluded all recreational water-associated outbreaks. Secondly, the authors did not analyze temperature as a predictor variable. Thirdly, the time periods analyzed were different between the two studies. Finally, they included all outbreaks associated with all etiologies, while our analysis focused on only four pathogens associated with gastrointestinal disease. Our analysis suggests that there may be important ways in which weather phenomena affect drinking water-associated outbreaks differently than recreational water-associated outbreaks and the ways in which these phenomena affect different illness types.

A nationwide study in The Netherlands investigated the relationship between untreated recreational water-associated disease outbreaks and extreme precipitation and temperature events (11). The authors found that the number of outbreaks during each summer swimming season was associated with the number of warm days in a summer season, defined as one with a maximum of ≥ 25 °C (11). Our analysis also suggests that a temperature threshold serves to increase the risk of waterborne disease. An important different between this study and ours in the inclusion of non-GI illness. GI illness only

represented 31% of illness in their study, while the majority (48%) were dermal conditions.

There are several limitations to this study. First, the sample size was small; 84 outbreaks met our study criteria. Because the effect did not change significantly between 5- and 6-week hazard periods, all four pathogens were analyzed in the same hazard period. Including all GI pathogens, instead of only *Cryptosporidium*, *E. coli*, *Giardia*, and *Shigella*, might have increased sample size and power in the models. There are inherent limitations in the use of passive surveillance data. State and local health departments are not required to report these outbreaks, and there is variability between states in the capacity to detect, investigate and report outbreaks. The case-crossover analysis was used to control for variability across counties and states, but it could not control for variability in health department capacity within a county in a given three-year strata. The surveillance data also only provided information on the date that the first person in the outbreak became ill, not on the date of exposure. Established incubation periods were used to determine hazard periods, further adding uncertainty to the analysis. The surveillance system only provided data on outbreaks at the county level, not on the particular town or beach where exposure occurred. This leads to limitations in assessing the association between an outbreak and the exposure variables, because weather stations are located at various places within a county. Accessing weather data from the station closest to the centroid of the county was a uniform way to choose weather stations for all study observations, but could result in a weather station being chosen that is not truly closest to the exposure site. There were also limitations accessing the weather stations.

Many stations did not collect either precipitation data or temperature data, while others had large gaps or too many missing observations to be useable for analysis.

The lack of an association in this study between average maximum temperatures and outbreaks, as well as average precipitation and outbreaks, in spite of biological and epidemiological evidence of a relationship in other settings, could be an indicator that current state and local regulations on beach closures are effective. Decisions to close beaches are made when water quality violations are measured or when predictive modeling, often based on precipitation events, indicates that water will be contaminated. Since the relationship between precipitation events and reduced water quality is well-established, beach closures are a public health strategy to reduce illness associated with these weather events. Further research should be done into how the effectiveness of such strategies varies across the county and what modifications might be needed due to a changing climate. Subsequent studies on the effects of temperature on GI illness should study average minimum temperatures as a separate predictor from maximum or average temperatures to investigate its impact.

VI. Conclusions and Recommendations

Our study helps fill a gap in the literature on the effect of temperature and precipitation on the incidence of GI outbreaks in untreated recreational water venues in the United States. Studies on a national scale have found positive associations between extreme precipitation events and increases in drinking water outbreaks in the United States (38) and extreme precipitation and temperature events and untreated recreational water outbreaks in The Netherlands (11). An analysis of these weather events with untreated recreational water outbreaks in the United States has not been previously published.

Such an analysis was needed because gastrointestinal illness is a significant burden in the United States and is most pronounced for vulnerable population groups. GI illnesses can be severe and even fatal in the immunocompromised, children, elderly, and pregnant women (4). It is imperative that we, as a society, evaluate the way in which we manipulate the environment and how such manipulations can cause illness. While natural water bodies become contaminated in a variety of ways, anthropogenic activities such as farming and urban sprawl are certainly factors. The farm environment is a particularly significant source of contamination, and cattle are an important reservoir for *E. coli* and *Cryptosporidium* (7,15). Urban runoff is another common source of contamination. This is because the impermeability of cement and asphalt lead to large amounts of runoff directly into the watershed, without the natural filtering of groundwater. Another significant source of untreated surface water contamination is sewage effluent (9), and an inverse relationship has been found between the frequency of gastrointestinal symptoms and distance from city wastewater outlets (13).

