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Hydrologic Impacts on Human Health

El Niño Southern Oscillation and Cholera

Elissa M. Yeates, Kayla A. Cotterman, and Angela M. Rhodes

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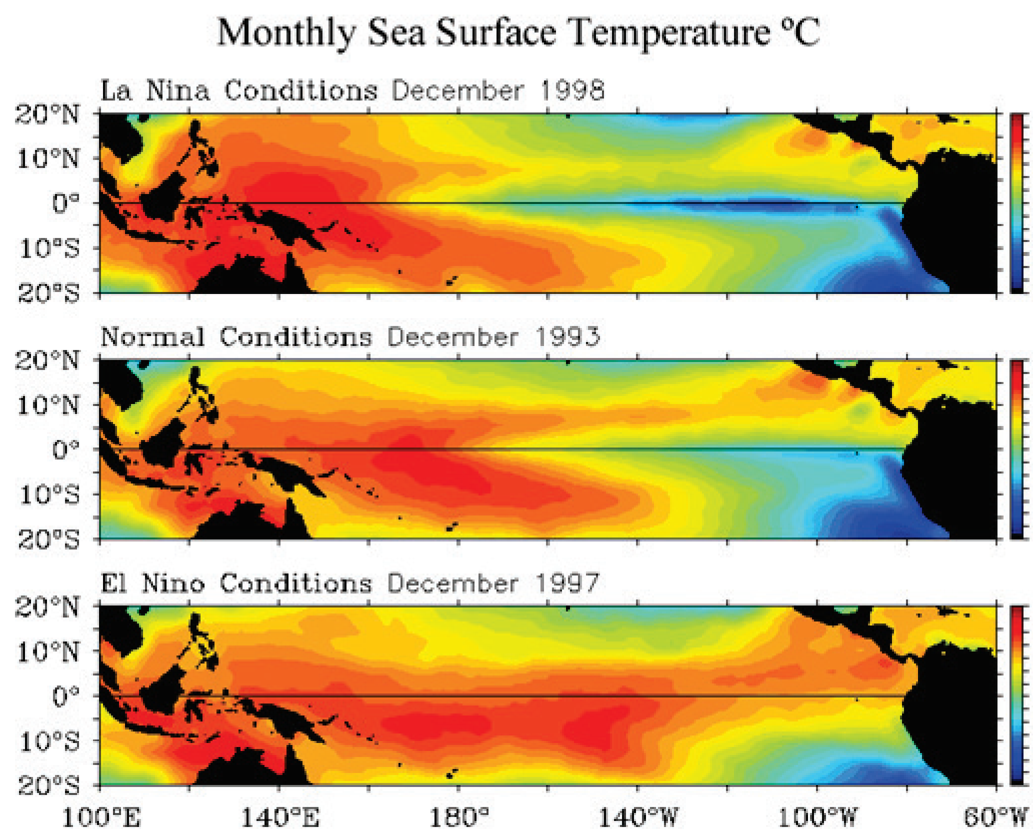

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Abstract

A non-stationary climate imposes considerable challenges regarding potential public health concerns. The El Niño Southern Oscillation (ENSO) cycle, which occurs every 2 to 7 years, correlates positively with occurrences of the waterborne disease cholera. The warm sea surface temperatures and extreme weather associated with ENSO create optimal conditions for breeding the *Vibrio cholerae* pathogen and for human exposure to the pathogenic waters. This work explored the impacts of ENSO on cholera occurrence rates over the past 50 years by examining annual rates of suspected cholera cases per country in relation to ENSO Index values. This study provides a relationship indicating when hydrologic conditions are optimal for cholera growth, and presents a statistical approach to answer three questions: Are cholera outbreaks more likely to occur in an El Niño year? What other factors impact cholera outbreaks? How will the future climate impact cholera incidence rates as it relates to conditions found in ENSO? Cholera outbreaks from the 1960s to the present are examined focusing on regions of Central and South America, and southern Asia. By examining the predictive relationship between climate variability and cholera, we can draw conclusions about future vulnerability to cholera and other waterborne pathogenic diseases.

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Preface

This study was conducted for the U.S. Army South under Program Element No. 622784, "Military Engineering Technology"; Project No: 477345, "Risk Assessment Planning and Tools for Operations" (RAPTOR). The technical monitor was Angela Rhodes, CEERD-CNC.

This work was performed by the Hydrologic Systems Branch, of the Flood and Stream Protection Division, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL); and the Land and Heritage Conservation Branch, of the Installations Division, U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Dr. Hwai-Ping Cheng was Chief of the Hydrologic Systems Branch and Dr. Cary Talbot was Chief of the Flood and Stream Protection Division. Dr. George Calfas was Chief of the Land and Heritage Conservation Branch and Ms. Michelle Hanson was Chief of the Installations Division. The Program Manager was Angela Rhodes and the Technical Director was Ritchie Rodebaugh. The Director of ERDC-CHL was Dr. Ty Wamsley and the Acting Director of ERDC-CERL was Dr. Kumar Topudurti.

COL Teresa A. Schlosser was Commander of ERDC, and Dr. David W. Pittman was the Director.

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1 Introduction

1.1 Purpose of this technical report

The purpose of this report is to review available literature linking hydrological phenomena with human health, and to apply this framework specifically to the problem of waterborne disease transmission as it relates to drought, flooding, and the El Niño Southern Oscillation (ENSO) cycle. As climate variability increases, resulting shifts in the ecosystem expose human populations to new health risks (McMichael 2014). This study explores this phenomenon in the context of the sea surface temperature and precipitation changes associated with the ENSO cycle, and their effect on transmission rates of the waterborne disease cholera. ENSO conditions are optimal for the spread of the cholera-causing bacterium Vibrio cholera, and evidence suggests that disease occurrence rates are higher in years characterized by the El Niño conditions. This link has been established by the work of climatologists and epidemiologists in Bangladesh and Haiti (Pascual et al. 2000; Rodó et al. 2002; Akanda et al. 2009; Hazushime et al. 2010; Eisenberg et al. 2013). Here, global cholera occurrence rates are analyzed as a function of the annual ENSO Index. While linear regression relationships are not successfully established, average global and regional cholera occurrence rates are found to be higher in ENSO years at the annual country level. As ENSO cycle trends may intensify with climate change (Cai et al. 2014), further study of environmental contributions to waterborne disease outbreaks will be critical to epidemic prevention and response.

1.2 Purpose for this research in the military context

Increasing climate variability within the next 100 years is of concern to military planners, who relate threats to stability around the globe. Disaster assistance and peacekeeping operations require global scale analysis of potential hazards. This analysis was undertaken to provide the 512th Engineer Detachment with background information regarding vulnerability to waterborne disease, and to anticipate future changes in population exposure to disease within the U.S. Army South (ARSOUTH) combatant command region, specifically in Central America. Key questions posed were:

- Within the ARSOUTH region of interest, what are the threats to public health that respond to hydrologic factors?
- How are the environmental factors that affect disease occurrence projected to change over time?
- How can quick, easily accessible climatic indicators support disease threat prevention and awareness?

To address these questions for the 512th Engineer Detachment, we sought to conduct a review of hydrologic factors on public health and to examine in particular the case of ENSO cycles and cholera occurrence to determine whether quickly accessible climactic indicators such as the ENSO Index would be useful in determining threat levels for particular disease hazards.

2 Review of the Impacts of Climate on Health

2.1 Emergence of the study of planetary health

Although academic study of contemporary climate change has been gaining traction since the 1960s, the examination of its effects on human health did not emerge until the 1990s (Ebi and Hess 2017). The father of the climate change and human health field, Australian epidemiologist Anthony J. McMichael, noted that

> Most of the biosphere's biophysical and ecological systems that help sustain human population health are climate-sensitive … hence, climate-related impacts on health signify much more than mere collateral damage; they signal that nature's life-supporting system is being disrupted sufficiently to harm human systems (McMichael 2014).

The Intergovernmental Panel on Climate Change Fifth Assessment Report devotes a chapter to assessing the impact of climate change on human health, asserting with "high confidence" that human populations are vulnerable to weather shifts (Smith et al. 2014).

