CHOLERA IN A TIME OF EL NIÑO AND VULNERABILITY IN PIURA, PERU: A CLIMATE AFFAIRS APPROACH

By

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ABSTRACT

CHOLERA IN A TIME OF EL NIÑO AND VULNERABILITY IN PIURA, PERU:
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The goal of my dissertation research is to reconstruct the temporal and spatial associations among El Niño-Southern Oscillation (ENSO), social vulnerability and cholera incidence in Piura, Peru from 1991 to 2001 in order to better understand El Niño's impact on the cholera epidemic in Peru during the 1990s. Piura is important to study because it was one of the first places to report cholera in Peru. It also had one of the highest incidence rates in the country, and historically, the region is known for El Niño. My overarching research questions are: (1) What was the impact of ENSO on cholera incidence in Piura; and (2) How did social vulnerability influence this relationship? My research hypotheses are: (a) There was a temporal association between ENSO, climate and cholera cases in Piura in the 1990s. Furthermore, these associations were stronger after 1992 compared to the onset of the epidemic in 1991; and (b) The spatial variability of the ENSO-climate-cholera associations in Piura in 1997-98 will be explained by the spatial distribution of social vulnerability. Moreover, the level of social vulnerability within districts in Piura will either antagonize or buffer the effects of ENSO and climate on cholera incidence.

I address my research questions and hypotheses using a *climate affairs* approach that is informed by disease ecology and vulnerability theories from the geographic subfields of medical and human-environment geography. *Climate affairs* is an integrating concept in the earth and social sciences used to understand the interrelationships among climate, environment and society worldwide. Using *climate affairs*, I developed a conceptual framework that: 1) examines cholera transmission within a broader conception of ENSO; 2) links ENSO-cholera associations to social vulnerability; and 3) considers ENSO-cholera interactions at multiple scales. The key findings of this research suggest that cholera's temporal association with ENSO was transient throughout the 1990s; the strongest association was found during the 1997-98 El Niño. I also found that cholera transmission occurred through the interactions of global and local sea surface temperatures with rainfall. Furthermore, I demonstrated that the spatial distribution of social vulnerability can in part explain the associations between global and local climate and cholera during the 1997-98 El Niño. However, these associations varied by time lag, district and variable. It also appears that districts on the west coast of the subregion of Piura were the most vulnerable. Lastly, important to the understanding of these findings is that interpretation of ENSO and its association with cholera will highly depend on the Niño definition and region chosen for analysis. This research contributes to future climate-informed initiatives that enhance societal capacities, while focusing on population health and the monitoring of populations during future climate events in Piura, Peru and the Latin American region.

This thesis is dedicated to my parents Jorge and Nilda Ramírez

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CHAPTER 1: INTRODUCTION

Understanding climate impacts on infectious diseases is becoming increasingly important as public health practitioners are concerned that a changing climate will not only affect the ecology of infectious diseases, but also the basic determinants of health that protect populations from disease transmission.[1] From an ethical perspective, an imminent concern is that climate-related impacts on infectious diseases will be disproportionately felt in developing countries (World Health Organization [WHO] 2008), where basic needs are inadequately met in large segments of populations (Gasper 2005: 1). The untoward effect of poor societal conditions on global health is already evident by the high prevalence rates of malnutrition and preventable diseases, such as cholera, in Latin America, Asia and Africa (WHO 2009). According to Harm de Blij (2009) these human conditions reflect the geography of uneven global development. The broader implication is that climate change along with existing human vulnerabilities will increase the risk of infectious disease outbreaks. Despite these concerns, most studies about climate change and infectious disease have focused on the ecology of disease with less attention paid to the influence of social vulnerability (Cutter et al. 2003). It is only recently that efforts have begun to address the intersections of climate and society and their duel potential effects on infectious disease and population health (Galvao et al. 2009).

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[1] By basic determinants of health, I am referring to factors, highlighted by the recent climate change initiative at the WHO (2008). They include clean water and air, adequate shelter and quality health care, and reflect Gasper's (1996) concept of basic needs ethics.

In this dissertation research, I will contribute to this emerging body of research by investigating the cholera epidemic in Peru during the 1990s. The epidemic was a significant event because cholera, a waterborne disease caused by the bacteria *Vibrio cholerae*, reemerged in Latin America after being absent for almost a century. Within one year of the initial outbreak approximately 400,000 cholera cases were reported in the region (Ministry of Health, Lima, Peru [MINSA] 1994b). Thereafter, cholera remained endemic in Peru and throughout Latin America until 2002 (MINSA 2005a). The emergence of cholera was initially attributed to contaminated waste dispelled from a passing ship from Asia (Gangarosa and Tauxe 1992: 353); however, this explanation was later challenged by another hypothesis, which suggested that the epidemic was precipitated by El Niño-Southern Oscillation (ENSO) (Epstein et al. 1993; Colwell 1996). ENSO, which includes El Niño (warm phase) and La Niña (cold phase), is an important source of climate variability in the Latin American region with ecosystem and societal impacts reported in Peru (Glantz 1981; Caviedes 1984; Lagos and Buizer 1992).

The El Niño-cholera hypothesis is a well accepted explanation for the epidemic supported by a few studies that found positive relationships between elevated ambient and sea water temperatures and cholera incidence in Peru, particularly during the 1997-98 El Niño (MINSA 1994b; 1998d; 2000; Speelmon et al. 2000; Huanca 2004; Gil et al. 2004). Adding credibility to the hypothesis is growing global evidence of climate-cholera links in Bangladesh (Pascual et al. 2000; Lobitz et al. 2003), India (Ruiz-Moreno et al. 2007; Constantin de Magny et al. 2008), Ghana (Constantin de Magny et al. 2007), and South Africa (Mendelsohn and Dawson 2008). In Peru, however, the El Niño and cholera association remains unclear for several reasons. First, there are questions about the timing of El Niño and the onset of the cholera epidemic in 1990-91. For example, to date, it has not been proven that El Niño precipitated the cholera outbreak (Salazar-Lindo et al. 2008). Second, most studies in Peru have focused on temperature-related impacts on cholera and not El Niño per se. Third, less is known about other aspects of ENSO, such as the best definition of the event to use when studying cholera impacts, the potential impact of the cold phase La Niña, temporal and geographic variations in ENSO-cholera impacts, and the potential impact of rainfall extremes. Moreover, social factors that contributed to population vulnerability, which may have exacerbated ENSO-related impacts, have not been considered in the El Niño explanation of the cholera epidemic in Peru.

The goal of my dissertation research is to reconstruct the temporal and spatial associations among ENSO, social vulnerability and cholera incidence in the health subregion of Piura, Peru from 1991 to 2001 in order to better understand El Niño's impact on the cholera epidemic in Peru. **Figure 1.1** is a map of the Department of Piura that highlights the subregion of Piura and the capital city of Piura. Piura is important to study because it was one of three places where cholera was first reported during the initial outbreak in 1991. Subsequently, Piura had one of the highest cholera incidence rates in the country (MINSA 1994b). Piura is also a region historically known for El Niño (Woodman 1998), poverty and preventable infectious diseases (Sandoval 1999; Ministry of Health, Piura, Peru [MINSA Piura] 2005). Therefore, more knowledge of this region will help to improve our understanding of the independent and interactive effects of climate variability and social factors on cholera transmission.

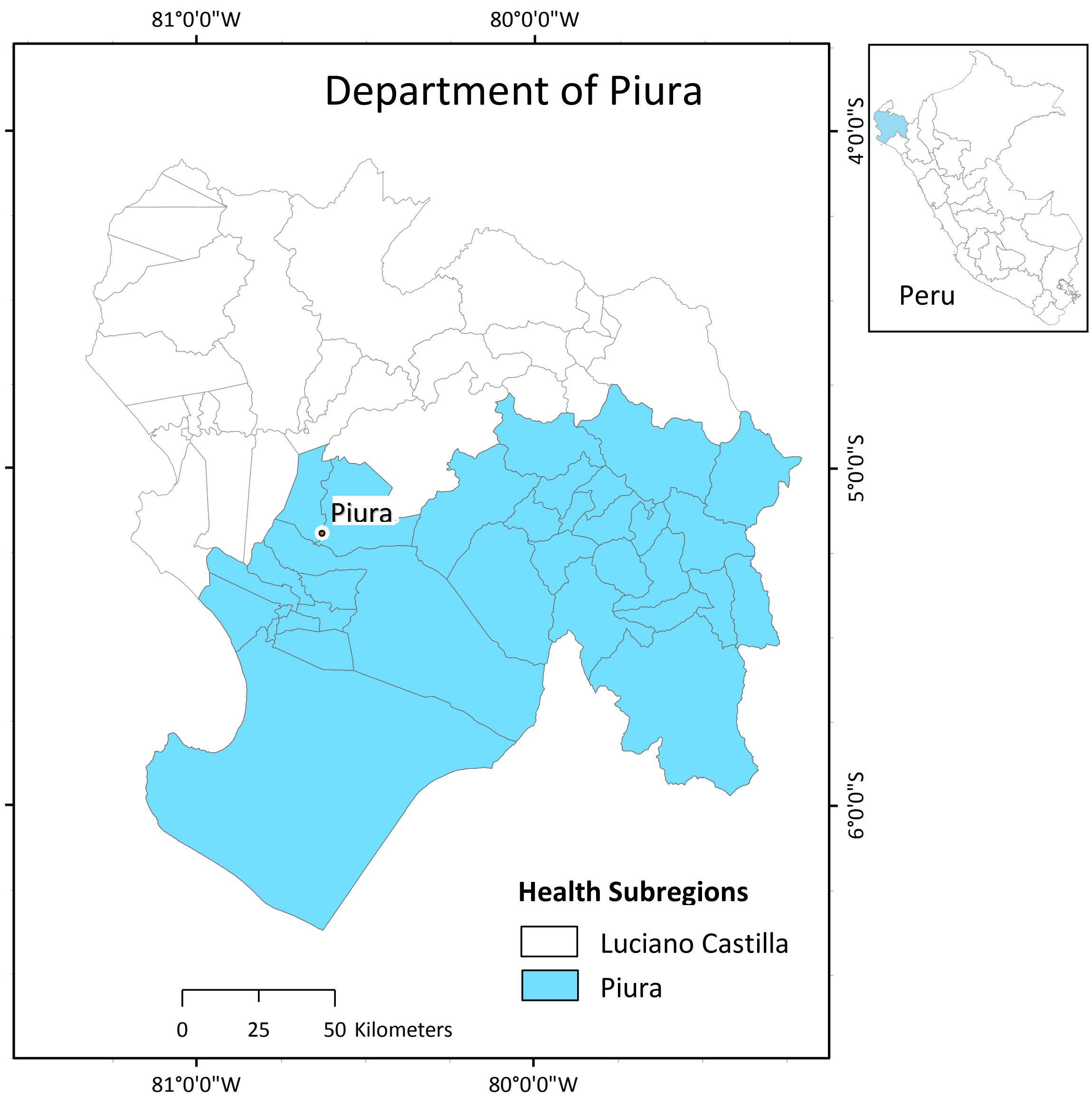

Figure 1.1 Map of the Department of Piura that highlights the subregion of Piura. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation.

My overarching research questions will be: (1) What was the impact of ENSO on cholera incidence in Piura; and (2) How did social vulnerability influence this relationship? I will address my research questions using a *climate affairs* approach (Glantz 2003; Consortium for Capacity Building [CCB] 2010) that is informed by disease ecology and social vulnerability theories from the geographic subfields of medical (Mayer 2000; Meade and Erickson 2005) and human-environment geography (Cutter 2003; Turner et al. 2003; Zimmerer and Bassett 2003). *Climate affairs* is an integrating concept in the earth and social sciences used to understand the interrelationships among climate, environment and society worldwide. A *climate affairs* approach encompasses, but is not limited to: 1) *climate science* and *knowledge* as a foundation to understanding atmospheric processes and interactions with natural and human environments; it also emphasizes the importance of multidisciplinary efforts and local and regional knowledge to this understanding; 2) *climate impacts* are the positive and negative effects on ecosystems and societies, and societal responses to these interactions; and 3) *climate ethics* and *equity* refers to moral issues that arise from climate-society interactions (e.g., differential vulnerability and impacts) (Glantz 2003).