Environmental events have immense significance in public health, particularly as they serve as determinants of infectious disease. Temperatures may enhance the growth of certain pathogens or the nutrients on which they feed and lead to increases in the capacity of the air to hold moisture. Extreme precipitation events cause large amounts of contaminated runoff from agriculture and livestock into surface waters, and high soil saturation can result in increased transport of pathogens (31). Extreme precipitation events can lead to illness and infection for days after the event has ended. The incidence of flooding can also increase due to deforestation and overgrazing as the lack of vegetation leads to a greater volume of runoff (32).

In addition to the ways in which humans are directly manipulating the environment, the effects of extreme weather events on waterborne disease is of increasing concern due to global climate change. There are projections of both an increase in average temperatures and an increase in severe rainfall events. Average daily temperatures have risen by approximately 1°F in the continental United States over the past century (33), and precipitation events have become more extreme than in the past (34-36). The US National Assessment on the Potential Consequences of Climate Variability and Change has identified an increase in research on the effect of weather on the incidence of waterborne disease outbreaks as a national public health priority (31).

The results of these studies provide a variety of areas for future research. Average minimum temperatures consistently arose as the only significant predictor variable in

multiple models. I would urge researchers who are analyzing the relationship between temperature and disease in the future to study average minimum temperatures as a separate predictor from maximum or average temperatures in order to further investigate its potential impact. Additionally, we found a stronger effect on *E. coli* during the 0-28 days preceding an outbreak compared to the other three pathogens. I would suggest that future studies might analyze this association with larger sample sizes to investigate if this association can be replicated in other scenarios. Finally, the lack of an association in this study between average maximum temperatures and outbreaks, as well as average precipitation and outbreaks, could be an indicator that current state and local regulations on beach closures are effective. Further research should be done into how the effectiveness of such strategies varies across the county, as well as the relationship between extreme weather events and beach closures. Adaptive strategies such as beach closures might be important leverage points at which to protect public health.

VII. References

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VIII. Tables and Figures

Table 1. Etiologic Agents involved in Outbreaks of Gastrointestinal Disease in an Untreated Recreational Water Venue, 1978-2010		
	N (Outbreaks)	% (of Total Outbreaks)
Number of Etiologies in a Single Outbreak		
1	74	88.10%
2	6	7.14%
3	4	4.76%
Number of Etiologies of Interest* in Single Outbreak		
1	78	92.86%
2	6	7.14%
Etiologic Agent Involved in Outbreak**		
<i>Cryptosporidium</i>	17	20.24%
<i>E. coli</i>	23	27.38%
<i>Giardia</i>	9	10.71%
<i>Shigella</i>	40	47.62%

**Cryptosporidium*, *E. coli*, *Giardia*, or *Shigella*

**Total is >84 (100%) because some outbreaks had multiple agents

Table 2. Number of US Counties Reporting Outbreaks of Gastrointestinal Disease in an Untreated Recreational Water Venue, 1978-2010		
Number of Outbreaks in a County	Number of Counties	Percentage of Counties out of Total Counties (69)
1	59	85.51%
2	7	10.14%
3	1	1.45%
4	2	2.90%

Month	Number of Outbreaks	Percentage of Outbreaks out of Total Outbreaks
January	0	-
February	0	-
March	3	3.57%
April	0	-
May	4	4.76%
June	20	23.81%
July	41	48.81%
August	12	14.29%
September	4	4.76%
October	0	-
November	0	-
December	0	-

	Odds Ratio Estimate	95% Wald Confidence Limits
Average Precipitation over Two Weeks (mm)	1.022	0.910 , 1.148
Average Maximum Temperature over Five Weeks (°C)	0.985	0.849 , 1.142
Average Minimum Temperature over Five Weeks (°C)	1.17	0.954 , 1.434

*1mm increase in average precipitation, 1°C increase in temperature

	Odds Ratio Estimate	95% Wald Confidence Limits
Average Precipitation over Two Weeks (mm)	0.997	0.883 , 1.126
Average Maximum Temperature over Five Weeks (°C)	0.839	0.678 , 1.038
Average Minimum Temperature over Five Weeks (°C)	1.378 [†]	1.031 , 1.841