The studied impacts of climate on health are very broad, encompassing primary, secondary, and tertiary pathways. Noted climate pathways of adverse health effects include: malnutrition due to loss and shift of agricultural growing areas, increased exposure to extreme heat and to natural disasters such as hurricanes and landslides, compromised sanitation due to reduced freshwater availability, increased exposure to pollution through urban heat effects, shifting risk of infectious disease as host and vector habitats expand, and increased health risks associated with migration and displacement of climate refugees (McMichael 2013). Seemingly small shifts in temperature can have drastic effects on health factors; for example, by increasing the altitude at which the dengue-carrying mosquito *Aedes aegypti* is able to breed, or by drying out previously wetted areas, causing increased suspension of fine particulate matter that exacerbates respiratory illnesses. Human health systems are complex; such complexity renders effects hard to judge (IPCC 2014). Extreme weather may compromise health infrastructure, resulting in worse impacts than predicted as coping capacity is compromised. Some areas may experience a reduction in exposure to certain hazards; for example, increased heat may shorten the breeding cycle of a disease host. Regardless, it is clear that changing climate regimes will have health consequences for people worldwide.

2.2 Areas of planetary health research

The public health implications of changing climate regimes are complex and difficult to predict. Some areas might experience reduced exposure to disease-causing agents, while other areas have new or increased exposure (Escobar et al. 2016). Populations are most vulnerable when exposed to diseases for which they have not previously developed immunity or prevention and treatment practices. To mitigate adverse health impacts, officials and planners should recognize the potential for shifts in disease extents. Table 1 describes pathogenic diseases that change geographic extent as a direct response to shifts in environmental factors including temperature and precipitation.

Table 1. Pathogenic diseases affected by environmental change.

Disease type	Environmental factors	Impact
Diarrheal • Cholera • Rotavirus • *E. coli* infection • Cryptospirosis • Shigella • Dysentery • Locally specific others	• Exacerbated by floods, which cause greater exposure to untreated wastewater. • Disease-causing agents flourish in warmer temperature bands. • Drought conditions can lead to increased concentration of pathogens in water supplies. • Drought conditions concentrate people at fewer limited water resources and drive selection of lower quality water resources for human use.	These are the leading causes of child mortality and morbidity worldwide. They respond directly to environmental changes, and can be mitigated by adequate access to improved drinking water and sanitation infrastructure.
Vector-borne • Malaria • Zika virus • Chikungunya • Dengue • Yellow fever	• Fluctuating temperature zones can widen host habitat areas and lengthen breeding seasons. • Hosts move into areas without local immunity. • Increased precipitation may lead to more standing water, providing breeding habitats.	These are a primary concern affecting working-age adults. They respond indirectly to environmental change, due to lag times for precipitation events, and differences in species' reactions to temperature change. Some can be mitigated by vaccination.
Sources: Diarrhoeal Disease: World Health Organization (WHO), 2017. Vector-borne disease: IWGCCH 2010		

Cholera is an environmentally-linked waterborne pathogenic disease that has had impacts worldwide over the past several decades. It is well-studied, with a firm connection to environmental factors, and can be viewed as a proxy to other, less common diseases in the waterborne pathogen category listed above in Table 1 (Colwell 1996). With the current ongoing epidemic in Haiti, there is a threat that cholera could re-emerge in the rest of the Central and Southern America domain (Poirier et al. 2012). Understanding the role that environmental change plays in creating epidemic conditions could enable planners to prepare for or prevent widespread epidemics like the one of the 1990s in Latin America, which resulted in over 100,000 cases.

3 The El Niño Southern Oscillation cycle

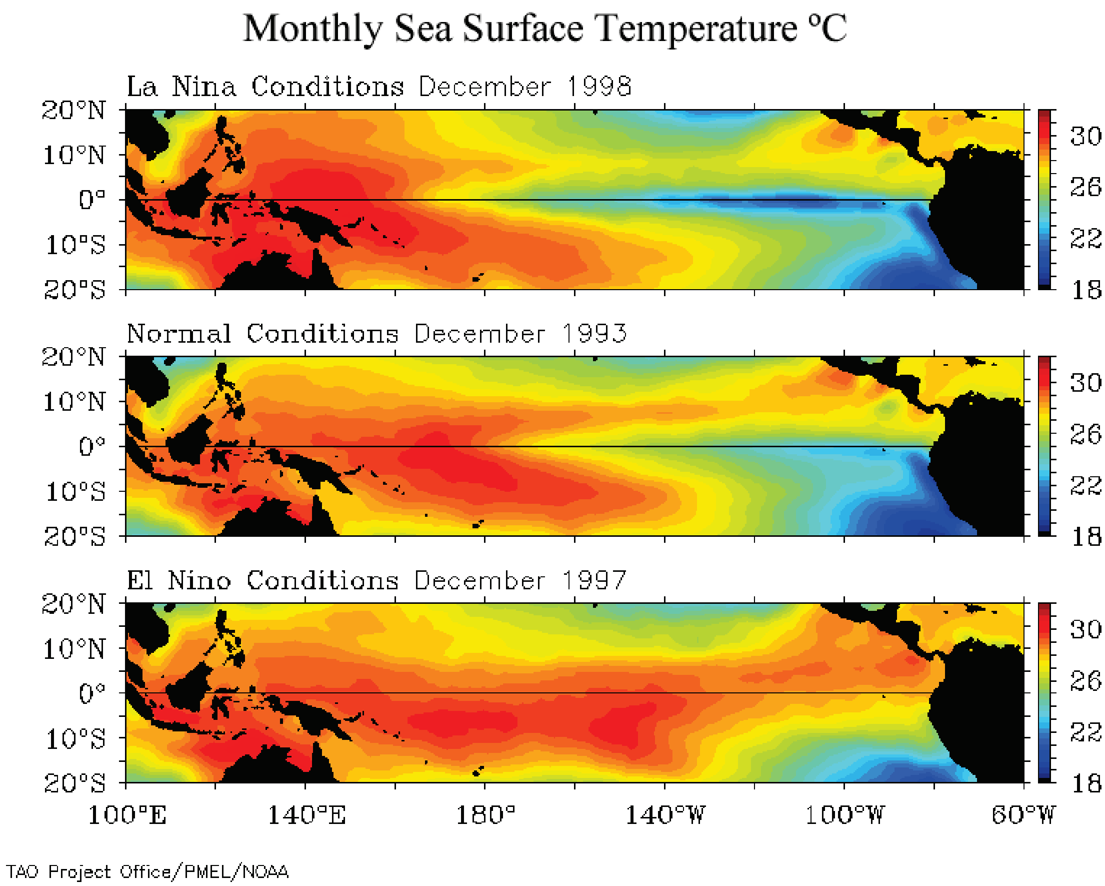
3.1 ENSO background

One climate system that is tied to adverse human health outcomes is the ENSO cycle. ENSO is a variable recurring weather pattern that encompasses major shifts in ocean water circulation patterns, trade wind patterns, sea surface temperatures, sea level pressures, and weather events, particularly along equatorial latitudes (Philander 1983). ENSO events have historically occurred every 3 to 10 years, and last around 1 year (Martinez-Urtaza et al. 2016). “El Niño” references the reoccurring pattern of above normal sea surface temperatures (SST) anomalies in the Pacific Ocean near the equator (Philander 1983). The second part of the phenomenon is the Southern Oscillation (SO), which represents global sea level pressure patterns associated with the El Niño event that bring variations in SST, rainfall, and intensity of the trade winds. When these patterns occur synchronously, they demonstrate the interaction of the atmosphere-ocean dynamics on the interannual timescale, called ENSO (Wallace and Hobbs 1977).

Figure 1 shows the monthly SST comparisons between La Niña, El Niño, and neutral conditions. The top map illustrates La Niña conditions. This is shown by cooler temperatures (approximately 22˚F) around the equator. Normal conditions (i.e., not La Niña or El Niño) are shown in the middle map. There are a wide variety of colors throughout the equator indicating a variety of temperatures, but the area is not dominated by warm or cool temperatures. The lower figure demonstrates El Niño conditions. Much of the equator region is red, indicating warmer temperatures globally (approximately 28-30˚Celsius at the equator).

While ENSO occurs in the tropic Pacific Ocean, it affects weather conditions across the globe (Figure 2). El Niño will likely cause warmer temperatures in much of southern Asia, southern Australia, western Canada, southern Alaska, and southern Brazil during the southern hemisphere summer. Additionally, parts of Asia and Africa will experience warm and dry conditions while other parts of eastern Africa, eastern Asia, and central North and south-central South America will experience wet conditions.