From a *climate affairs* orientation, I will suggest a conceptual framework that: 1) examines the cholera transmission cycle within a broader conception of ENSO; 2) links ENSO-cholera associations to social vulnerability; and 3) considers ENSO-cholera interactions at multiple scales. This study is also informed by previous research on cholera (Cueto 2003; Nelson et al. 2009); climate impacts on cholera ecology (Constantin de Magny and Colwell 2009); El Niño, climate and society studies (Glantz

2001a; Caviedes 2001); and dissertation fieldwork in Lima and Piura, Peru in the summers of 2008 and 2009. The quantitative and qualitative associations among ENSO, social vulnerability and cholera incidence will be explored using a mix of time series approaches, multivariate and geostatistical methods, and a historical review of documents from the period of the epidemic.

In this introductory chapter, I will present a brief review of the cholera epidemic in Peru and explanations for the epidemic including the El Niño-cholera hypothesis. I will then present a set of arguments that motivated me to challenge the current assumptions about El Niño impacts on cholera in Peru. I will conclude this chapter with the study significance and format of the dissertation.

1.1 The Cholera Epidemic in Peru

In the early 1990s, Peru experienced the first cholera epidemic in the western hemisphere since the 1890s (Centers for Disease Control and Prevention [CDC] 1991). It marked the arrival of the *El Tor* strain of *V. cholerae*, which was responsible for the Seventh Cholera Pandemic that originated in Indonesia in 1961 (Glass et al. 1991). The first cases of cholera were reported almost simultaneously in January 1991 across three coastal cities: Chancay, Chimbote and Piura (MINSA 1994b). One year following these initial outbreaks the epidemic spread throughout Peru and subsequently to other Latin American countries, infecting almost 400,000 people (Pan American Health Organization [PAHO] 1991a). The disease was so widespread because populations lacked immunity and public water and sanitation infrastructures were either in decline or not accessible

(PAHO 1991b; Salazar-lindo et al. 1993: 401-413; Tauxe et al. 1995). Over the next decade, 52.0% (n=703,000) of all reported cholera cases in the Latin American region were reported in Peru (PAHO 2008).

The emergence of cholera in Peru took public health authorities at MINSA, PAHO and CDC by surprise. Initially, they could not believe it was cholera because the disease had not been reported in Latin America for almost a century (Gangarosa and Tauxe 1992). However, a joint effort led by MINSA and CDC in February 1991 confirmed that cholera was indeed the disease afflicting hundreds of Peruvians (CDC 1991). Health officials were also puzzled because the disease had not appeared in previous decades when living conditions in Latin America were reportedly worse (Gangarosa and Tauxe 1992). Authorities across the region were anticipating a major cholera outbreak in the 1970s after an explosive epidemic was reported in West Africa (Glass et al. 1991). In response, many countries in Latin America including Peru began to foster diarrheal disease programs with the help of multilateral organizations who supplied them with resources including oral rehydration solutions (Glass et al. 1991; Gangarosa and Tauxe 1992). Cholera, however, did not appear as expected in the 1970s or 1980s, but instead, emerged unexpectedly in the 1990s.

1.2 Explaining the Cholera Epidemic in Peru

1.2.1 Passing Ship Hypothesis

The source of the cholera epidemic in Peru remains unknown, but several hypotheses have been put forth to explain the emergence. Two initial explanations were associated with a passing ship. The first explanation suggested that an infected person on a ship from Asia docked off the coast of Peru and through unknown activities, introduced *V. cholerae* to the mainland's public water system. The second explanation suggested that a passing ship dumped *V. cholerae* contaminated ballast water (waste and discharge from ballast tanks) into a harbor along the coast infecting marine organisms, which subsequently came into contact with human populations (Gangarosa and Tauxe 1992: 353). Both explanations were plausible since cholera outbreaks in the past had been associated with travelers (Glass et al. 1991) and ballast water (McCarthy and Khambaty 1994).

1.2.2 El Niño-cholera Hypothesis

Evidence that disputed the passing ship hypothesis was later reported by Seas et al. (2000) who identified 5 clinical cases of cholera preceding the epidemic (as early as October 1990) in coastal cities in Peru. The study suggested that *V. cholerae* was already present in the coastal environment of Peru (prior to the arrival of the ship[2]), and that cholera transmission was at low levels among the population. The earliest case was found on 23 October 1990 in Trujillo (approximately 600 km north of Lima). The study by Seas et al (2000) was important because it supported a second hypothesis that linked the cholera epidemic to El Niño (Epstein et al. 1993; Colwell 1996; Mourino-Perez 1998). This alternative explanation suggested instead that El Niño contributed to ecological changes in the eastern equatorial Pacific Ocean, which in turn promoted the abundance of plankton (assumed to harbor *V. cholerae)* off the coastal shores of Peru. Subsequently, storm surges transported infected plankton inland where transmission occurred at multiple locations along the coast (Colwell 1996; Seas et al. 2000). Epstein (1992; 1993) was the first to associate the epidemic with climate but also suggested that nutrient runoff (due to agricultural activities) contributed to the reproduction of plankton blooms. It was later suggested by Colwell (1996) and Mourino-Perez (1998) that contaminated plankton from Asia may have been transported via eastward-flowing ocean currents induced by El Niño, which was presumed to have lasted from 1990 to 1995 (Colwell 1996). The reasoning underlying the El Niño-cholera hypothesis was that El Niño seemed the most logical, if not obvious, mechanism for simultaneous outbreaks on the Peruvian coast spanning a distance of 1100 km (Seas et al. 2000).

[2] It should be noted that finding the original report that documents the arrival of the ship and time is difficult. I have been citing secondary sources that mention the hypothesis.

1.3 Challenging the El Niño-cholera Hypothesis

Although El Niño's impact on the epidemic in Peru is plausible, there are several arguments that motivated me to challenge El Niño's association. These arguments are based on characteristics about ENSO, which I argue have been overlooked in previous studies.

The importance of definition

The El Niño-cholera hypothesis is based upon a contentious El Niño period (1990 to 1995). During this time, there was disagreement among experts about the timing of El Niño events and the number of events that developed (Glantz 2001: 21). As such, the timing of El Niño and its impact on the epidemic remains questionable. One factor which may resolve this issue is the definition of an ENSO event, which affects how one interprets the cycle characteristics of an El Niño (Trenberth 1997). Considering this factor may shed new light on the El Niño association and the ENSO context during cholera transmission in Peru.

The La Niña factor

Preceding and following the 1997-98 El Niño were La Niña events during which cholera cases appeared to decline. La Niña events are also associated with societal impacts; however, knowledge about its impacts is less known because this phase is less studied (Glantz 2002b: 8). Perhaps La Niña periods were protective years for cholera transmission.

Geography of El Niño impacts

Previous El Niño-cholera studies in Peru were limited in their geographic scope of analysis. These studies followed the initial outbreak and examined cross-sections of the 1990s. No study has ever examined the entire decade when cholera was prevalent in Peru or investigated the initial time segment when cholera first emerged. Reasons why the entire period has not been examined despite its significance are perhaps related to the lack of data and funding challenges.[3] Another reason could be that after cholera subsided in 2004 other urgent health issues became public health priorities. Furthermore, El Niño-cholera studies were generally focused on Lima. El Niño-cholera associations in other geographies of the country are less known.

Rainfall extremes

Rainfall extremes are important teleconnections in Peru, which have not been investigated in relation to the cholera epidemic. In 1997 to 1998, there was an extreme El Niño, which became historical because of its impacts on economic sectors, infrastructure and human health including a resurgence of cholera in Peru (Consejo Nacional del Ambiente [CONAM] 1999: 159-161; Amat y Leon et al. 2008: 18-19). Much of the reported damages and health impacts were associated with heavy rains, which suggests that rainfall extremes may have been an important pathway for cholera transmission in Peru in 1997-98 and perhaps previously.

[3] Lack of funding may be a reason for researchers at Peruvian institutions. Dr. Ana I. Gil at the International Institute of Nutrition in Lima conveyed to me that resources were limited (personal communication July 2009).

Social dimensions

Prior to the emergence of cholera in 1990/91, several El Niños were reported in Peru including the mega event of 1982-83, and yet cholera outbreaks were not reported during that time. Therefore, this may suggest that the presence of El Niño alone cannot solely explain the cholera epidemic in Peru. It has been reported that cholera diffused rapidly because of widespread infrastructure and socioeconomic deprivation across Peru (PAHO 1991b; Brooke 1991; Ries et al. 1992; Swerdlow et al. 1992; Besser et al. 1995; Ticker and Gouveia-Vigeant 2005). Furthermore, the country was responding to humanitarian crises (United Nations Disaster Relief Organization [UNDRO] 1990b; 1990a), while restructuring its economy (Nash 1991) and combating terrorism (Youngers 2000). Integrating this underlying context of population vulnerability will be important to fully understand the role of ENSO impacts on cholera outbreaks and transmission in Peru.

In light of these arguments, the cholera epidemic in Peru and the association with El Niño warrants further inquiry. In particular, the story and explanations about the cholera epidemic in Peru require rethinking, not only because of the arguments presented above, but also because the explanations (climate and social) have not been integrated. Thus, retelling the story about cholera in Peru with combined elements from existing explanations and new information would yield a better understanding of the epidemic in Peru and the role of ENSO and climate on cholera incidence and transmission.

1.4 Study Significance

This research will advance knowledge in geography by developing a framework that integrates theoretical approaches from medical geography and human-environment geography to address climate impacts on infectious disease and health, an emerging area of inquiry among disciplines and policy interest among communities, governments, and international relations. Specifically, this research links knowledge in Piura, Peru to the growing research on climate and cholera in Bangladesh, India, Vietnam, South Africa and Ghana. More broadly, it speaks to the larger body of work pertaining to climate change, health and society (WHO 2008). It also contributes to the growing body of literature on development ethics and the newer field of 'climate' ethics and justice by engaging moral concerns and questions about ethics and equity issues that arise from climate-disease-society interactions. As such, this research is part of and promotes *climate affairs*, an approach to climate and society studies that emphasizes multidisciplinary research that bridges the natural and social sciences with the humanities. For public health and development policymakers this study provides an analogy from which to learn lessons about climate variability and extremes, infectious disease, and human well-being.

1.5 Dissertation Format

I divided my dissertation into seven chapters. Chapter 1 is the introduction. Chapter 2 presents a literature review of topics pertinent to this study. It includes ENSO science and knowledge, climate and cholera ecology, cholera transmission and human ecology, and cholera and population vulnerability. Chapter 3 reexamines El Niño's association with cholera in Peru, presents several arguments that challenge the association, and concludes by stating my research objectives and hypotheses. Chapter 4 describes my research design including the research approach, theoretical concepts and framework, and the data and methods for each research objective. Chapter 5 highlights key findings. Chapter 6 discusses the findings, addresses my research questions and hypotheses, and reflects on the ethical geographies of the study. Chapter 7 presents some concluding thoughts and implications for future research, policy and ethics.

CHAPTER 2: LITERATURE REVIEW

In this chapter, I present a literature review of topics relevant to this dissertation research. I begin with ENSO, its cycle and phase characteristics, physical teleconnections and ecosystem and societal impacts in Peru. In the next section, I review what we currently know about the relationships among ENSO, climate and cholera disease ecology in studies around the world. I then discuss cholera transmission routes and human ecology. In the final section, I describe cholera incidence in relation to population vulnerability.

2.1 ENSO Science and Knowledge

ENSO is a quasi-periodic natural phenomenon resulting from ocean-atmosphere interactions in the equatorial Pacific Ocean. It is the second most predictable climatic fluctuation after the natural flow of the seasons. El Niño, the oceanic component of ENSO, is known as a warming of waters off the coast of Peru, but also refers to basin-wide oceanic changes that extend across the equatorial Pacific Ocean (Bjerknes 1969). It was first named by Peruvian fishermen (on the northern coast) who noticed a periodic warming coinciding with Christmas (Carillo 1892). The Southern Oscillation considered the atmospheric component of ENSO is a seesaw-like pattern of sea-level pressure measured between Darwin, Australia and Tahiti. Together these components make up the ENSO cycle, which influences local to global variability and extremes of weather and climate and impacts ecosystems and human populations within its sphere of influence (Graham and White 1988; Caviedes 2001; Glantz 2001a; Cane 2004; Philander 2006).