*1mm increase in average precipitation, 1°C increase in temperature

[†] $p < 0.05$ for the parameter

Table 6. Univariate ORs and 95% CIs for Associations Between Average Minimum Temperature (°C) and Reported Outbreaks of Gastrointestinal Illness, 1978–2010		
	Odds Ratio Estimate	95% Wald Confidence Limits
Average Minimum Temperature, Days 0-7 Preceding Outbreak (°C)	1.162*	1.017 , 1.327
Average Minimum Temperature, Days 8-14 Preceding Outbreak (°C)	1.078	0.967 , 1.202
Average Minimum Temperature, Days 15-21 Preceding Outbreak (°C)	1.076	0.968 , 1.197
Average Minimum Temperature, Days 22-28 Preceding Outbreak (°C)	0.935	0.834 , 1.047
Average Minimum Temperature, Days 29-35 Preceding Outbreak (°C)	1.000	0.894 , 1.118

* $p < 0.05$ for the parameter

Table 7. Univariate ORs and 95% CIs for Associations Between Average Minimum Temperature and Reported Outbreaks of Gastrointestinal Illness due to <i>E. coli</i> , 1978–2010			
	Odds Ratio Estimate	95% Wald Confidence Limits	Likelihood Ratio p-value
Average Minimum Temperature, Days 0-28 Preceding Outbreak			0.031
Average Minimum Temperature, Days 0-7 Preceding Outbreak	1.324	0.950 , 0.846	
Average Minimum Temperature, Days 8-14 Preceding Outbreak	1.245	0.936 , 1.656	
Average Minimum Temperature, Days 15-21 Preceding Outbreak	1.423	0.997 , 2.031	
Average Minimum Temperature, Days 22-28 Preceding Outbreak	0.794	0.595 , 1.060	

Figure 1. Reported Outbreaks of GI Illness in Untreated Recreational Water Venues, 1978–2010

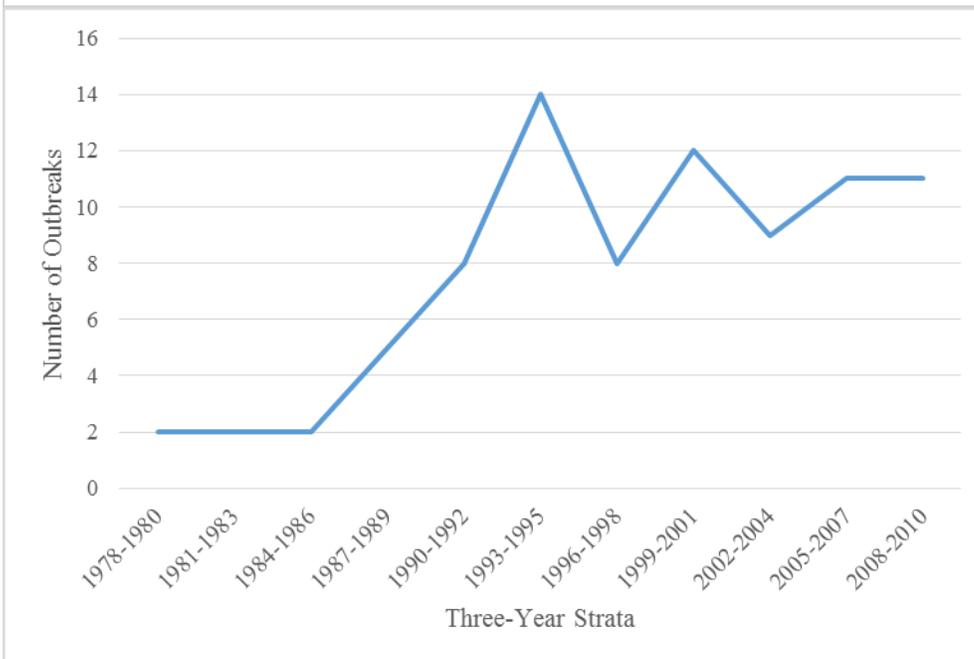


Figure 2. Odds ratios for the multivariate model including average precipitation over the two-week hazard period (mm), average minimum temperature over the five-week hazard period ($^{\circ}\text{C}$), and average maximum temperature over the five-week hazard period ($^{\circ}\text{C}$)