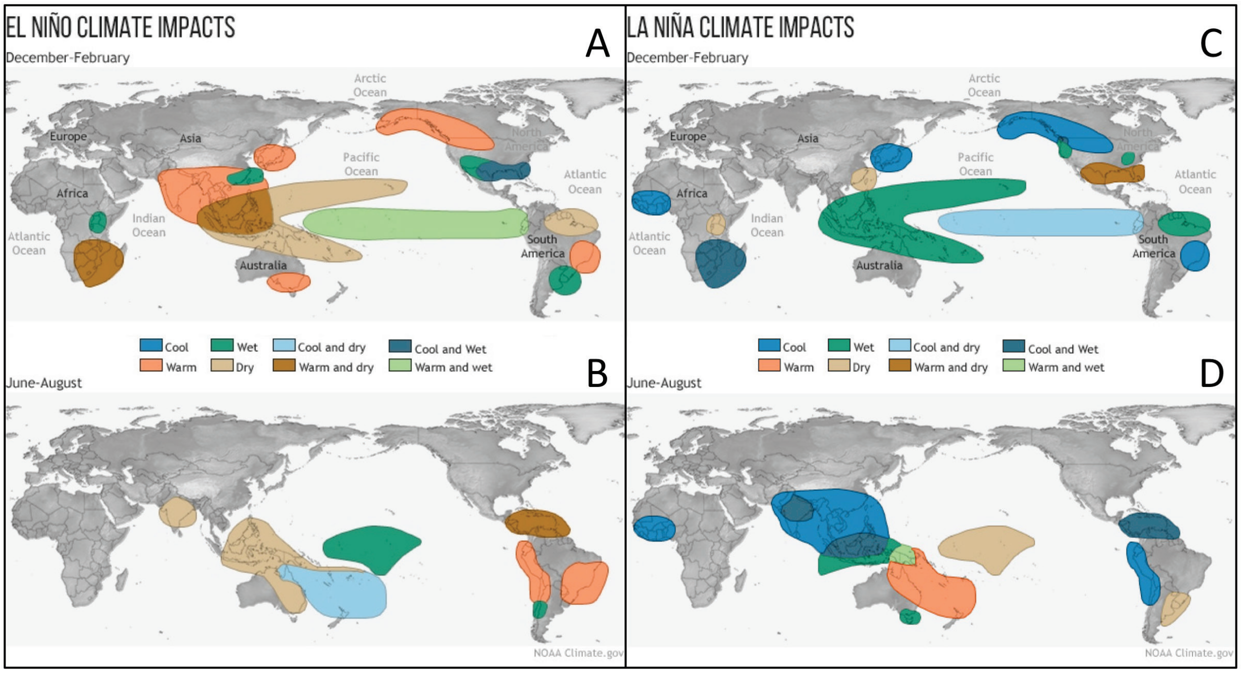
Figure 1. Anomalous sea surface temperatures (SSTs) are indicative of an El Niño or La Niña event, with La Niña exhibiting cooler temperatures and El Niño exhibiting warmer temperatures.



Source: Pacific Marine Environmental Laboratory.

During northern hemisphere summer, much of the South American coast will experience warm conditions while parts of southeast Asia, and Australia will experience dry conditions. Central America will likely experience warm and dry conditions. La Niña, during the southern hemisphere summer, is linked with cool conditions in Africa, east Asia, northern North America, and parts of South America. Parts of northern Australia and Indonesia will likely experience wet conditions, which is completely opposite of those regions' experiences of dry conditions during El Niño. During northern hemisphere summer, parts of Africa, southern Asia, and western South America are likely to experience cool conditions. Central America along with parts of southeast Asia are likely to experience cool and wet conditions. Therefore, El Niño has wide consequences on human systems, including disruption of agriculture and fisheries and increased risk of flood and fire damage.

Figure 2. El Niño and La Niña impacts during winter and summer months.



Source: NOAA (2016).

3.2 Predicted future climate

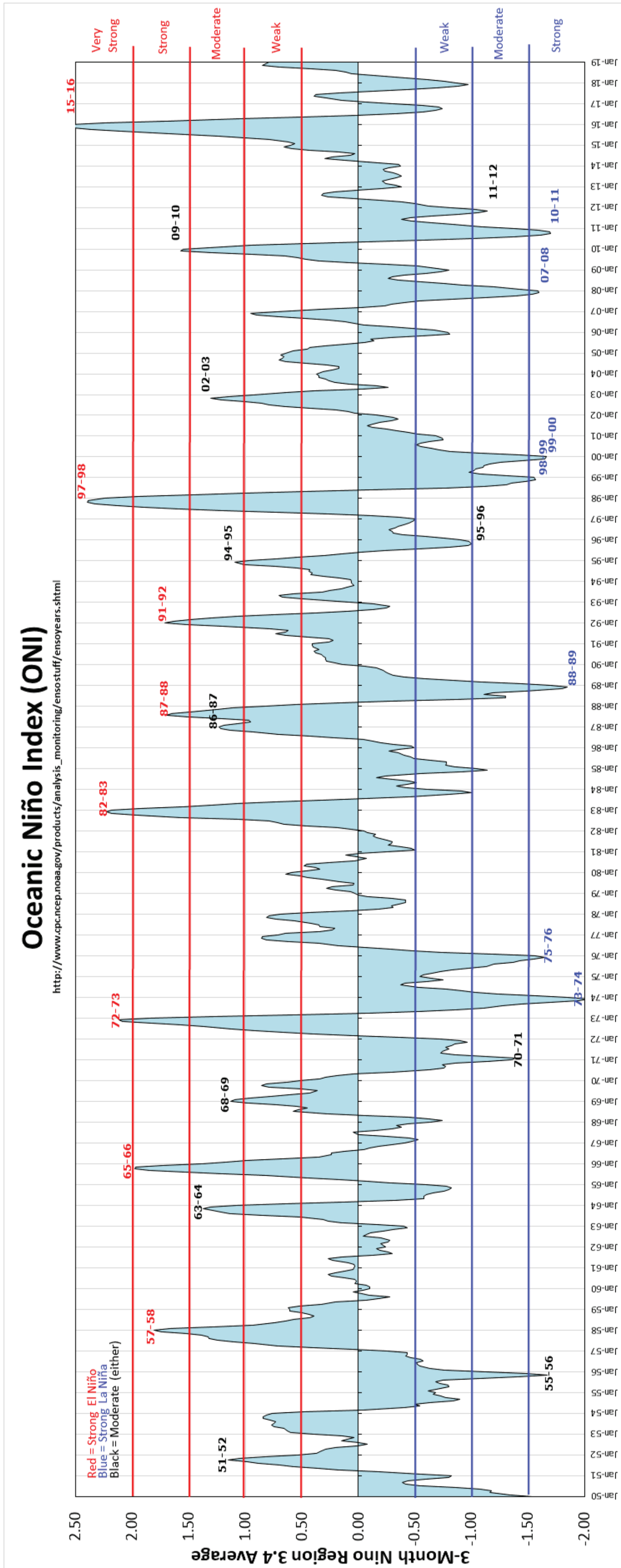
Scientists are unsure of the effects of climate change on ENSO cycles. Some believe that due to the natural variability of ENSO, it is difficult to separate out the effect of natural climate variability and variability due to anthropogenic activity. Others propose that there are numerous ways that climate change could affect both the intensity and frequency of ENSO, but have low confidence in their capability of predicting the exact effects of a warmer climate on ENSO (NOAA 2019). However, scientists are highly confident that ENSO has been occurring for thousands of years and will continue to occur in the future.

Past climate reconstructions show that ENSO patterns have intensified within the past 100 years, and future projections indicate that the cycle may continue to increase in frequency (Cai et al. 2014). Recent research made use of multiple proxy data sources, including tree rings, coral samples, ice cores, and historical documentation to reconstruct an ENSO records stretching back to A.D. 1525 (Gergis and Fowler 2009). The authors found that longer, more intense ENSO events over that nearly 500-year record have all occurred in the 20th century, and conclude that industrial carbon forcing has affected and intensified the ENSO phenomenon.