The ENSO cycle consists of El Niño (warm) and La Niña (cold) extreme events, which alter "average" SST conditions in the equatorial Pacific Ocean (National Oceanic and Atmsopheric Administration [NOAA] 2005). Warm and cold events are characterized by a multi-phase-process: precursor, the onset (development), growth and maturity, and decay. Each event is unique in the way it evolves including in magnitude and duration and the location and intensity of impacts (Glantz 2001a: 100). Although an event is unique from one time period to another, some common aspects are generally found, including how often an event occurs (e.g., every 3 to 7 years) and how long an event lasts (e.g., 12 to 18 months) (Goddard et al. 2001). In the 1990s, however, it appeared there were more frequent warm episodes, including the strongest event of the twentieth century (Bell and Halpert 1998). In the next subsections, a general description is given of ENSO event characteristics and impacts on climate and society in Peru.

2.1.1 ENSO Events

During "average" conditions in the equatorial Pacific Ocean basin, upwelling processes off the coast of Peru bring cold and nutrient rich waters from the deep ocean to the sunlit sea surface zone, which provides an abundance of food for many marine species including plankton. Easterly winds driven by pressure differences contribute to upwelling by dragging waters from the eastern Pacific towards the western Pacific, where warm waters pile up, the oceanic thermocline deepens, and sea level rises (Philander 1985). Over the western Pacific warm air rises and falls over the eastern

Pacific, contributing to low air pressure and wet conditions over Indonesia and N. Australia, and high air pressure and dry conditions off the coasts of Ecuador and Peru (Walker 1924).

When El Niño develops, easterly winds weaken and appear to reverse disrupting upwelling off the coast of Peru and movement of surface waters from the eastern Pacific to the western Pacific. The interactions and changes in the ocean and atmosphere are basin-wide and result in a positive feedback: a mass of warm waters shifts from the west and travel via Kelvin (internal) waves toward the west coast of South America (i.e., Ecuador, Peru and Chile); convective rainfall activity follows the warm pool of water, which expands into the central and eastern Pacific, where the oceanic thermocline deepens; consequently, sea-level heights rise and sea surface temperatures increase as Kelvin waves carrying warm water reach the coast of Peru (Philander 1985). Over the western Pacific, air pressure becomes high, suppressing rainfall over N. Australia and Indonesia; over the eastern Pacific air pressure becomes low and storms and rainfall occur on a normally arid coast of Peru. During La Niña, the opposite occurs and "average" conditions are enhanced; easterly winds strengthen and air pressure rises in the eastern Pacific suppressing rainfall convection and enhancing coastal upwelling (NOAA 2005).

2.1.2 ENSO Monitoring and Definition

ENSO events are monitored across the equatorial Pacific Ocean basin in 5 delimited areas known as Niño regions: Niño 1 – (5-10°S, 80-90°W); Niño 2 – (0-5°S, 80-

90°W); Niño 3 – (5°N-5°S, 150-90°W); Niño 3.4 – (5°N-5°S, 120-170°W); and Niño 4 – (5°N-5°S, 160°E-150°W). **Figure 2.1** shows a map of these regions. Events are identified by observing the ocean-atmosphere parameters and conditions described previously that denote the different stages of the ENSO event life cycle. The most common indicators of ENSO events are anomalous changes of sea surface temperature (SST), surface winds, and east-west pressure (NOAA 2005). El Niños and La Niñas are typically estimated using the aforementioned variables to generate indices, such as Niño Region Indices (SST anomalies in each region), the Southern Oscillation Index ([SOI], sea level pressure differences between Darwin and Tahiti) or the Multivariate ENSO Index (a combination of SST, sea-level pressure and surface winds) (International Research Institute for Climate and Society 2007; Bureau of Meteorology in Australia [BOM] 2010; Walter 2010). Other important variables are outgoing longwave radiation (OLR) (e.g., to estimate convection) and sea-level height off the coast of Peru (NOAA 2005).

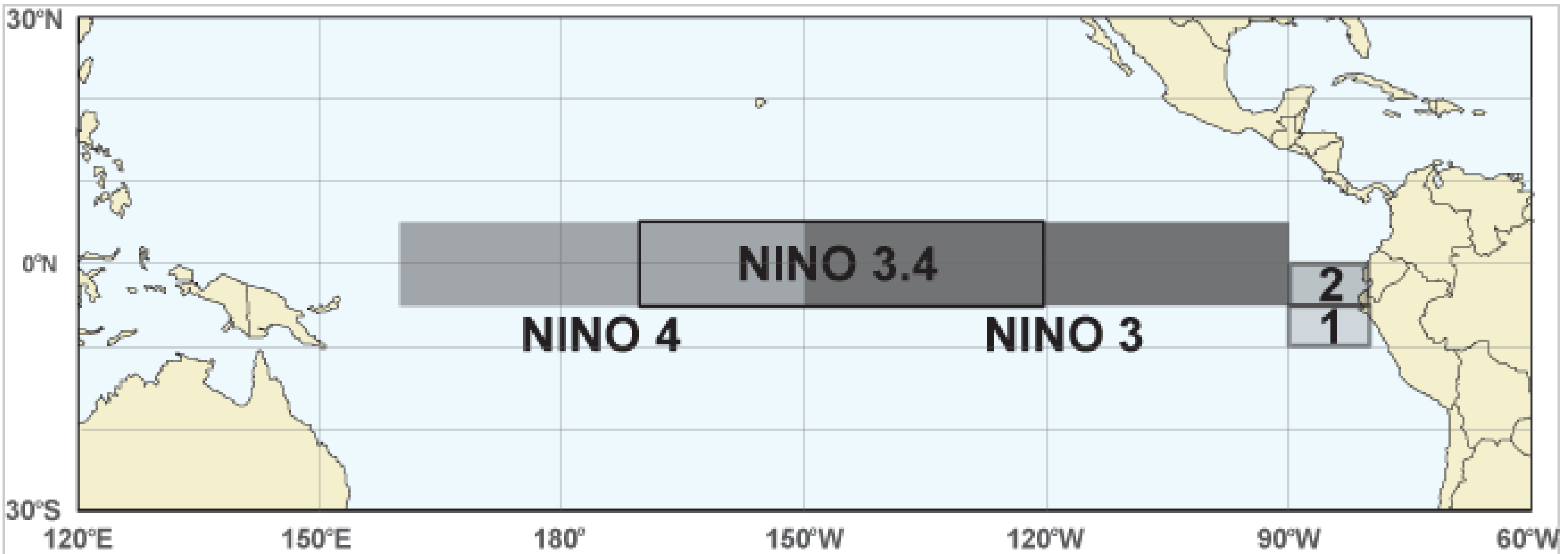

Figure 2.1 Map of Niño Regions.

Source: http://www.bom.gov.au/climate/enso/indices/about.shtml.

The characterization of an ENSO event and its cycle is determined by the definition applied. Several definitions of ENSO have emerged since the 1980s that range from quantitative to qualitative interpretations, as well as regional definitions (Trenberth 1997), such as that utilized by some Peruvian institutions.[4] Quantitatively, an ENSO event is commonly defined by observing monthly mean SSTs in a selected Niño region (this depends on the user) over periods where a selected threshold (e.g., +0.4°C) is exceeded. Trenberth (1997) demonstrated the importance of definition using a modified operational definition from the Japanese Meteorological Agency, which requires a minimum of 6 months for a 5-month running means of monthly SST anomalies to exceed an anomaly threshold. He compared the results of different anomaly thresholds (i.e., +0.3°C, +0.4°C, and +0.5°C) in Niño 3 and Niño 3.4 regions in the Equatorial Pacific. The results demonstrated that the anomaly threshold and Niño region influenced when an event began and ended. Trenberth also found that the Niño 3.4 index was more consistent with historical studies; however, he also recommended using a definition and criteria that suits the region or needs of the user. Clearly understanding the ENSO definition that is used is important in health studies because it

[4] By Peruvians I am referring to the general understanding and interpretation of El Niño by the institutions that are responsible for monitoring this phenomenon. The definition utilized in Peru is based on the Scientific Committee for Ocean Research (SCOR) working group which states the following criteria signify the appearance of an El Niño along the coast of Ecuador and Peru as far south as Lima (12°South): 1) normalized sea surface temperature (SST) anomaly exceeding one standard deviation for at least four consecutive months; and 2) normalized SST anomaly should occur at least at three of five Peruvian coastal stations. It differs from NOAA's operational definition based on SST anomalies in the Niño Region 3.4 (Lagos et al. 2008); however, I should add that Peruvians also use the NOAA index for comparison.

defines: (a) which indicators will be utilized in the study; (b) how each event is subsequently identified; and (c) the interpretation of the timing and intensity of events**.**

2.1.3 ENSO Teleconnections in Peru

During ENSO events, temperature and rainfall patterns are influenced around the world such that some places may become wetter while others become drier during El Niño and La Niña (Kousky et al. 1984; Ropeleski and Halpert 1987; 92). These impacts on climate known as 'teleconnections' are based on statistically and physically proven linkages between ocean-atmosphere interactions in the central and eastern equatorial Pacific and climate anomalies in distance places (Wyrtki 1973; Flohn and Fleer 1975; Kiladis and Diaz 1989; Glantz 2001a: 3). Teleconnections are generalized in terms of El Niño and La Niña associations by season from December to February and June to August (Ropeleski and Halpert 1987; Diaz et al. 2001). They are strongest during the Southern Hemisphere (SH) summer (e.g., December to March) when SST is warmest in the equatorial Pacific (NOAA 2005). Furthermore, the strength of teleconnections depends on the magnitude and spatial extent of SST anomalies in the Niño regions (Goddard et al. 2001), as well as the distance from the central and eastern equatorial Pacific Ocean (Glantz 1998). In this dissertation research the term teleconnections is used more broadly to include: 1) all places that are commonly associated with ENSO; and 2) impacts based on historical and local references.[5]

In Peru, ENSO teleconnections vary by region, but are most notable on the northern coast, an area which is typically arid, except during El Niños when torrential rains are reported from December to March (Caviedes 1973; 84; Horel and Cornejo-Garrido 1986; Woodman 1998; National Meteorology and Hydrology Service of Peru [SENAMHI] 2004; Rodriguez et al. 2005). In other regions in Peru, El Niño teleconnections are less well-defined, but can be generalized as follows: warmer than average conditions from June to August on the central coast (SENAMHI 2004); above average rains in the Southern Andes in November; below average rains from January to March in the Southern and Central Andes (Lagos et al. 2008; SENAMHI 2009); and rainfall deficit in November and December in the Amazon (Marengo 1999; Marengo et al. 2008). La Niña teleconnections are less known but some reports indicate that colder than average temperatures and severe drought have been documented in the coastal north in July and August during cold events (Ordinola 2002). In general ENSO teleconnections should be interpreted with caution, because of ENSO's variability in character from event to event and the influences of other factors on Peru's climate, such as the Andes, the Humboldt Current, the InterTropical Convergence Zone, and

[5] It is important to broaden the term because using a strict definition of teleconnections would exclude Piura, the area of study in this research. It would also dismiss impacts based on local unpublished literature consisting of reports, anecdotes and descriptive statistics documenting the experiences of Peruvians during ENSO events.

conditions in the tropical Atlantic (Lagos and Buizer 1992; Marengo et al. 2008; SENAMHI 2009).

2.1.4 ENSO Ecosystem and Societal Impacts in Peru

In Peru, ENSO teleconnections and impacts on ecosystems and societies are documented as far back as the 1500s (Glantz 2001a: 165). Years associated with El Niños are synonymous with climate-related hazards and disasters (Glantz 2001a: 27; CONAM 2002). In the last century, the most memorable El Niño years in Peru were 1925, 1972-73, 1982-83 and 1997-98 because of the magnitude of damage to infrastructure, economy, and people's lives (Lagos and Buizer 1992; Woodman 1998; Caviedes 2001). The latter two events were the strongests in the twentieth century. Impacts are reported during and after events and are sometimes generalized as a pre-event, event and post-event in order to compare the effects of ENSO events on different sectors and population factors. According to a study by Bouma et al. (1997), societies experience the greatest impacts in post-event years based on the number of persons affected by El Niño-related disasters. The study suggested that impacts on society are felt well after El Niño/ La Niña years.

El Niño-related weather and climate can contribute to ecosystem disruption and damages to economy and infrastructure via temperature and rainfall variability and extremes. In Peru, some of the most vulnerable sectors to impacts from ENSO extremes are fisheries, agriculture, energy, and public health (CONAM 2002; SENAMHI 2004).