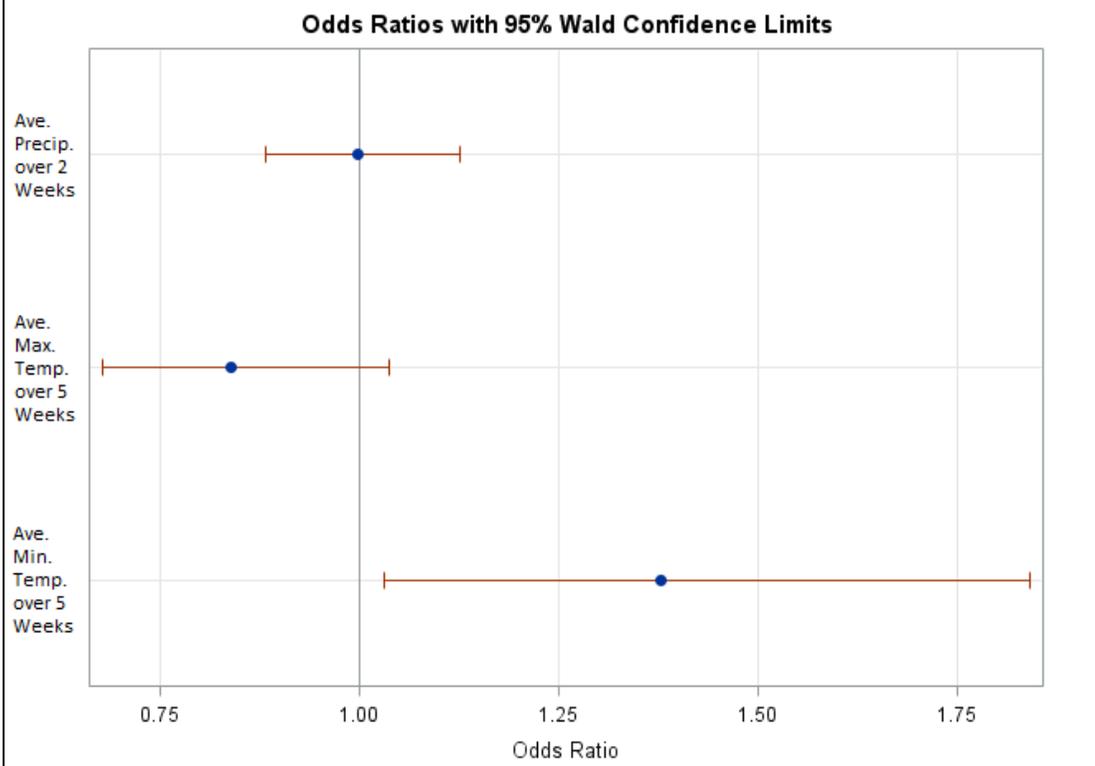


Figure 3. Partial Correlation between Five-Week Average Minimum Temperature and Five-Week Average Maximum Temperature