Projections of future ENSO cycles under the assumption of CMIP5 climate scenarios indicate that variation of ENSO cycles in the future is entirely non-stationary and could vary widely through the 21st century. CMIP5 Model agreement between potential scenarios on El Niño patterns is low (Chen et al. 2017). The authors of the ENSO in CMIP5 Simulations study conclude that between the 34 scenarios examined, common themes found are the eastward propagation of El Niño and La Niña patterns over time, and general increases in SST for the cycles. Over time, this may result in more areas globally experiencing El Niño conditions.

Cai et al. (2014) conducted a study that produced evidence that the extreme El Niño occurrences in the future will double due to greenhouse warming. This is due to projected warming of surface water around the eastern equatorial Pacific, which occurs faster than that of the ocean waters nearby and thus enables more incidences of atmospheric convection (Cai et al. 2014). The study suggests that we should expect more incidents of destructive weather events. Figure 3 shows numerous peaks and troughs in the historical record of the Oceanic Niño Index, indicating El Niño and La Niña events (Null 2019). However, when looking at El Niño events through time, the peaks show an upward trend increasing generally from the late 1950s to the mid-2010s. There are also six strong El Niño events on record but only three strong La Niña events. Similarly, there are 12 moderate and strong El Niño events and only nine moderate and strong La Niña events. While these trends could be associated with the data window, it is important to see how they develop and continue to change through time.

Figure 3. Oceanic Niño Index.



Source: Null, 2019. "El Niño and La Niña Years and Intensities."

4 Linking ENSO and Cholera Occurrence Rates

Cholera outbreaks are strongly linked to SST, precipitation, and streamflow (Hashizume et al. 2008, 2010; Jutla et al., 2013a; Jutla et al. 2013b; Ostfeld 2009; and Pascual et al. 2000). The *Vibrio cholerae* bacterium is thought to be native to the Bay of Bengal, a warm estuarine environment, and is now established in similar deltas around the world (Akanda et al. 2009). During hot, low-flow drought conditions, the bacteria flourish in these warm, undisturbed estuaries. Low riverine flow during these times allows for estuarine intrusion higher up into river systems, increasing human exposure to the bacteria. Phytoplankton flourish in these steady conditions, allowing the bacteria that feed on it to flourish. Akanda et al. (2009) describe a hydroclimatological pattern in which these hot, dry conditions correlate with initial, lower intensity cholera outbreaks. Then, during times of higher intensity precipitation, flooding can compromise sanitary infrastructure and bring more people into contact with *Vibrio cholerae*-infested waters. These wetter conditions characterize secondary, more devastating outbreaks as cholera moves away from the estuary and delta environments inland, very quickly.

In the Latin American cholera epidemic beginning in 1991, the disease began in Peru and reached epidemic proportions throughout Latin America by the next year (Guthmann 1995). It has not been conclusively determined how the unexpected 1991-1993 epidemic of cholera in Latin America began. The disease-causing bacteria was initially thought to have been introduced from the bilge water of a cargo ship docked in Peru, but more recent analyses suggest that the *Vibrio cholerae* are widely dispersed in seawater plankton populations globally (Colwell et al. 2000). From Peru, the disease spread very rapidly and was present at epidemic levels throughout South and Central America within that year (Guthmann 1995).

The primary risk factor for cholera transmission is lack of access to improved sanitation and drinking water infrastructure (Ali et al. 2015). However, given those living conditions, epidemic rates are subject to the described environmental and hydrologic factors.

Cholera in Bangladesh is a common case study for analyzing this environmental link because the disease has been present in that area longer than anywhere else in the world. The active data collection and research being done at the International Centre for Diarrhoeal Disease Research in Dhaka, Bangladesh* enables researchers to examine occurrence rates at fine spatial and temporal scales. This is generally difficult to do with cholera, as cases are drastically underreported due to limited capacity and fear of loss of tourism (Ali et al. 2015).

One study of climate factors on disease occurrence in Bangladesh used a mathematical model to examine seasonal and interannual variability in outbreak size. The model incorporated infected population, susceptibility levels in the population, and transmission rates incorporating climate variability (Koelle 2009). The author concluded that the climate forcing signal correlated with transmission rates at three levels: seasonal precipitation variations in the delta, river discharges associated with upstream precipitation, and an 8- to 10-month lagged correlation with the global ENSO Index. The study emphasizes the number of confounding factors, like prior presence of the pathogen in an area and differing levels of population immunity, which make the modeling of disease transmission difficult.

Another study used the cholera occurrence record from Bangladesh to demonstrate that the dominant frequency of the ENSO time series matches that of cholera case variability in that region (Pascual et al. 2000). However, the authors caution that the ENSO forcing of cholera dynamics is mitigated by a number of other factors, including epidemiological time lags, the direction of the ENSO Index shift (moving from neutral into an El Niño event indicated a larger increase in disease level than increasingly positive ENSO Index values within the El Niño event), local temperature patterns, and melting of Himalayan snowpack. Again, the lesson is that disease dynamics are complex and cannot be reduced to a single environmental factor.

* http://www.icddrb.org

5 Methodology

This chapter details data sources and analytical methods used to examine relationships between the ENSO climate system and pathogenic cholera disease incidence. The lack of available global disease data at higher spatial and temporal resolutions created difficulties when conducting these analyses. The purpose of this study was to work within that global, high-level perspective to analyze the potential to use climate phenomena indices such as the Oceanic Niño Index to characterize geographic vulnerability to disease. To accomplish this, the available country-level cholera occurrence data were aggregated and analyzed against the Oceanic Niño Index to demonstrate potential correlation between various Oceanic Niño Index values and rates of cholera infection in regions with susceptibility to that disease.

5.1 Cholera occurrence data source and description

Cholera occurrence historical data were obtained worldwide from the Global Infectious Disease and Epidemiology Network (GIDEON Informatics 2019, Berger 2005). GIDEON data were aggregated from available web sources, including World Health Organization reports, peer-reviewed journals, world government publications, and abstracts. Cholera case numbers and mortality statistics are available annually at global, regional, and country-level spatial extents. Additional notes may specify sub-country regions or monthly extents, but sub-annual and sub-country-level cholera occurrence data were not widely available enough to conduct analyses at those scales for this study.

For this analysis, annual cholera occurrence rates were downloaded for the aggregated globe, and regionally for Latin America, Asia, and Africa, which all are currently experiencing endemic cholera outbreaks (in Latin America the current outbreak is limited to Haiti but has had a much wider extent within the past 20 years). Country-level data were downloaded for four countries in Central America that were of particular interest to the study sponsor U.S. Army South: El Salvador, Nicaragua, Guatemala, and Honduras. This subregion experiences the greatest exposure to El Niño effects and was therefore selected for further analysis.

Cholera occurrence numbers were divided by global, regional, and country-level populations by year, which were obtained from the United Nations Population Division *World Population Prospects: The 2017 Revision*

(UN 2017), to produce annual cholera occurrence rates for the globe, and by region and country. Cholera occurrence numbers were scaled into disease occurrence rates per 1,000 people.

5.2 ENSO Index data source and description

Annual Oceanic Niño Index values were obtained from the National Weather Service, Climate Prediction Center (NWS 2019) where they are available as a 3-month moving average from 1950 to the present (Climate Prediction Center). Oceanic Niño Index data are made available monthly. To produce an annual value to match with the temporal resolution of the available cholera occurrence data, the Oceanic Niño Index monthly value with the maximum absolute value for each year was selected to represent that year in terms of the "worst case." This new maximum value representing the year is referred to as the ENSO Index value. The ENSO Index for this period ranges from -2.0, indicating a strong La Niña event, to 2.5, the maximum historical El Niño event, which occurred in 1997. The index incorporates sea level pressures, sea and air surface temperatures, cloudiness measures, and wind measures (NOAA/NWS 2012).

5.3 Methodology for analysis

The co-occurrences between the ENSO Index annual extremes and annual cholera occurrence rates were explored via time series visualization, linear regression of annual cholera occurrence rates as a function of the annual ENSO Index, and examination of average occurrence rates in El Niño years separately from La Niña and neutral years. These steps were taken for cholera occurrence rates at the global level; at the regional level for Africa, Asia, and Latin America; and at the country level for El Salvador, Guatemala, Honduras, and Nicaragua. Results are presented in the next chapter. Given that disease occurrence data were available at a coarser resolution (annually and by country), further empirical analysis would not be reliable.