As stated earlier, El Niños disrupt upwelling, which, along with invading warm waters affect marine ecosystems off the coast of Peru (Barber and Chavez 1983; Tarazona and Valle 1999; Escribano et al. 2004; Chavez et al. 2008), and ultimately the livelihoods of coastal communities and the fishing industry. Fish populations respond by migrating north and south, going to greater ocean depths, or swimming closer to shore. For some species, such as anchovy, which is an important commercial resource in Peru, El Niño-related extremes can adversely impact spawning (Pizarro 1999; Carr and Broad 2003). In 1973, the collapse of the anchovy industry was blamed on El Niño, but later it was recognized that overharvesting was also a major contributing factor (Caviedes and Fik 1992; Glantz 2001a: 232).

In the agricultural sector, ENSO-related rainfall and temperature extremes can impact the harvest of crops and livestock (Lagos 1998; Woodman 1998; CONAM 2002). Two examples are potatoes and rice. In the central highlands of the Andes, it has been reported that potatoe harvesting is vulnerable to El Niño-related drought (Orlove et al. 2000). While in northern coastal Peru, colder than average conditions during La Niñas correlate with lower rice yields (Ordinola 2002). ENSO can also impact agriculture through ecosystem changes which affect the ecology of insects and pathogens that either feed on or attack crops (e.g., potatoes) (Cisneros and Mujica 1999).

ENSO-related extreme weather can also impact the built environment including energy infrastructure. Power outages related to storms are particularly damaging since they can affect water and sanitation systems, electrical service in homes, businesses and hospitals. During such events, public water supply can be interrupted (e.g., chlorination) and foods can spoil (e.g., no power for refrigeration). In addition, infrastructure damage because of flooding (e.g., the washing out of bridges, roads and communication lines) can isolate communities and displace persons who lose their homes (PAHO 1998b).

Furthermore, when collapse of infrastructure (e.g., water and sanitation systems) co-occurs with ecosystem changes (e.g., changing environmental conditions for vectors and pathogens) in Peru, human exposure to disease and injury can increase (Gueri et al. 1984; PAHO 1998a; Valverde 1998; PAHO 1998a; Sandoval 1999; CONAM 2002; Kovats et al. 2003). Overall, ENSO extremes can potentially disrupt societal well-being in Peru.

2.2 Climate and Cholera Ecology

Cholera is a diarrheal disease caused by the waterborne bacteria *Vibrio cholerae*. There are over 200 serotypes of *V. cholerae* that exist naturally in aquatic environments, with two serogroups of public health concern, serogroup 0139 and serogroup 01. Currently serogroup 0139 is primarily found in Bangladesh, India and Pakistan (Zuckerman et al. 2007), while serogroup 01, specifically the biotype El Tor, is endemic in many countries of the world (WHO 2009). The El Tor biotype was responsible for the Seventh Cholera Pandemic, which began in 1961 in Indonesia and subsequently spread to South and West Asia, the former Soviet Union, Europe, the Mediterranean, Africa, and eventually reached the Americas (Glass et al. 1991).

Historically it was thought that humans were the only reservoir for *V. cholerae*, but in recent decades studies strongly suggest that aquatic organisms, such as plankton, aquatic plants (Tamplin et al. 1990; Lipp et al. 2002) and biofilm (Alam et al. 2007), can act as environmental hosts. It is suspected that *V. cholerae* live in a symbiotic relationship with marine hosts whereby the bacteria attaches itself to the surface of organisms that inhabit aquatic ecosystems (Tamplin et al. 1990).

In particular, phytoplankton is an important factor in the climate and environment association with cholera, and the hypothesis in Peru. When phytoplankton multiplies it is a prime source of food for organisms called zooplankton, which include crustaceans (e.g., shrimp and lobster) and copepods (small crustaceans) (Constantin de Magny et al. 2011). Lipp et al. (2002) has suggested that zooplankton is a disease vector in the cholera transmission cycle. One copepod may contain up to 10^4 cells of *V. cholerae*, an adequate dosage for human infection (Glass and Black 1992: 136). Exposure to the bacteria is reported to occur when humans drink untreated water or consume *V. cholerae*-carrying crustaceans or fish without proper cooking (Huq et al. 2001).

Studies also suggest that *V. cholerae* is autochthonous to brackish and estuary waters. That is, these organisms can live naturally in the environment without humans (Tamplin et al. 1990; Colwell 2004). The suspicion that *V. cholerae* could reproduce without human fecal contamination was speculated by Robert Koch who first discovered the organism in 1883 (Colwell and Spira 1992). Reinforcing this notion were historical reports of outbreaks in coastal areas without the discovery of a human carrier (Huq et al. 2001; Pascual et al. 2002). This conjecture along with *V. cholerae's* known association with water, and the evidence of an environmental reservoir has led many researchers to consider climate as an environmental factor in the cholera transmission; namely, through impacts on the habitat and reproduction of *V. cholerae* and plankton (Colwell 1996; Lipp et al. 2002). Climate and environmental factors that are important to the ecology of *V. cholerae* and phytoplankton include elevated temperature, pH, salinity, and iron (Lipp et al. 2002); however, it has also been reported that *V. cholerae* can survive in low salinity conditions (Singleton et al. 1982).

Thus far, studies have shown that climate has been associated with cholera in Bangladesh (Lobitz et al. 2000; Pascual et al. 2000; Emch et al. 2008; Hashizume et al. 2008; Akanda et al. 2009; Hashizume et al. 2010), India (Ruiz-Moreno et al. 2007; Constantin de Magny et al. 2008), Ghana (Constantin de Magny et al. 2007) and South Africa (Mendelsohn and Dawson 2008). The following subsections will review these studies and the global and local climate parameters that were investigated in relation to cholera incidence.

2.2.1 Global Climate Parameters and Cholera

Niño SST is an important global climate factor that has been associated with cholera ecology in Bangladesh (Pascual et al. 2000). Pascual et al. (2000) was the first to demonstrate this association in a study showing that peaks in monthly cholera rates in the Bay of Bengal, Bangladesh fluctuated with the Niño 3.4 index from 1980 to 1998 during northern hemisphere (NH) spring. It was also observed that another peak occurred in NH fall (unassociated with ENSO) suggesting that interannual and seasonal climate variability impacted cholera transmission indirectly through its influence on local coastal air-water temperatures and plankton blooms. Importantly the authors noted that previous disease levels in the population were also likely to determine cholera fluctuations overtime. In another study, Rodo et al. (2002) examined monthly cholera data in relation to the SOI and Niño 3.4 index in order to estimate these relationships across two periods in Dhaka, Bangladesh from: (a) 1893 to 1940 and (b) 1980 to 2001[6]. The study found a stronger relationship in the latter period during which ENSO explained 70.0% of the variance. Niño 3.4 was associated with peaks from 1991 to 1994; however, SOI was not.[7] Cholera peaks were primarily associated with extreme ENSO events, suggesting to the authors that the climate-cholera link was transient overtime; and that perhaps there was a climate threshold during these periods.

To further investigate the relationship between ENSO and cholera in Bangladesh, two studies assessed the comparative contributions of climate variability (referred to as extrinsic) and herd immunity (referred to as intrinsic) on cholera incidence. In the first study Koelle and Pascual (2004) examined monthly cholera mortality data in Dhaka, Bangladesh from 1892 to 1940. The study investigated whether population immunity (defined by birth rates and vaccination coverage data) could partly explain the temporal variabilty observed by Rodo et al. (2002). These authors showed that immunity decayed after 9 yrs, and may explain cholera variability incidence on 4 and 8 yr cycles. However, there was no clear climate association with ENSO, SOI or local rainfall. In conclusion, the

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[6] Data were unavailable for the years in between the two periods.

[7] This observation may reflect the ecological relationship between SST and cholera ecology; the association between surface pressure and cholera has yet to be discerned.

study suggested that seasonality and partial population immunity contributed to rates of cholera.

In a subsequent study, Koelle et al. (2005) demonstrated that ENSO's relationship was mediated by local climate impacts on cholera. In this study monthly cholera cases in a rural region south of Dhaka, Bangladesh were examined in relation to the Niño 3.4 index, Bay of Bengal (BOB) SSTA, rainfall and river discharge data for 1966 to 2002. Rainfall was included because it has been reported that cholera decreased with the monsoon rains due to a dilution effect. The study found that cholera increased after the monsoon rains because flooding contributed to population congregation (density was also a factor), and collapse of sanitary conditions due to flooding. River discharge was a proxy for water levels. Although the focus of the study was cholera associated with the El Tor strain, cases of the classical strain were also included to estimate herd immunity in the population.[8] The study showed different associations among the variables (e.g., Niño 3.4 and BOB SSTA and Niño 3.4 and cholera), which depended on the temporal scale and the strain (e.g., the classical strain was associated with low water levels). Herd immunity was shown to decay after 3yrs, but partial immunity existed up to 10 yrs. The authors concluded that after large outbreaks, there was a marked decrease in cholera incidence due to a decrease in a susceptible population and increase in population immunity; the authors referred to these time

[8] The study considered both strains because it has been reported that cross-immunity among cholera serotypes can occur; cross-immunity can provide partial immunity (Koelle et al. 2006).

intervals as ‘refractory periods’. It was hypothesized that even if favorable climate conditions emerged, the likelihood of transmission would be low in times of refractory. This was believed to explain the non-stationary link between climate and cholera in Bangladesh.

Outside of Bangladesh, two studies in Africa examined cholera patterns in relation to global climate parameters associated with the Indian Ocean. In a study by Constantin de Magny et al. (2007), monthly cholera incidence was investigated in 5 countries (Cote d’Ivoire, Ghana, Togo, Benin, and Nigeria) in the Gulf of Guinea to understand how the disease evolved overtime in relation to the Indian Oscillation Index (IOI) and local rainfall from 1975 to 2002. The study found 2 to 5 yr cycles between cholera and climate in countries except Cote d’Ivoire. Generally, the association between IOI and rainfall and cholera incidence was particularly significant from 1989 to 1994. Rainfall was reported to be associated with flooding and water contamination. The authors proposed that the lack of significant associations in Cote d’Ivoire could be explained by refractory periods. In another study Constantin de Magny et al. (2007) examined cholera incidence in Ghana from 1975 to 1995 in relation to IOI, SOI, rainfall, and air temperature anomaly. The results were similar to those found in the Gulf of Guinea study by Constantin de Magny et al. (2007); it was shown that cholera was temporally associated with IOI and rainfall from 1989 to 1995.

2.2.2 Local Sea Surface Temperature

Lobitz et al. (2000) was one of the first to examine local climate and cholera in coastal Bangladesh using Bay of Bengal SSTA and sea surface height anomaly (SSHA).

This study found a seasonal pattern between weekly SSTA and percent of confirmed cholera cases from 1989 to 1995. There were significant associations in 1992, 1994, and 1995. It was also observed that SSHA preceded cholera outbreaks in 1993 and 1995. Plankton counts were not measured, but it was suspected that rising coastal waters may have transported plankton inland.

In another study, Constantin de Magny et al. (2008) examined SST, rainfall, and phytoplankton biomass in relation to monthly cholera cases in two areas: Kolkata, India and Matlab, N. Bay of Bengal from September 1997 to December 2006. It was assumed that phytoplankton were environmental reservoirs for *V. cholerae*. SST was initially included in the models, but was later removed because of collinearity; furthermore, it was found that chlorophyll (a proxy for plankton productivity) and rainfall were better explanatory variables. Importantly, the authors found that cholera hospital admissions were associated with different climate pathways that varied by place and time (time lag associations are discussed in section 2.2.4; also refer to Appendix 1). In Kolkata, which is closer to the coast (relative to Matlab)[9], plankton blooms were associated with heavy rains, nutrient run-off and blooms, while in Matlab, Bangladesh tidal intrusion transported plankton inland to the low-lying coast. The authors suggested that cholera transmission occurred when people used local rivers for cleaning and drinking water.

The importance of geographic differences in local climate and cholera dynamics was further elucidated in a study by Emch et al. (2008), which investigated environmental drivers of monthly cholera outbreaks in Matlab and Hue and Nihau Tran,

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[9] The distance between the two locations is approximately 210 km.