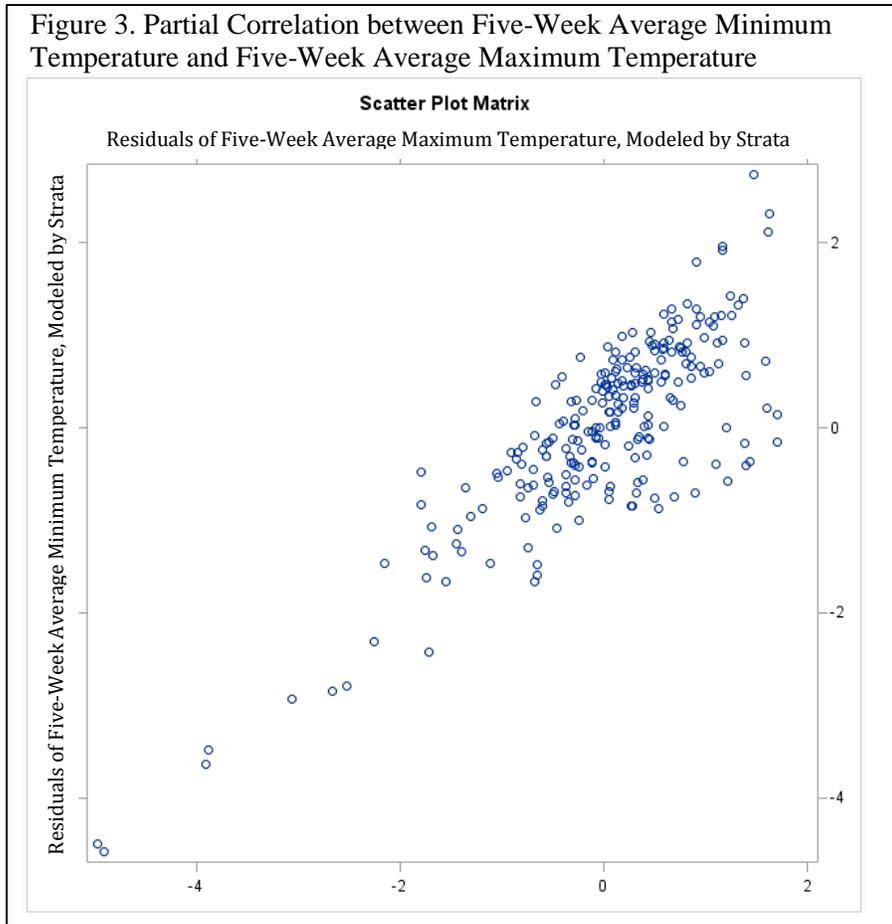


Figure 4. Multivariate Adjusted ORs and 95% CIs for Associations between Average Minimum Temperature ($^{\circ}\text{C}$, Days 0-28 Preceding Outbreak) and Reported Outbreaks of Gastrointestinal Illness, 1978-2010

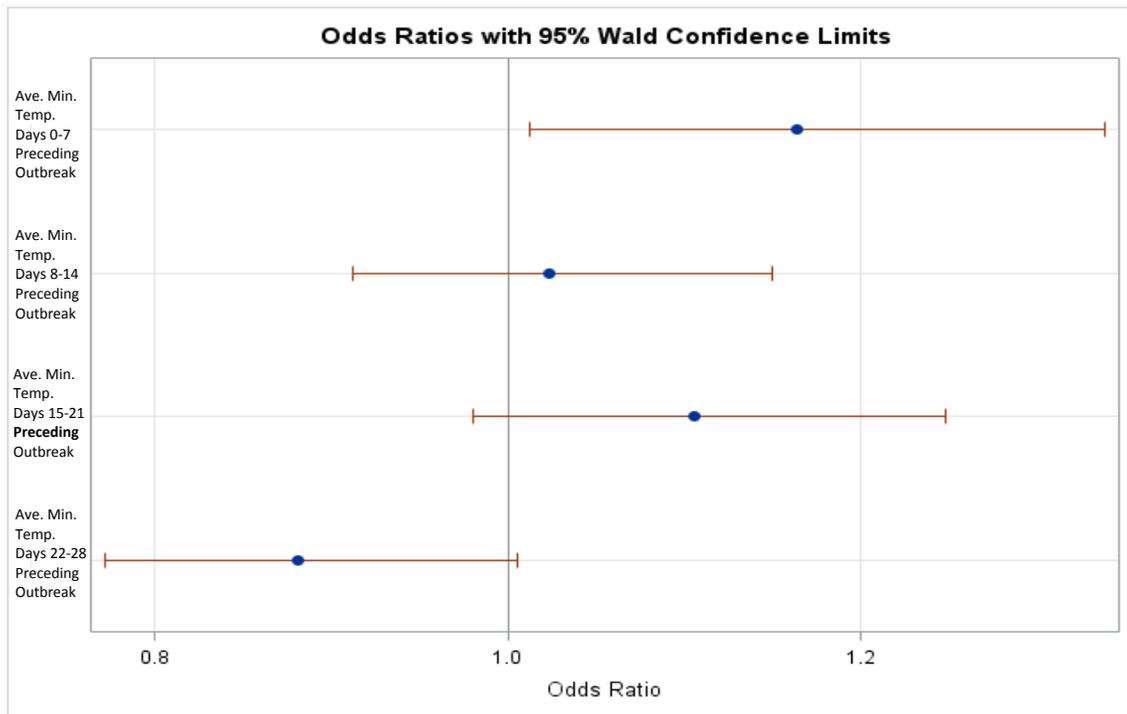


Figure 5. Multivariate Adjusted ORs and 95% CIs for Associations between Average Minimum Temperature ($^{\circ}\text{C}$, Days 0-14 Preceding Outbreak) and Reported Outbreaks of Gastrointestinal Illness, 1978-2010