6 Results and Discussion

Across all spatial scales analyzed (global, continental region, and country level), average rates of cholera incidence were significantly different in El Niño years versus years without an El Niño event. This chapter presents results from the analyses conducted: time series analysis, linear regression on cholera rates as a function of ENSO Index, and Wilcoxon Signed-Rank tests on cholera rates in years with different types of ENSO events.

6.1 Time series

Figure 4 shows the time series of global cholera occurrence rates (per 1,000 people, left axis) and the annual ENSO Index (i.e., the most extreme monthly ENSO Index value within a year, right axis) for all available years. Global cholera incidence rates soar in 1991, when the modern epidemic reached Peru and spread into the western hemisphere. Rates rise again drastically in 2010 and 2011, when the Haiti earthquake and resulting aid efforts and infrastructure loss caused the most recent epidemic there. A general pattern of annual peaks is discernable between the ENSO and cholera time series. The peaks and valleys track similarly among both measured fields. Cholera occurrence rates sometimes lag behind peak ENSO events, which could be explained by the disease spreading among communities after the initial outbreak caused by environmental conditions.

As noted by Pascual et al. (2000), shifts in the direction of the ENSO Index may have greater impact on disease rates than increases in the index do. Figure 5 shows this same time series, with cholera occurrence rates broken out into approximately three continental regions. Some of the same pattern is apparent, particularly in Latin America and Africa. In Asia, cholera occurrence rates by population were much lower, and opposite impacts of the ENSO cycle on different parts of the continent resulted in a flattening of the occurrence rate time series. Note that cholera was not present in Latin America for most of the 20th century. It emerged in Peru in January 1991 to cause a multi-country, 9-year epidemic and again in Haiti in 2010.

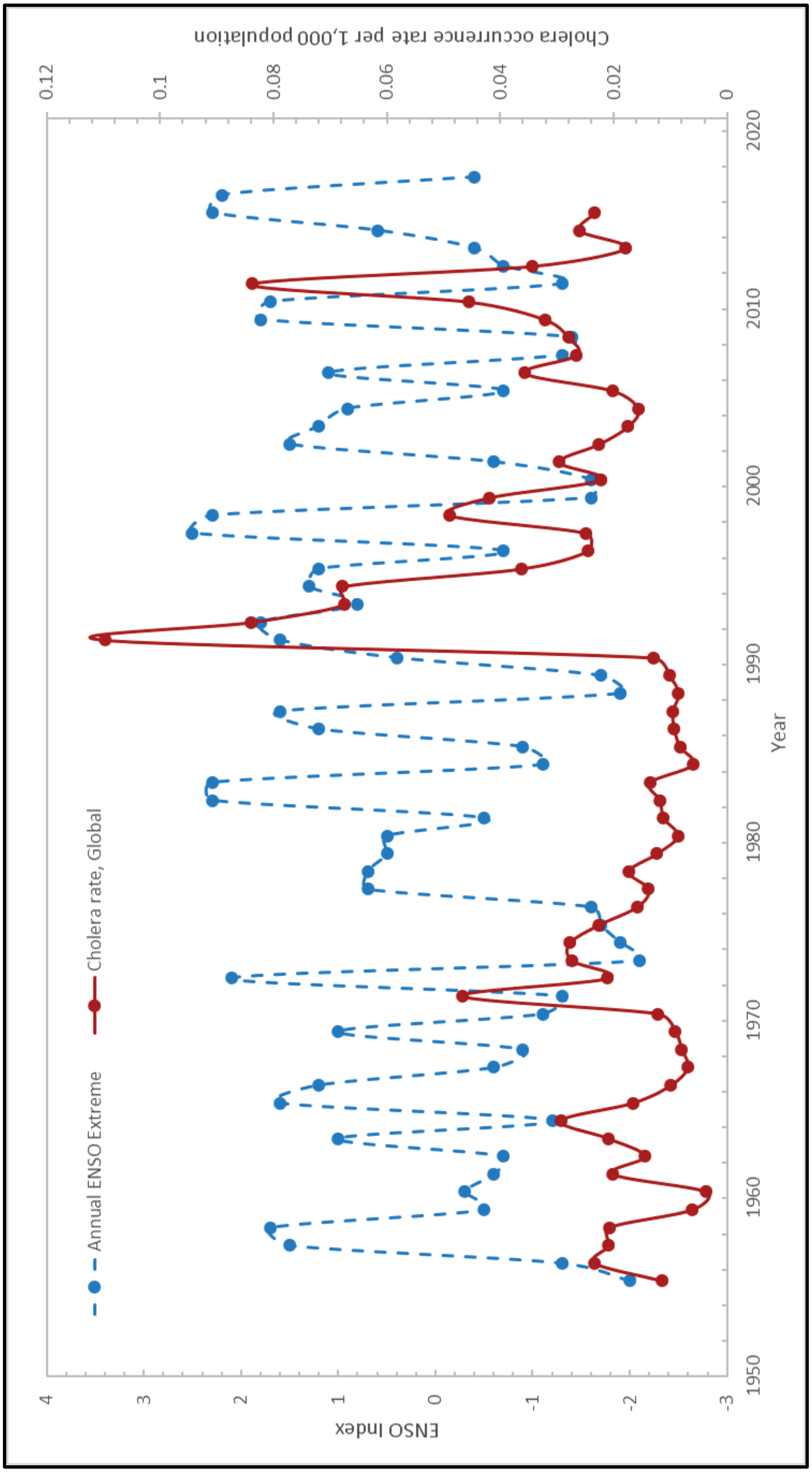
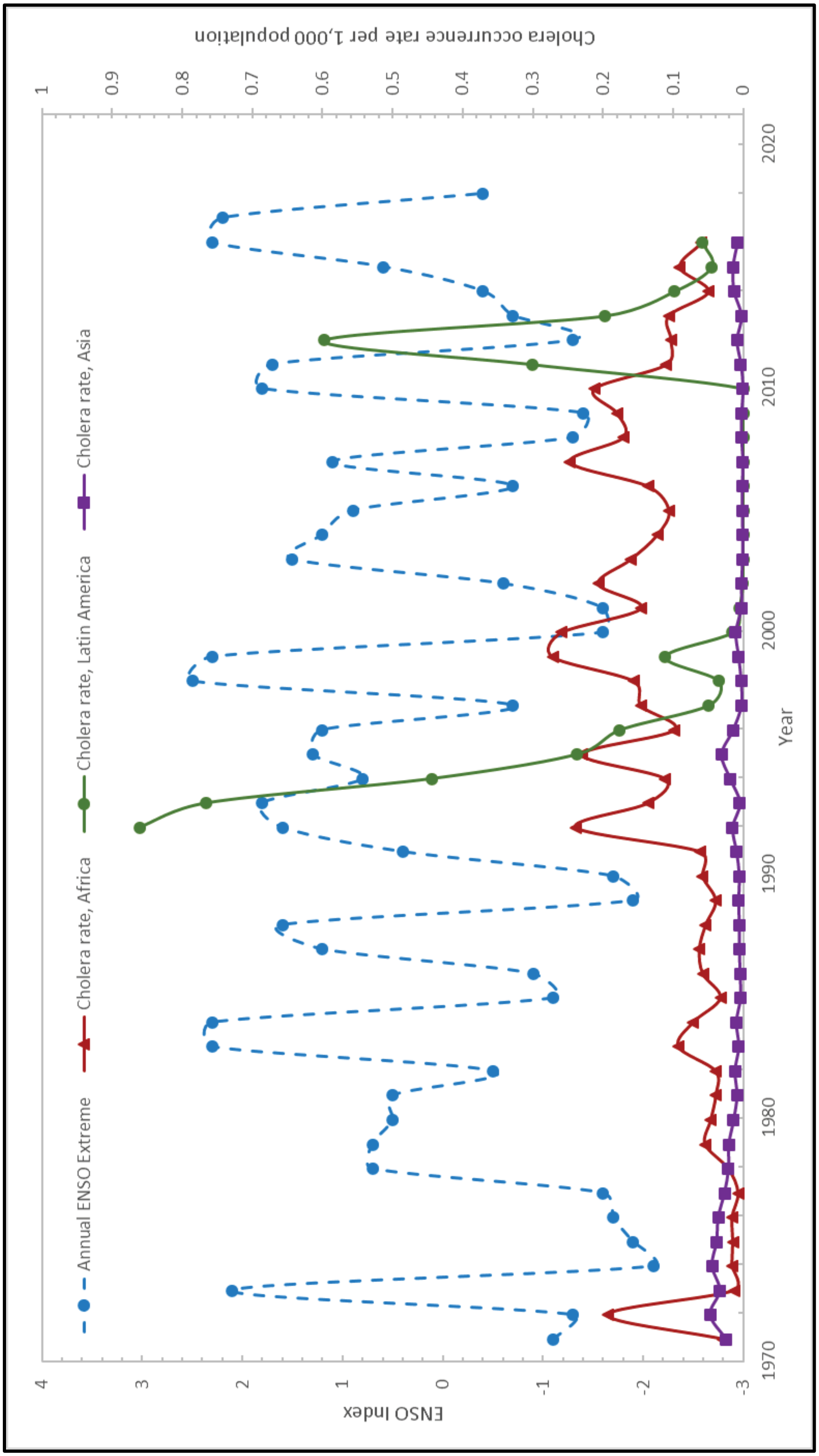