Vietnam from 1983 and 1985 to 2003. The authors showed that in Matlab, chlorophyll was significant and positively associated with outbreaks; while river discharge was negatively associated with outbreaks. SST, SSH, rainfall and air temperature were not statistically significant. However, in Hue, elevated SST was significant and increased the risk of a cholera outbreak; whereas, elevated SSH and river height decreased cholera risk. SST was only significant when SSH was controlled in the model. In Nihau Tran, SST and SSH were not significant, but an increase in river discharge and height were positively associated with cholera outbreaks. Emch et al. (2008) suggested that river discharge and height were related to flooding and possibly dual transmission pathways. The differences in SST associations by place were not explained by the authors.

A possible explanation for the differences in SST associations in the Emch et al. (2008) study could be local geography. Hue is separated from the ocean by several kilometers of estuary, while Nihau Tran is a city on the central coast of Vietnam suggesting that the physical environment and proximity to coast may have influenced the climate mechanisms in each place. According to Mendelsohn and Dawson (2008), topography may have explained why SST was a predictor of cholera and SSH was not in KwaZulu-Natal, South Africa during an outbreak in 2000-01. In this study, the authors explained that coastal intrusion did not occur via SSH because the low-lying coast in KwaZulu-Natal becomes abruptly steep as you travel inland. Thus, the physical geography may have prevented coastal instrusion and potential human-environment interactions with *V. cholerae*. In a more recent study, Emch et al. (2010) showed that results in Matlab were similar to those found by Emch et al. (2008). SST was not significant and SSH and chlorophyll were associated with cholera incidence in the late NH spring or pre-monsoon period. In this study, the authors suggested that the scale of the study may have contributed to the difference in results (i.e., compared to other studies that found an association).

2.2.3 Local Rainfall

As stated earlier, there is evidence that rainfall may increase and/or decrease cholera risk (Kovats et al. 2003). For example, Ruiz-Moreno et al. (2007) demonstrated that heavy rains increased the risk of cholera through exposure from floods, transport and contamination of water supply in Madras, India. Similarly, Hashizume et al. (2008) found that weekly cholera incidence in Dhaka, Bangladesh increased (14.0%) with a 10 mm increase in rain from 1996 to 2002. River levels partly explained this association but overflow was not a likely transmission pathway. Instead, it was suggested that heavy rains washed away predators of *V. cholerae,* and thereby, increased the bacteria's survival. In KwaZulu, South Africa, Mendelsohn and Dawson (2008) also found strong associations between rainfall and cholera rates during an outbreak in 2000-01. These authors hypothesized that heavy rains impacted the distribution of plankton, which subsequently led to cholera transmission. Although they found statistically significant results, they recommended longer time series analyses to support their findings.

Ruiz-Moreno et al. (2007) also showed that heavy rains decreased cholera risk by diluting the concentration of bacteria in Madras, India, a pathway suggested earlier by Koelle et al. (2005) in Bangladesh and Codeco (2001) in the Brazilian Amazon.

Furthermore, cholera transmission may also depend on the season and the rainfall extreme (abundance or deficit). Akanda et al. (2009) demonstrated this aspect of the rainfall-cholera relationship by examining Bay of Bengal SSTA and streamflow (i.e., associated with rainfall) from the Brahmatuputra and Ganges rivers in Bangladesh. This study found that from 1980 to 2000 cholera outbreaks in the NH spring were associated with rainfall deficient years; while in the NH fall, rainfall abundance years were associated with outbreaks, most likely via coastal intrusion. It was also shown that SST was significantly associated with cholera in the NH fall. These authors, like others (Mendelsohn and Dawson 2008; Constantin de Magny et al. 2008), attributed rainfall's impact on cholera to conditions of the water supply in a place; therefore, it was suggested that the combination of local rainfall and local infrastructure conditions may affect the transmission cycle through influences on hygienic practices and other water-related activities that lead to exposure.

2.2.4 Temporal Lags

The literature review showed that climate and cholera associations are found at global (e.g., Niño Region SST and IOI) and local (e.g., SST, rainfall, temperature and other environmental variables) scales. It also suggested a need for climate-cholera studies that are specific to 'place' to better understand how local climate impacts local cholera ecology. Within the study of 'place', there is also a need to understand time based associations. Climate was shown to influence cholera transmission at different time scales (e.g., interannual and seasonal) in different geographies. These associations could be characterized as periodic, quasi-periodic, or non-stationary depending on the climate parameter. Furthermore, the literature indicated that there existed a wide range of time lags (e.g., zero to 16 months) with apparent trends among the parameters. Refer to **Appendix 1** for a table of climate-cholera studies by area and the time associations reported in several of the key studies discussed earlier.

Global parameters, such as Niño SST and the IOI, were associated with impacts on cholera transmission with lags of 8 to 12 months. In contrast, river height and rainfall, two local parameters, were associated with shorter time lags (e.g., Emch et al. [2008] found zero-2 month lags). This difference between global and local parameters may suggest that cholera impacts are also influenced by the distance from the climate source (e.g., the further away from the climate source, the longer the time-delay). In studies that examined local SST impacts on cholera, it was reported that time lags ranged from zero to 9 months (e.g., Bouma and Pascual [2001] and Koelle et al. [2005]). Temporal lags by 'place' (i.e., Piura, Peru) are important factors that will be explored in this dissertation research because they will help to explain the time-space process between climate teleconnections and impacts on cholera transmission.

2.3 Cholera Transmission and Human Ecology

Cholera is transmitted to humans through the ingestion of water and food contaminated with *V. cholerae*. Once a person is infected the incubation period can be 1 to 5 days before the onset of symptoms (Glass and Black 1992: 141). Symptomatic cholera infection may occur in several stages beginning with acute watery diarrhea and vomiting followed by severe dehydration and death if supportive treatment via oral or intravenous rehydration is not immediately initiated (Mahalanabis et al. 1992: 253). A person must ingest a dosage of approximately 10^8 *V. cholerae* organisms in order to become symptomatic (Glass and Black 1992: 140). According to the WHO (2009), 80.0% of persons that become symptomatic develop mild cholera symptoms, while 20.0% experience acute symptoms. Importantly, the WHO reports that 75.0% of infected persons show no symptoms, but are still capable of transmitting the disease to susceptible populations. This lack of complete understanding of underlying population(s) at risk (e.g., susceptibles versus non-susceptibles) makes disease surveillance and the planning of prevention and control efforts challenging.

Cholera is commonly transmitted through water contamination. Some common sources of water contamination are municipal water supplies, surface water, lakes, rivers and aquifers for drinking and bathing (Butler and Sack 1990) and open wells. Municipal water supplies may become contaminated if there are leaks due to infrastructure decline and/or are not adequately treated with chlorine that kill the *V. cholerae*. It has also been reported that people who are in need of water illegally break into water pipes, and in doing so contaminate the water supply. In places with intermittent electricity (common in many rural areas in developing countries), the municipal water supply can also become contaminated because the system may interrupt chlorination (Tickner and Gouveia-Vigeant 2005). In communities where sanitation services are unavailable or inadequate, it has been reported that diarrheal disease is associated with wastewater and solid waste disposed in streets and landfills, which can contaminate surface water, aquifers and wells, as well as rivers and lakes through run-off (Govender et al. 2011). If wells and rivers are the only water available, local people using these water sources can be exposed to *V. cholerae* as well as to other water-borne pathogens. Another source of water contamination is tanker trucks that may sell water obtained from the public water supply. Water trucks are found in many places in developing countries where potable water infrastructure is unavailable in homes or a clean water source is scarce. If the public water supply is infected, then the water disbursed from tanker trucks can lead to widespread cholera transmission (WHO 2006).

Cholera is also transmitted through contaminated foods such as fruits and vegetables washed with contaminated water or undercooked food. A person can become infected or infect food if hygienic practices in the household are unsanitary (e.g., do not wash hands or boil water). Furthermore, transmission can occur due to improper food handling and storage. In homes of lower socioeconomic status, unsanitary hygienic practices could be associated with lack of access to clean water because they not have the financial resources to obtain this basic need. This disadvantage can limit a person's capacity to wash their hands and food. Washing fruits and vegetables is particularly important in places where crops are irrigated with contaminated water (Ticker and Gouveia-Vigeant 2005). Street vendors and local markets are also sources of food contamination. They are common and cheap sources of food and drink for many people, especially the poor living in developing countries. In Peru and Guatemala vendors were found to spread cholera because they stored food in places exposed to warmer temperatures, an environment conducive for bacteria growth (Tauxe et al. 1995; Koo et al. 1996). They also used contaminated ice for beverages (Ries et al. 1992; Tauxe et al. 1995).

In addition, a person may also become infected by the consumption of undercooked food contaminated with *V. cholerae.* Tauxe et al. (1995) reported that leftover rice and uncooked seafood (inadequately heated) were two routes of transmission in Latin America. However, it should be noted that uncooked seafood is commonly eaten in coastal communities in Latin America because of cultural traditions. For example, ceviche, a raw seafood dish served during festivities, was associated with the Latin American cholera epidemic. According to local practice, raw fish is marinated in acidic lime- juice, which is believed to 'cook' the seafood and neutralize bacteria (Tauxe et al. 1995).

2.4 Cholera and Population Vulnerability

Susceptibility to symptomatic cholera can vary by individual-level risk factors, such as genetic predisposition, previous exposure to cholera, nutrition, age and gender. Persons with blood type O appear to have a predisposition for severe cholera (Gangarosa and Tauxe 1992: 355). The mechanism underlying this risk factor is unclear but was observed during the 1991 cholera outbreak in Peru and Latin America (Huq et al. 2001), and in studies in Bangladesh (Glass and Black 1992: 148). Another factor that is important is herd immunity, presented earlier as an intrinsic variable in cholera dynamics that can contribute to low transmission in a population (Koelle et al. 2005;

Koelle et al. 2006). Infants who are breastfed have been shown to receive protection through their mother's immunity (Glass and Black 1992: 137). Immunity can also be obtained through a vaccination; however, it is advised that public authorities provide vaccinations with caution because it only provides short-term protection (2 yrs). A cholera vaccination is also limited in terms of its effectiveness for prevention, and is reported to have adverse side effects (WHO 2009).

2.4.1 Cholera and Determinants of Health

Although *V. cholerae* is the causative agent of cholera infection, cholera transmission is also dependent upon the socioeconomic and environmental conditions in which people live and work. As described earlier, these factors are referred to as determinants of health (Marmot 2005; Cockerham 2007; WHO 2008). These determinants are associated with the basic needs of people (Gasper 1996). They may include clean water and air, sufficient food, adequate shelter, basic education, safety and security, and health care (WHO 2008). Whether these instruments of health are met or deprived in a place can contribute to exposure, infection and ability or disability to respond. People also need the economic means to obtain these resources. Having these fundamental human necessities can contribute to the reduction of cholera transmission and also help infected persons cope if they become ill. Furthermore, public policies and underlying societal norms can also affect the determinants of people's health, and subsequent vulnerability to cholera undermining prevention and control efforts.

According to Thisted (2003) infrastructure and income deprivation are potential pre-conditions for cholera transmission. Cholera and other diarrheal diseases are generally prevalent in places where water and sanitation infrastructure is inadequate, declining or unavailable (WHO 2009). As discussed earlier, an important factor that contributes to cholera risk is a lack of clean water. People may become exposed to bacteria because they lack potable water connection in their homes or they are limited to untreated municipal water supply, a marginal source of drinking water. They may also lack the money to build adequate infrastructure in their homes or purchase filtered water. The limited access of water in general, and clean water in particular, may affect how often a person washes their hands or food.[10] Therefore, the disadvantage of not having clean water can place some people at greater risk to cholera transmission, as well as to other water and food-borne illnesses.

The availability and accessibility of health care services is also an important determinant of how well people can cope and recover from infectious disease, such as cholera (UNRISD 2007). Cholera rates are higher in places with few healthcare clinics and services, such as those in rural areas and shantytowns. A study in Bangladesh found that the case-fatality rates during a cholera epidemic were higher for people who lived farther away from treatment centers (Ali et al. 2002). As people became infected and developed symptoms they must immediately seek care and treatment before they

[10] In a discussion with a nurse from the Ministry of Health in Sullana, Piura I learned that many of the people in her district of lower socioeconomic status have limited access to potable water, and therefore, they do not wash their hands fully; instead they only wash their fingertips.

dehydrate, which can occur within a few hours. If oral rehydration therapy or intravenous fluids are not provided during the incubation period, a person can die. Furthermore, if people do not have access to health insurance or cannot afford to pay for healthcare services, they may not seek treatment and fully recover.