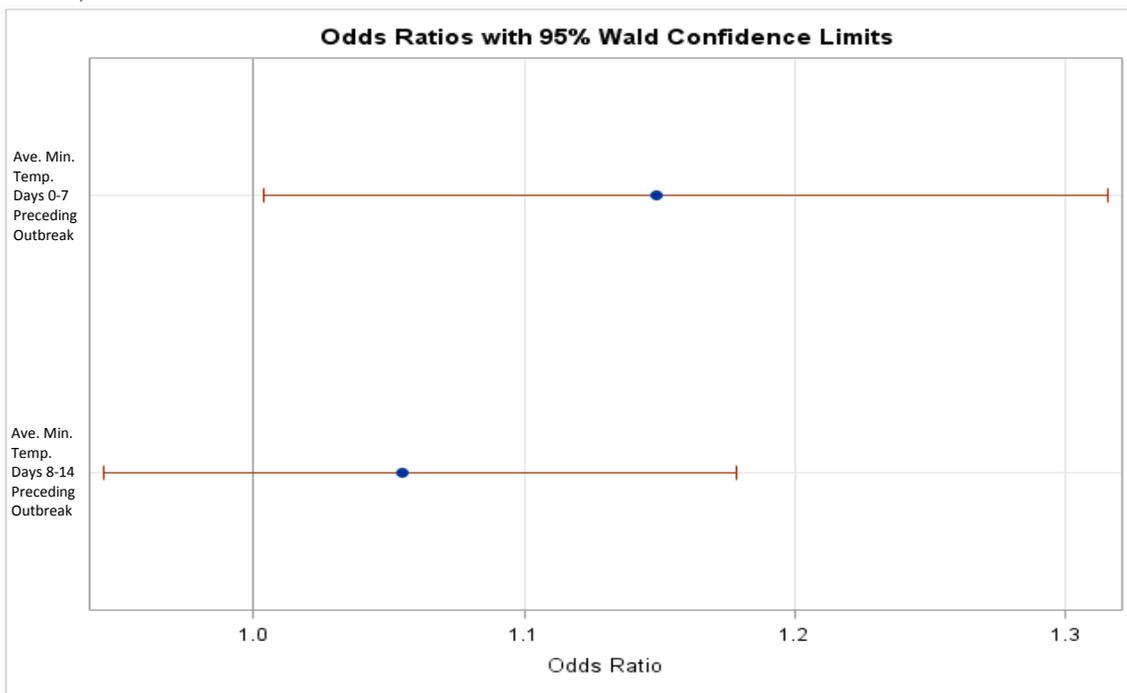
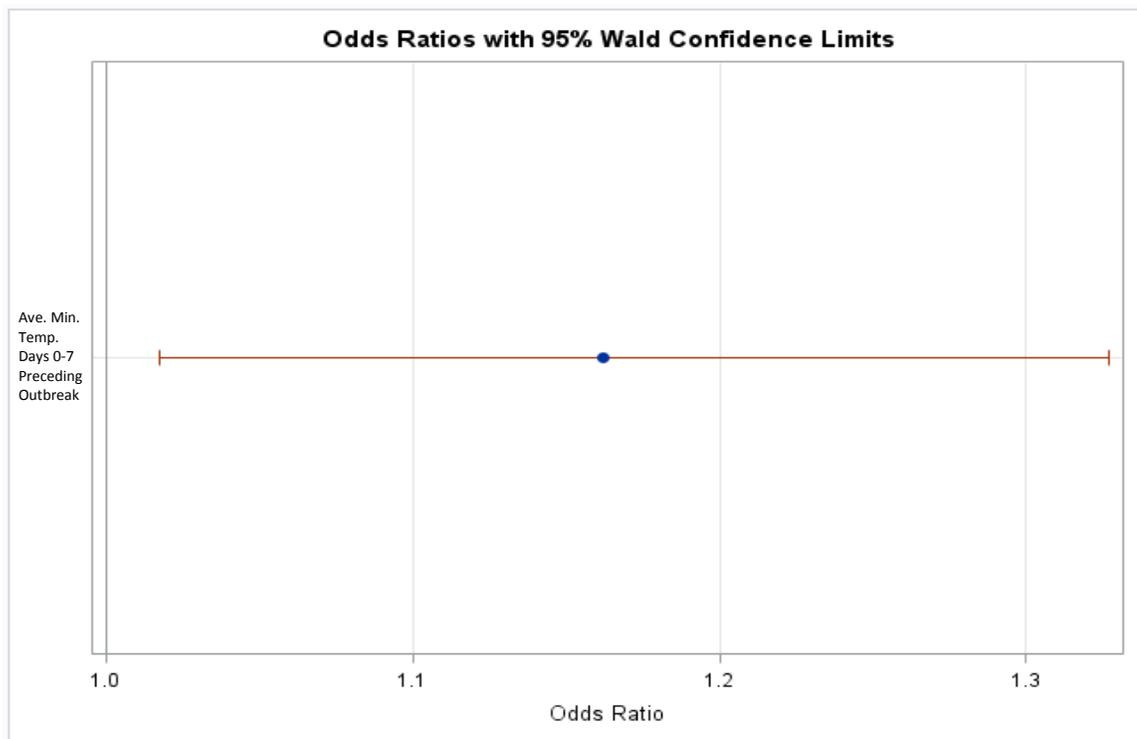