Figure 4. Global cholera occurrence rates and ENSO Index extremes time series.

Figure 5. Regional cholera occurrence rates and ENSO time series.



Cholera occurrence data in each of these analysis domains were linearly regressed with the annual ENSO Index extreme as the forcing variable, but in no region did the R-squared value for this regression rise above 0.03. Lagging cholera occurrence rates 1 year behind ENSO Index values did raise the R-squared value for this regression, but not in a significant way.

6.2 Occurrence rates in El Niño and La Niña or neutral years

Average cholera occurrence rates per 1,000 people were calculated for El Niño years and La Niña/neutral years in each of the analyzed spatial domains, and for the four countries in Central America of note to ARSOUTH. Note that for the Central American country domains, only the years 1991-2001, when cholera was present, were analyzed. These rates were higher in El Niño years without exception. Table 2 shows these values.

Table 2. Average cholera occurrence rates during years cholera was present.

Domain	Average cholera occurrence rate per 1,000 people	
	El Niño years	La Niña/neutral years
Global	0.028	0.021
Asia	0.007	0.005
Africa	0.066	0.038
Latin America	0.117	0.037
El Salvador	0.793	0.041
Honduras	0.379	0.034
Guatemala	1.173	0.096
Nicaragua	0.916	0.176

Cholera occurrence rates were on average over 10 times higher during El Niño years in Belize, Honduras, Guatemala, El Salvador, and Nicaragua than during neutral or La Niña years. The strongest El Niño years during this decade-long outbreak were 1991 – 1992 and 1997 – 1998. The 1991 – 1992 period saw the initial cholera outbreak and the highest occurrence rates, and the 1997 – 1998 period saw a resurgence in Latin American rates. This indicates that the environmental conditions associated with El Niño in many parts of the globe – higher SSTs and more extreme precipitation – can provide a fertile environment for the spread of the cholera-causing bacteria, and that the ENSO Index has potential as a proxy indicator for waterborne disease risk during times when the disease is considered present or epidemic in a region.

The boxplots in Figures 6 through 9 illustrate the average and range of cholera incidence rates across the four categories of ENSO type for the globe and the three examined continental regions. ENSO type in this analysis is determined from the annual extreme ENSO value (the maximum absolute monthly ENSO Index value in the year). For the boxplot analysis, years were categorized as the ENSO types listed in Table 3. Note that none of the years in the analysis had 0.0 as the most extreme ENSO Index value. Table 3 lists the number of years from 1970 to 2015 of each ENSO type.

Table 3. ENSO characterizations for boxplot analysis.

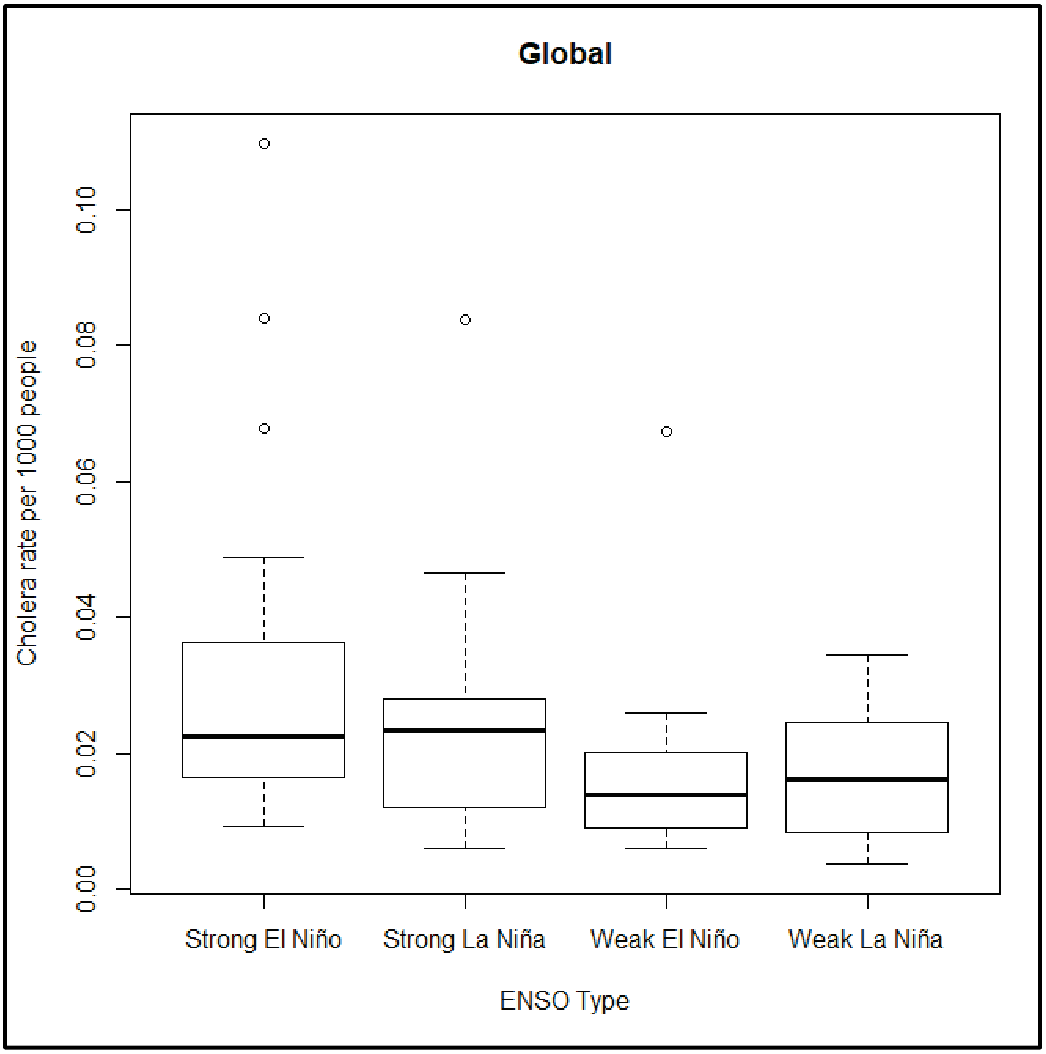
Characterization	ENSO Index range	Number of years
Strong El Niño	1.0 or greater	17
Weak El Niño	0.0 to 0.9	9
Weak La Niña	−0.9 to 0.0	6
Strong La Niña	−1.0 or lower	14

Globally, cholera incidence rates were highest in strong El Niño and strong La Niña type years (Figure 6). The most variance in cholera rates is also present in these strong ENSO type years. Years with most extreme ENSO Index values between -1 and 1, categorized as “Weak El Niño” and “Weak La Niña” for this analysis, had lower average cholera incidence rates worldwide. This encompasses years with an absolute maximum ENSO Index value between 0 and 0.5, which are considered truly neutral.

A Wilcoxon Signed-Rank test was performed on the global incidence data to compare El Niño years and La Niña years (lumping together the strong and weak variants of each type). The Signed-Rank test determines whether two samples are likely from the same population distribution. For the global data, the test indicated that the distribution of cholera incidence rates in El Niño years is different from the rates in non-El Niño years. The p-value for this test was 0.00, indicating strong evidence that global cholera incidence rates differ significantly between El Niño and non-El Niño years.