Although not a direct determinant of health, public policy can play an influential role in the public's access to resources which help prevent disease or support coping strategies (Wallace 1988; Briggs and Mantini-Briggs 2003). Two examples that are relevant to the cholera epidemic in Peru and Latin America are structural adjustment programs (SAPs) and public health educations messages.

SAPS are economic austerity measures in accordance with the International Monetary Fund (IMF) and the World Bank designed to address economic problems and stimulate economic growth through a process of loans, privatization, market integration, and decrease in public spending. During the 1980s and 1990s, SAPS were negatively associated with public suffering in developing countries because public services cuts were disproportionately felt by groups of poorer socioeconomic status (Abouharb and Cingranelli 2007; Jacobsen 2008: 254). When public services are cut the allocation of monies into public health prevention of infectious diseases is decreased; thereby, increasing the risk of transmission and illness in a population (Farmer 2001: 43; Briggs and Mantini-Briggs 2003: 27).

Another example associated with public policy is the public health campaign about seafood implemented during the cholera epidemic in Peru. These education campaigns were promoted to alert the public about the association between cholera and uncooked seafood. Specifically, it suggested avoiding the consumption of ceviche. Local people on the coast, however, were apprehensive because it was Peru's national dish and an important part of their diet that has cultural meaning. Reportedly, the warnings prevented many people, particularly the poor, from acquiring a cheap source of protein. Consequently, the nutritional levels among the population declined following these campaigns (MINSA 1994b; Cueto 2003).

2.4.2 Vulnerable Subpopulations

Cholera rates are highest among vulnerable populations, such as children, the elderly and women in developing countries (WHO 2009). Although cholera is thought to typically be associated with adults, a recent study across three countries (Indonesia, India and Mozambique) demonstrated that children bear the greatest burden. The authors showed that annual incidence rates ranged from 0.5 to 4.0 (per 1,000) in children under 5 yrs of age (Deen et al. 2008). There are gender differences as well. Women are at greater risk, relative to men, because they might participate more in water-related activities, such as collecting and managing water resources. This has been observed in rural households in many developing countries (United Nations Development Fund for Women [UNIFEM] 2009).

Children, women and other groups may also be vulnerable to cholera because they face unequal treatment in their households and societies. Moreover, these groups may also be living in impoverished conditions. Undernourished children along with persons who have compromised immune systems (e.g., those living with HIV) are the most vulnerable to cholera mortality (WHO 2009). In rural communities, women could be at greater risk of cholera than men because of unequal food distribution, education and healthcare access. This was reported in Piura, Peru in the rural highlands (Reyes 2002).

Belonging to a certain social or ethnic groups may also be a risk factor for cholera transmission. For example, it has been documented that persons of poorer socioeconomic status or indigenous ethnicty face discrimination and unequal treatment in Latin America. Often these groups may be associated with negative societal stereotypes (e.g., ignorance and laziness). In the context of a cholera outbreak, such images portray certain segments of populations at greater risk than others because of their behaviors and culture (e.g., blame may be directed toward individuals rather than the institutions that are responsible for providing basic needs) (Cueto 2003: 281; Briggs and Mantini-Briggs 2003). For example, during cholera epidemics in Peru and Venezuela, it was reported that public health campaigns were directed to 'at risk' groups, such as persons of poor socioeconomic status and indigenous groups (Joralemon 1999: 53-55; Cueto 2003: 281; Briggs and Mantini-Briggs 2003). The campaigns reinforced negative stereotypes, which influenced differential treatment. In Peru, people from shantytowns (e.g., associated with poor socioeconomic status) experienced discrimination in healthcare services. In some cases, people did not seek healthcare because of the stigma of cholera (Cueto 2003: 283). In Venezuela, the Warao people from the Delta Amacuro faced racial and ethnic profiling, which led to limited access to treatment (Briggs and Mantini-Briggs 2003). Overall discrimination can hinder the efforts of certain social and ethnic groups to respond to cholera illness.

CHAPTER 3: REEXAMINING EL NIÑO AND CHOLERA IN PERU

In this Chapter, I reexamine El Niño's link with the cholera epidemic in Peru. I begin by recounting what is currently known about temperature-related impacts on cholera incidence associated with El Niño. I then discuss several arguments, presented in Chapter 1, which reflect characteristics of ENSO that have not been considered in previous El Niño-cholera studies in Peru. These characteristics include: (a) the importance of definition; (b) the La Niña factor; (c) geography of El Niño impacts; (d) rainfall extremes; and (d) social dimensions. My aim is to set a precedent for the case study of Piura, which is the focus of this dissertation research. I conclude the chapter by stating the research hypotheses and objectives of this study.

3.1 Recounting El Niño Impacts on Cholera in Peru

Following the initial cholera outbreak in January 1991, evidence of El Niño-related impacts on the cholera epidemic was suggested by research in Peru that examined the effects of temperature on diarrheal disease (Salazar-Lindo et al. 1997; Checkley et al. 2000; Lama et al. 2004) and *V. cholerae* (Franco et al. 1997; Lipp et al. 2003). According to Checkley et al. (2000), daily admissions of children with diarrhea at the National Institute of Health (in downtown Lima) increased by 8.0% when mean air temperature increased by 1.0°C from 1993 to 1997 in SH summer. These authors also found that the effect of elevated temperature was greatest in SH winter (June to August). Furthermore, peak in hospital admissions lagged by approximately one month with the peak in air temperature. In another study, Lama et al. (2004) found a similar association between monthly mean air temperature and diarrhea in adults at a hospital in northern Lima from 1991 to 1998. Indirectly, these studies supported reports that cholera incidence increased during the warmest months (e.g., January to March in Lima) throughout the 1990s (MINSA 1994b; 1995a; Huanca 2004).

The association between El Niño and cholera incidence did not become apparent until 1997 in Peru. The association was based on two coinciding events: the onset of the strongest El Niño of the century and a resurgence of epidemic cholera in July 1997 (MINSA 1998d). According to the World Meteorological Organization (WMO), in April 1997, El Niño conditions were rapidly developing across the central and eastern equatorial Pacific Ocean (1999: 29-38). By December El Niño was in a mature phase. It was reported that sea surface temperatures exceeded 28.0-29.0°C along the coast, an observation not seen since the extreme El Niño of 1982-83 (WMO 1999). El Niño's effects on local climate in Peru became evident as air temperatures in Lima grew approximately 3.0-4.0°C above the mean (e.g., 21.0°C).[11]

The development of an El Niño, particularly a strong one, during the winter months meant that Peruvians experienced a warmer than average winter followed by a warmer than average summer (Bell and Halpert 1998). The impacts for public health and cholera risk were severe. For example, in North Lima at the Cayetano Heredia Hospital, admissions for diarrhea and dehydration incidence rose by 35.0% during the

[11] The mean was based on monthly air temperature in Lima from 1993 to 1997 (Checkley et al. 2000).

winter months (Salazar-Lindo 1997). Checkley et al. (2000) estimated an excess (due to El Niño) of 6,225 daily admissions of children with diarrhea relative to an expected number of cases based on a pre-El Niño pattern of cholera (for 1993 to 1996). Speelmon et al. (2000) found that from November 1997 to July 1998 a rise in weekly cholera cases was preceded by a rise in mean air temperature by 3 weeks. These authors also found a temporal lag of an estimated 9 weeks between the presence of *V. cholerae* in sewage waters and a rise in air temperature. This finding supported a previous study by Franco et al. (1997), which showed that *V. cholerae* was present in Lima water sources prior to cholera outbreaks from 1993 to 1995. Franco et al. suggested that cholera transmission in Lima was amplified by the combined processes of human fecal contamination and elevated air temperature, which led to a proliferation of bacteria.

Other studies in Peru examined the effect of seawater temperature on *V. cholerae* and cholera incidence. In one study, Lipp et al. (2003) detected *V. cholerae* in samples collected monthly from seawater and plankton at 3 coastal sites (Trujillo – *North*, Lima – *Central,* and Arequipa – *South*) from November 1998 to March 2000 and October to December 2000. Measurements of air and sea surface temperature were also taken at these locations. The authors observed that *V. cholerae* was significantly correlated with and followed air temperature increases from January to March at each site. Interestingly, seawater temperature was not significantly associated with *V. cholerae*. Cholera cases were not measured in relation to these findings. In a second study, Gil et al. (2004) revisited the same study areas as Lipp et al. (2003), but included one additional site at Callao (considered part of the greater Lima). The study collected similar variables as Lipp et al., but also measured them in relation to cholera incidence. In this study the time period was extended to begin in October 1997 and end in June 2000. Gil et al. (2004) found a significant association between monthly cholera incidence and elevated seawater temperature during the SH summer of 1998. The detection of *V. cholerae*, particularly at the Lima site, coincided with these observations suggesting to the authors that a link existed among seawater temperature, *V. cholerae* and cholera incidence. The effect of elevated SST was particularly an important finding because Lipp et al. (2003) had not observed this association; perhaps because the 1997-98 El Niño was not included in the study. It was also important because this finding linked El Niño impacts on coastal water changes to cholera incidence on the coastal mainland.

3.2 The Importance of Definition

The El Niño-cholera hypothesis rests on the assumption that El Niño impacted the reproduction and transport of *V. cholerae* off the coast of Peru to initiate cholera transmission from October 1990 to January 1991. Although plausible, and suggested by studies in the previous section, the timing of El Niño with the emergence of cholera in Peru remains debatable because researchers as well as Peruvian fisheries could not agree on the number and timing of events during the first half of the 1990s (WMO 1999; Glantz 2001: 21). This aspect raises an important question about a fundamental component of the El Niño explanation: was an El Niño present before and during the onset of the epidemic?

The first half of the 1990s was considered an “extraordinary” time for El Niños (Glantz 2001: 21). According to Trenberth and Hoar (1996), 1990 to 1995 was the longest El Niño of the twentieth century, estimated to occur once every 1500 to 3000 years. McPhaden (1993) and Kessler and McPhaden (1995) identified a prolonged El Niño, but reported that it lasted from September 1991 to July 1993. Goddard and Graham (1997) suggested that 3 events took place in: (1) March 1991 to June 1992; (2) 1993 (approximately February-March to October); and (3) 1994 (June to November). There were also differences between regions. As Glantz (2001) notes, the Australians saw it as a 5-year El Niño, while the Peruvians believed it was 3 consecutive events within a 5-year period (99-100). Peruvian fishermen questioned the Australian view of a five year El Niño because they noted that they were catching near-record-setting anchovy landings in 1991, highly unlikely during an El Niño episode (Flores 1998). The difference in views suggests that perhaps each country used an El Niño definition suited to their own needs or region.

For example, Australia, like Peru, is a region well known for ENSO-related teleconnections and impacts on its society. There, SST anomalies in the Niño 4 Region are important to identify and characterize ENSO’s development in the equatorial Pacific (Glantz 2000). Equally important for scientists is the use of the SOI in Australia; El Niños are identified when values are consistently negative for several months (BOM 2005; The Long Paddock 2010). From 1990 to 1995, the SOI values suggested to Australians and

NOAA—at the time—that El Niño-like conditions were present (reported by NOAA in June 1993). Furthermore, there were reports of drought during this time in Austrialia, a climate teleconnection often associated with El Niño (Glantz 2001: 99). In contrast, Peruvian scientists may consider SST anomalies in the Niño 1+2 Region as better estimates of El Niño in the equatorial Pacific (Glantz 2000; Lagos et al. 2008). By observing this region, it appeared that several events may have developed, an observation reported by Peruvian fishermen (Flores 1998).

If one compared the onset of the cholera epidemic (January 1991) with SST anomalies in these two Niño regions, different associations may arise according to the region and threshold chosen (Trenberth 1997). This is demonstrated in **Figure 3.1**, which shows that using the Niño 4 region might satisfy the El Niño-cholera hypothesis since SST anomalies in that area of the equatorial Pacific were substantially greater relative to anomalies in the Niño 1+2 region. Whereas using the Niño 1+2 region might suggest that El Niño began after the initial cholera outbreak in January 1991. That is, assuming *V. cholerae* was present in coastal waters.