Figure 6. Univariate OR and 95% CI for Association between Average Minimum Temperature ($^{\circ}\text{C}$, Days 0-7 Preceding Outbreak) and Reported Outbreaks of Gastrointestinal Illness, 1978-2010



IX. Appendix

Appendix A. US States Reporting Outbreaks of Gastrointestinal Disease in an Untreated Recreational Water Venue, 1978-2010		
State	Number of Outbreaks	Percentage of Outbreaks in State out of Total Outbreaks
Arkansas	2	2.38%
California	2	2.38%
Colorado	3	3.57%
Connecticut	1	1.19%
Florida	3	3.57%
Georgia	2	2.38%
Idaho	1	1.19%
Illinois	4	4.76%
Indiana	1	1.19%
Kansas	1	1.19%
Maryland	2	2.38%
Massachusetts	4	4.76%
Michigan	1	1.19%
Minnesota	14	16.67%
Missouri	2	2.38%
New Jersey	5	5.95%
New York	5	5.95%
North Carolina	1	1.19%
North Dakota	1	1.19%
Ohio	3	3.57%
Oklahoma	1	1.19%
Oregon	2	2.38%
Pennsylvania	5	5.95%
South Carolina	2	2.38%
Tennessee	3	3.57%
Virginia	1	1.19%
Washington	4	4.76%
Wisconsin	5	5.95%
Wyoming	3	3.57%

Appendix B. Univariate ORs and 95% CIs for Associations Between Weather Events* and Reported Outbreaks of Gastrointestinal Illness, 1978–2010, by Etiology			
	Strata (n)	Odds Ratio Estimate	95% Wald Confidence Limits
Average Precipitation over Two Weeks (mm)			
<i>Cryptosporidium</i>	17	0.969	0.743 , 1.263
<i>E. coli</i>	23	1.108	0.907 , 1.353
<i>Giardia</i>	10	0.686	0.337 , 1.395
<i>Shigella</i>	39	1.017	0.856 , 1.208
Average Maximum Temperature over Five Weeks (°C)			
<i>Cryptosporidium</i>	17	0.888	0.643 , 1.225
<i>E. coli</i>	23	1.091	0.813 , 1.465
<i>Giardia</i>	10	0.898	0.618 , 1.306
<i>Shigella</i>	39	1.010	0.815 , 1.252
Average Minimum Temperature over Five Weeks (°C)			
<i>Cryptosporidium</i>	17	1.147	0.711 , 1.848
<i>E. coli</i>	23	1.622	0.976 , 2.697
<i>Giardia</i>	10	0.873	0.490 , 1.554
<i>Shigella</i>	39	1.084	0.825 , 1.424

*1mm increase in average precipitation, 1°C increase in temperature