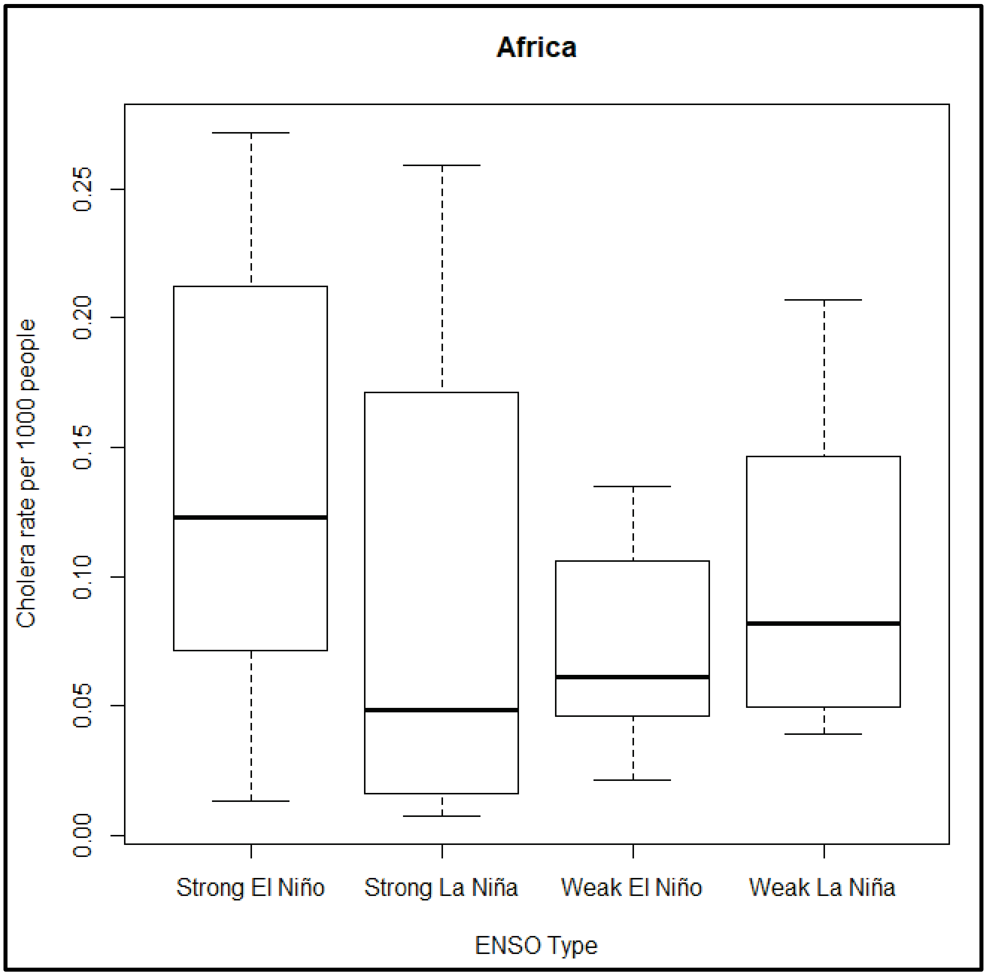
Narrowing the analysis to a geographic subregion (even a very large one, such as a whole continent), brings into focus the environmental factors that may drive the spread of pathogenic waterborne disease. On the African continent, the differences in cholera occurrence rates by ENSO type are more starkly disaggregated than they are for the global data). This makes intuitive sense, as the ENSO cycle affects different parts of the globe differently.

Figure 6. Annual cholera incidence rates by ENSO type, Global, 1955-2015.



The cholera data on the African continent indicate that disease rates are much higher during years characterized by strong El Niño events than in other ENSO type years. Impacts of El Niño events on the African continent include relatively hotter and drier conditions, which can drive initial flourishing of Vibrio cholerae bacteria and increased human contact with water sources. The ENSO type with the next highest average rate of cholera occurrence is weak La Niña, which is associated with wetter conditions that may drive flooding. A Wilcoxon Signed-Rank test performed on these averages indicated that the cholera incidence rates for Africa in El Niño years is distributed differently from the rates in non-El Niño years (with a p-value of 0.00).

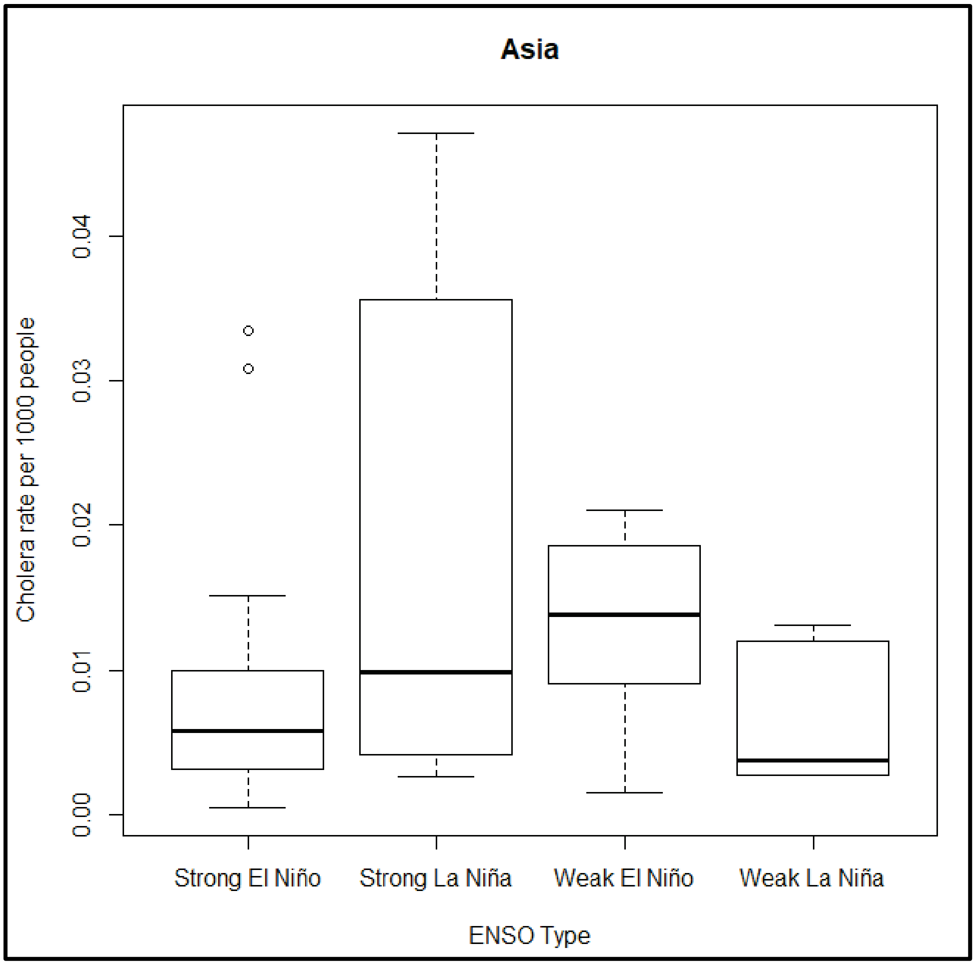
Figure 7. Cholera incidence averages by ENSO type, Africa, 1970-2015.



The pattern of cholera incidence averages by ENSO type is inverted on the Asian continent, compared with Africa, Latin America, and the global data: average incidence rates are highest with weak El Niño event years, followed by strong La Niña years (which have the highest range of rates). Figure 8 shows this distribution.

This distribution accords with the characteristics of the ENSO cycle presentation in the Asian continent, which follow an opposite pattern than that in the West. During El Niño events, parts of Asia are likely to experience drier conditions. Therefore, during weak El Niños, these areas may be predominately dry and hot but still experience sporadic rain. This promotes conditions during which the bacteria causing cholera flourish, and drives increased human contact with less potable waters. Strong La Niña events present the next highest average cholera occurrence rates in Asia, and the largest range of rates by far of the ENSO types.