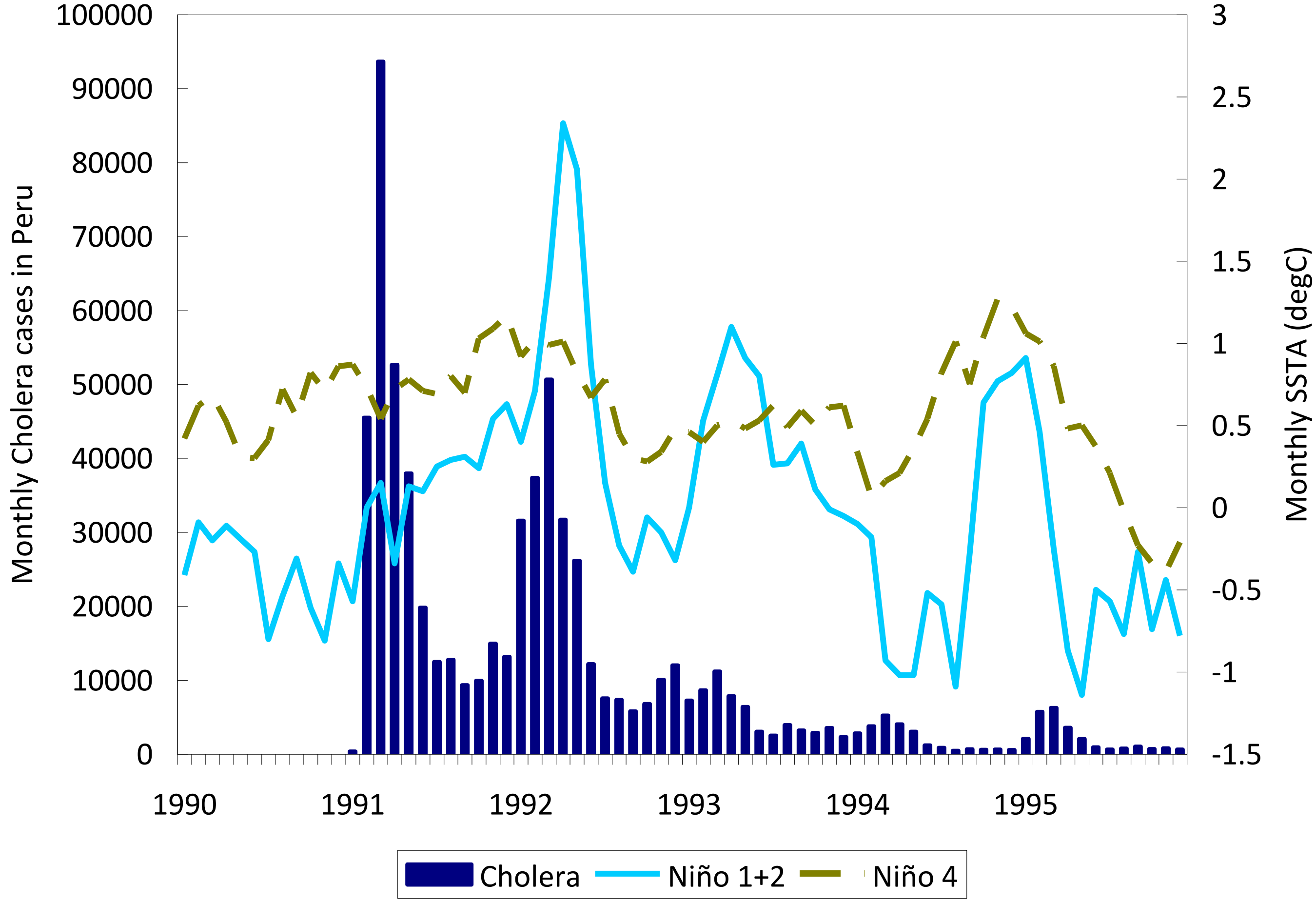


Figure 3.1 Monthly Cholera Cases in Peru and Niño 1+2 and Niño 4 Sea Surface Temperature Anomaly (SSTA) from 1990 to 1995.

Source: MINSA 2005b; NOAA 2009.

Evidence of El Niño

While defining El Niño in Peru is important, it is also necessary to identify El Niño-related impacts on ecosystems and society in order to assess whether El Niño contributed to the onset of the epidemic in 1990/91. However, identifying impacts in the early 1990s is challenging since reports of El Niños in Peru during this time are not well documented in scientific studies (Glantz 1998; personal communication August 2009) or even in popular media (Zapata- Velasco and Broad 2001: 191). Still, some evidence in the literature suggests there were impacts on marine ecosystems and local climate in Peru.

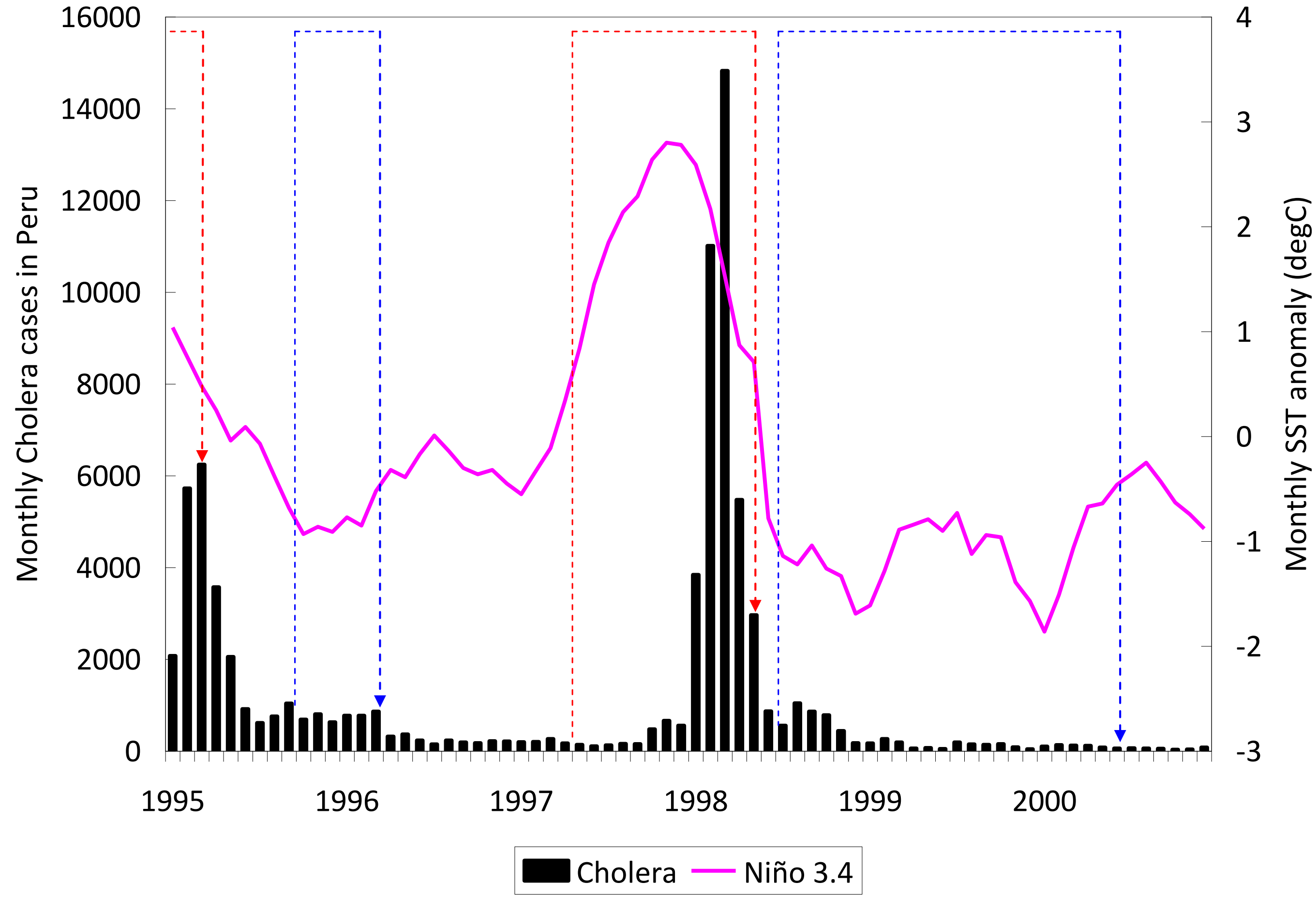
According to the Peruvian Marine Institute, 1991 was described as a year with cold coastal waters and good for anchovy catch (Pizarro 1999). It implies that average SST conditions in the eastern equatorial Pacific were present and that upwelling and marine biological productivity was normal too. In other areas of the eastern Pacific Ocean, ecological impacts (associated with El Niño) were reported off the coast of Costa Rica (e.g., coral bleaching and mortality) in March to April 1992 (Jimenez and Cortes 2001), in the Galapagos (e.g., penguin populations declined associated with lower food supply) from 1991 to 1993 (Hernan Vargas et al. 2006), and off the coast of Chile (e.g., changes in planktic fauna species) from November 1991 to March 1992 (Marchant et al. 1998).

There were also reports by NOAA's ENSO Advisory (1992) that an El Niño was in development during the SH summer of 1992; and that rainfall teleconnections were reported in northern coastal Peru. Although speculative, this evidence along with biological changes in marine ecosystems in 1991-92 suggests an El Niño connection well after the cholera epidemic was underway.

3.3 The La Niña Factor

A dimension that has not been explored in relation to cholera in Peru is La Niña, the cold phase of ENSO. La Niñas enhance cold SST conditions in the central and eastern equatorial Pacific Ocean (Philander 1985). In relation to cholera, La Niña periods appeared to decrease risk at a national level. **Figure 3.2** shows how cholera cases subsided significantly before and after the 1997-98 El Niño, coincidently with the development of La Niñas in 1995/96 and 1998-2000 (NOAA 1996; Halpert and Bell 1997; Trenberth 1997; Bell et al. 2000; Lawrimore et al. 2001). Concurrently, La Niñas may also have increased cholera risk depending on the location in Peru as well as regional and local conditions. For example, in February 1999 health ministries across Peru were on alert because of rain-related disasters in the country's south and central highland and jungle regions. Ten Peruvian departments (Junin, Lima, Loreto, Cusco, Madre de Dios, Apurimac, Ica, Huancavelica, Arequipa, and Ancash) were affected by floods and were in need of assistance with food, water and sanitation (MINSA 1999b). The implications for cholera transmission, however, were unclear because there appeared to be a greater concern (in reports discussing La Niña) for respiratory disease, dermatitis and latigazo (insect-borne disease that causes lashes on the skin) during that time (MINSA 1999a). Nonetheless, segments of the population were experiencing climate-related impacts on human health. La Niña conditions along with those in the tropical

Atlantic were blamed (MINSA 1999a). Examining these associations further is important because La Niñas and their societal impacts in general are less studied in ENSO research (Glantz 2002b: 8).



El Niños (red) and La Niñas (blue) events were defined according to the current NOAA definition (2010).

Figure 3.2 Cholera Cases in Peru and El Niños and La Niñas from 1995 to 2000.

Source: MINSA 2005b; NOAA 2009.

3.4 Geography of El Niño Impacts

Although a temperature link with cholera is plausible because of its potential impact on the reproduction of the vibrio and marine hosts, whether this effect on cholera was observed across Peru is uncertain. First, previous studies in Peru were mainly based on observations in Lima, located on the central coast, where climate is strongly modulated by maritime effects; it is also closer to the source of *V. cholerae* (assuming it was present on the coast). Therefore, considering the country's diverse natural regions (e.g., coast, highlands, and jungle) and the geography of teleconnections discussed earlier, it is uncertain that findings in Lima can be generalized to other areas of Peru. **Figures 3.3** to **3.5** compare plots of monthly cholera cases by year from 1993 to 1998 in three Peruvian departments (each associated with a natural region). Although Lima (coast) and Cajamarca (mountain) appear to show a general trend (cholera peaks) in the summer, there are some differences by years (e.g., 1993 and 1994); Loreto's (jungle) seasonal pattern was quite different in comparison to Lima and Cajamarca; overall the cholera pattern in Loreto was lagged in time (peaks in the winter) and less well-defined. Second, studies were also primarily focused on the time period after 1993. To date, the entire decade has never been examined including the time period of the epidemic onset in 1990/91, which is the basis of the El Niño-cholera hypothesis (Salazar-Lindo 2008). Therefore, investigating the time associations between El Niño and its potential impacts on cholera throughout the 1990s will be necessary to fully comprehend cholera patterns in Peru.