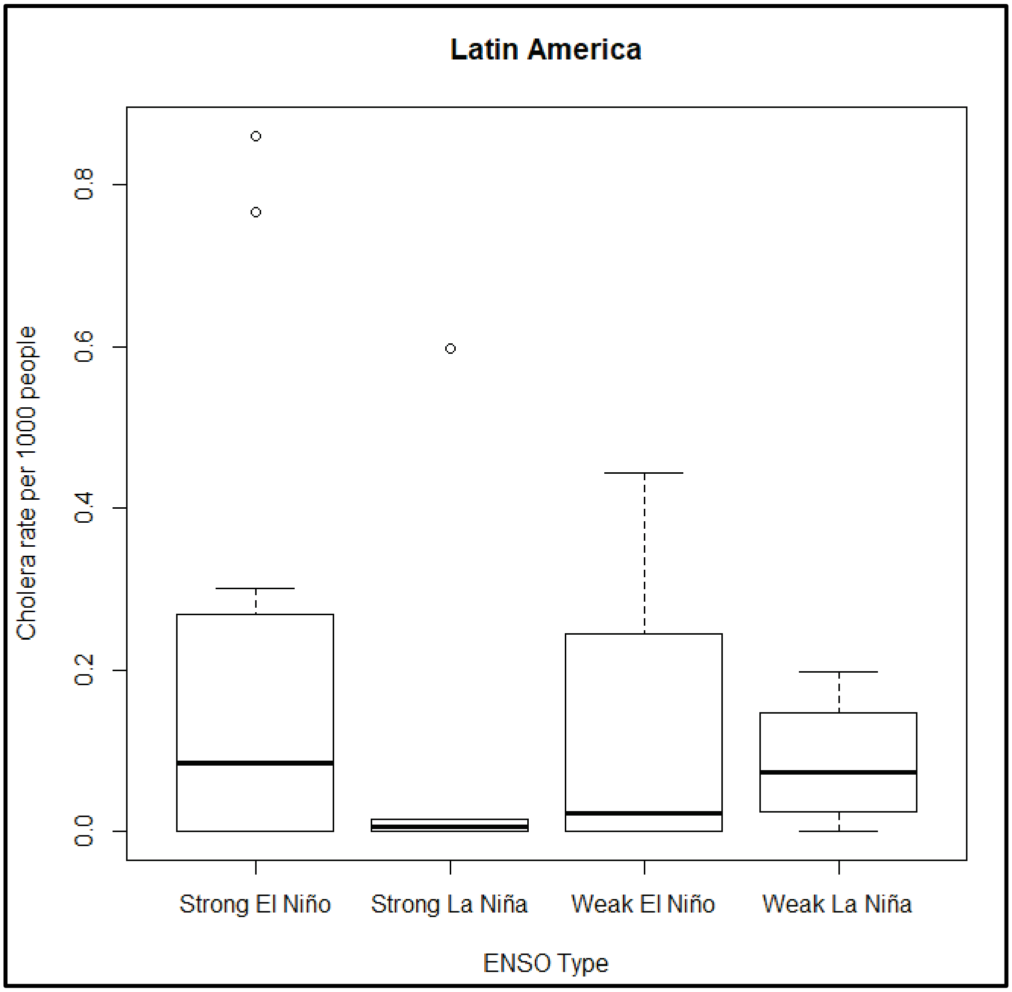
Figure 8. Cholera incidence averages by ENSO type, Asia, 1970-2015.



La Niña events in Asia cause predominantly heavy precipitation (as shown in Figure 2), driving flooding and secondary infection rates through increased contact with contaminated waters. A Wilcoxon Signed-Rank test performed on these averages indicated that the average cholera incidence rate for Asia in El Niño years is different from the average rate in non-El Niño years (with a p-value of 0.00).

Since cholera emerged in Latin America in 1990, there are only 25 years of available annual data for this analysis. Still, the pattern of cholera incidence averages by ENSO type tracks with that of the data from Africa: average incidence rates are highest with strong El Niño event years (Figure 9). In the past 3 decades, Latin America has been the most impacted region in terms of higher cholera incidence rates and exposure to direct ENSO weather effects. A Wilcoxon Signed-Rank test performed on these datasets indicated that the cholera incidence rates for Latin America in El Niño years is distributed differently from the rates in non-El Niño years (with a p-value of 0.00).

Figure 9. Cholera incidence averages by ENSO type, Latin America, 1990-2015.



6.3 Discussion of results

Results in this study indicate that the environmental conditions associated with El Niño in many parts of the globe – higher SSTs and more extreme precipitation – are positively associated with a spread of the cholera-causing bacteria, and that the ENSO Index has potential as a proxy indicator for waterborne disease risk during times when the disease is considered present or epidemic in a region. The El Niño climate alone does not indicate cholera risk; the disease must be present in the population for the environment to have an effect on transmission rates. For example, the current level of the cholera pathogen reservoirs in Haiti creates a risk for a future outbreak in this domain. Other diarrhea-causing waterborne diseases are already endemic throughout this region, and the ENSO Index could be used as a readily available information tool to predict likelihood of further outbreaks. These diseases are a leading cause of morbidity and mortality in children, the elderly, and other vulnerable populations in this domain.

Globally and in all three continental regions examined, cholera occurrence rates appear to correlate with the ENSO Index by having averaged cholera occurrence rates appear higher in El Niño years than in La Niña years. However, attempts to produce a linear relationship between the ENSO Index and occurrence rates failed to yield acceptable values of fit, even when occurrence data were lagged. This is unsurprising, given the much greater nuance of the mathematic models described in the work of Akanda et al. (2009), Hashizume et al. (2010), and Jutla et al. (2013a), which did not result in a well-defined relationship between ENSO and cholera.

Although the specific relationship between ENSO conditions and cholera occurrence rates is difficult to tease out, it is clear that there is a relationship between the two in most of the world where cholera is endemic. Our results show that ENSO cycles likely correlate with the incidence of waterborne pathogenic disease, potentially through increased SSTs providing a suitable breeding ground for bacteria and extreme weather events exposing more people to these waters. Likely future scenarios show that risk of waterborne disease will increase with very high confidence and the risk of vector-borne disease will increase with medium confidence (Smith et al. 2014).

Increasing weather variability produces ecosystem shifts that can alter the distribution of human health risks globally (McMichael 2014). For example, small shifts in temperature distributions affect the areas where mosquito populations can thrive, which in turn exposes new populations to mosquito-borne diseases such as malaria and dengue. Temperature increases can degrade urban air quality, causing greater incidences of respiratory disease. Asthma and other respiratory diseases can also be triggered by drought, which causes higher levels of dust to be suspended in the atmosphere (McMichael et al. 2006). As weather patterns tend to become more variable, extreme weather events such as droughts and floods are more likely to occur. Extreme events compromise public health and sanitation infrastructure, leaving populations more vulnerable to treatable diseases (McMichael et al. 2006). It also seems likely, from past climate reconstructions and future climate projections, that ENSO cycles will intensify in the future. Investments in sanitary infrastructure, drinking water treatment, and access to medical care may mitigate this impact in future ENSO cycles.

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Acronyms and Abbreviations

Term	Definition
ARSOUTH	U.S. Army South
ENSO	El Niño Southern Oscillation
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
SO	Southern Oscillation
SST	Sea Surface Temperature
WHO	World Health Organization

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A non-stationary climate imposes considerable challenges regarding potential public health concerns. The El Niño Southern Oscillation (ENSO) cycle, which occurs every 2 to 7 years, correlates positively with occurrences of the waterborne disease cholera. The warm sea surface temperatures and extreme weather associated with ENSO create optimal conditions for breeding the Vibrio cholerae pathogen and for human exposure to the pathogenic waters. This work explored the impacts of ENSO on cholera occurrence rates over the past 50 years by examining annual rates of suspected cholera cases per country in relation to ENSO Index values. This study provides a relationship indicating when hydrologic conditions are optimal for cholera growth, and presents a statistical approach to answer three questions: Are cholera outbreaks more likely to occur in an El Niño year? What other factors impact cholera outbreaks? How will the future climate impact cholera incidence rates as it relates to conditions found in ENSO? Cholera outbreaks from the 1960s to the present are examined focusing on regions of Central and South America, and southern Asia. By examining the predictive relationship between climate variability and cholera, we can draw conclusions about future vulnerability to cholera and other waterborne pathogenic diseases.

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