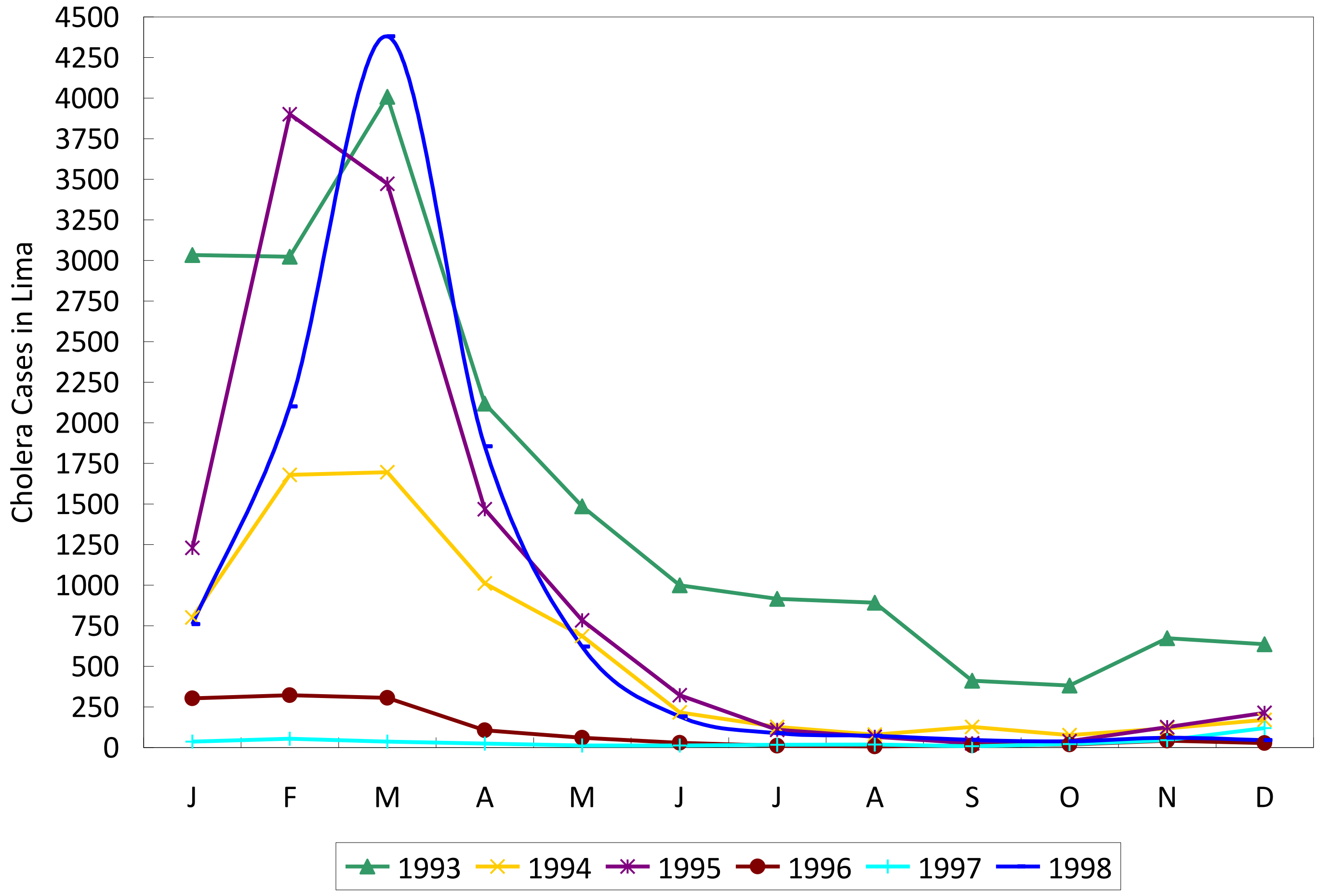


Figure 3.3 Cholera Cases from 1993 to 1998 in Lima (coast).

Source: MINSA 2005b.

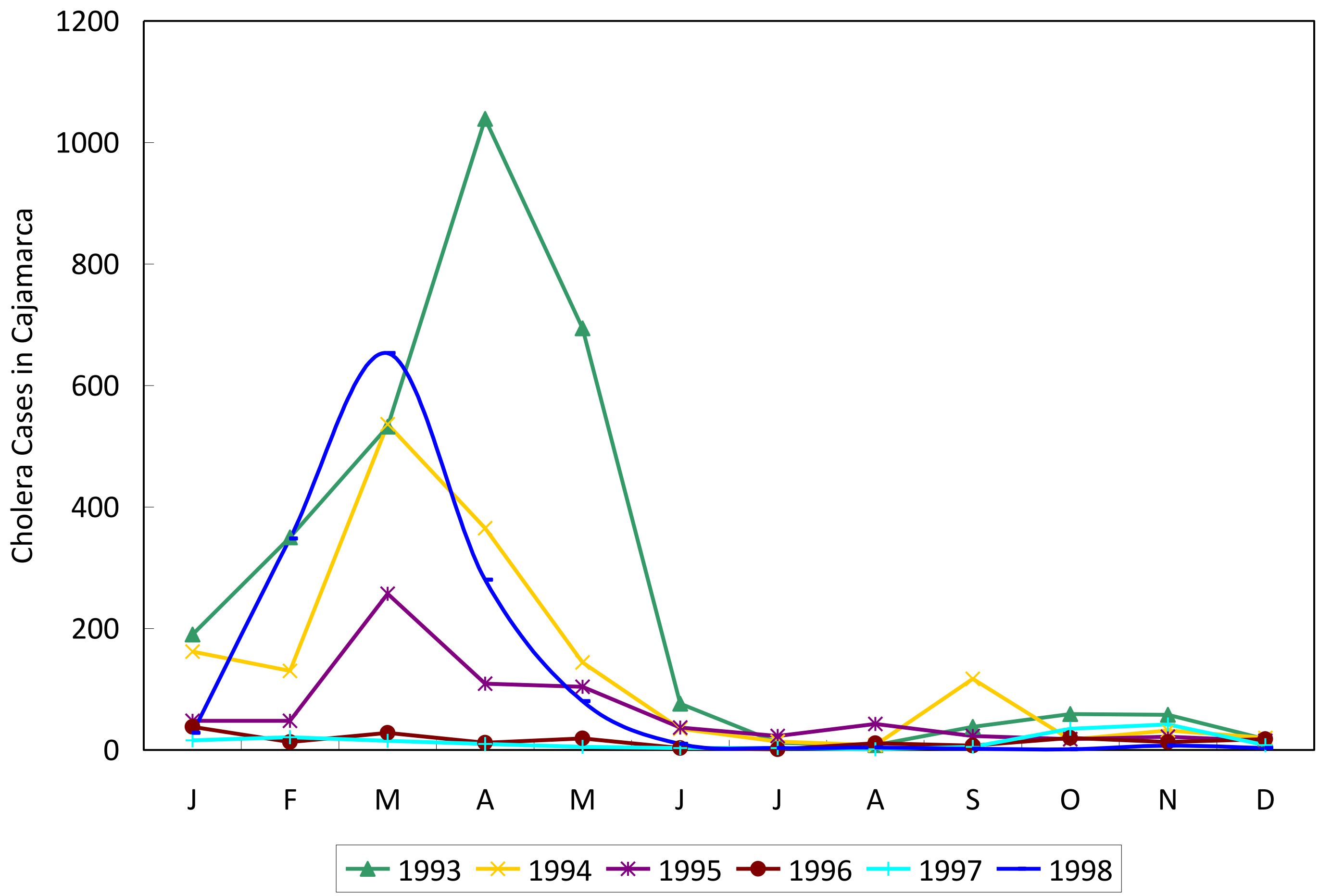


Figure 3.4 Cholera Cases from 1993 to 1998 in Cajamarca (mountain).

Source: MINSA 2005b.

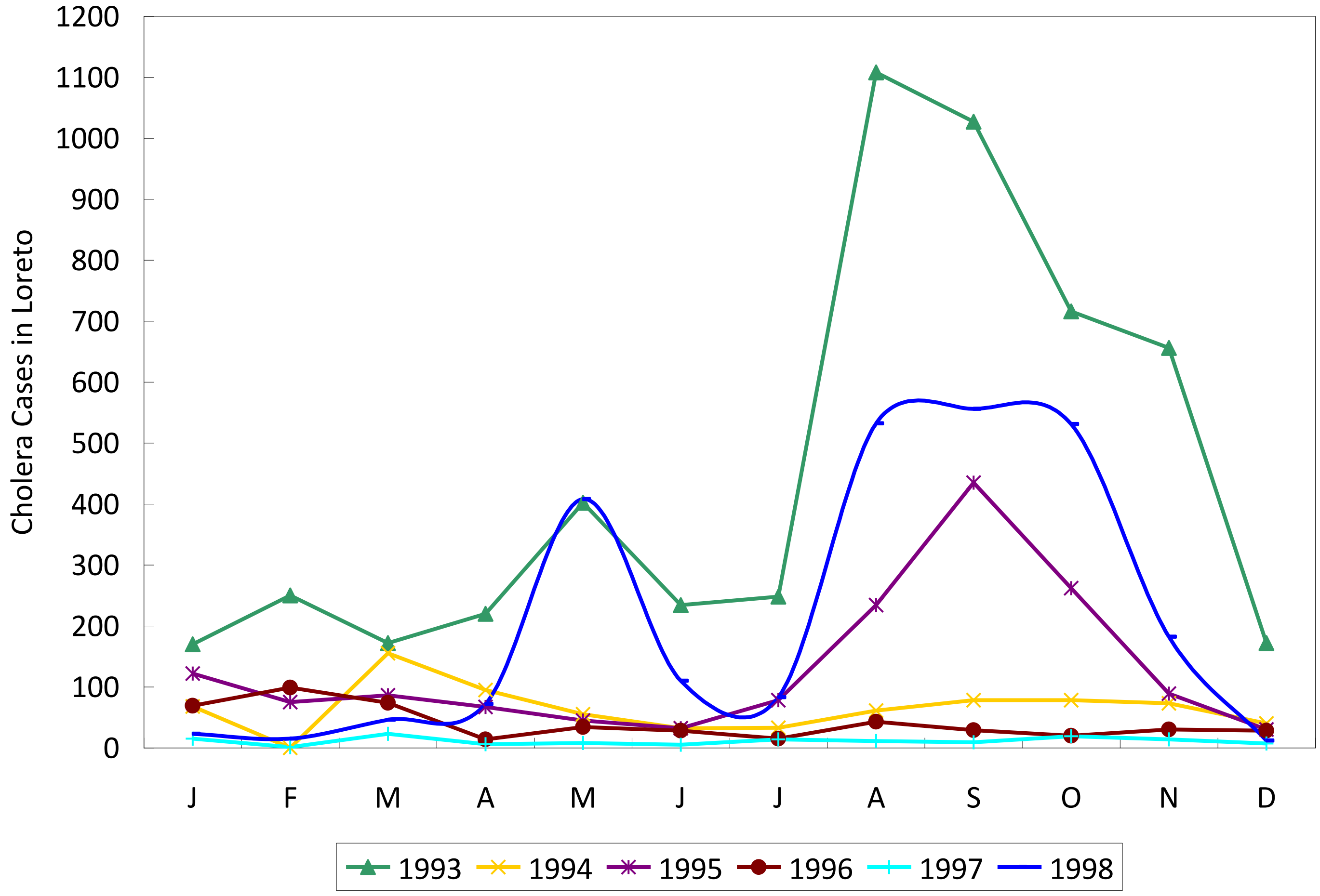


Figure 3.5 Cholera Cases from 1993 to 1998 in Loreto (jungle).

Source: MINSA 2005b.

3.5 Rainfall Extremes

Rainfall extremes is an important El Niño teleconnection in Peru (Lagos et al. 2008). In the late 1990s there were reports in Peru of diarrheal disease and cholera risk attributed to heavy rains and climate-related disasters (MINSA 1997; 1998a; 1998d; 1999a). During the 1997-98 El Niño, rains in northern coastal Peru began in December 1997 and lasted until April 1998. Record-breaking river levels, flooding and landslides were reported. Subsequently, these series of events contributed to damaged infrastructure (e.g., homes and sewer systems) and human exposure not only to cholera (MINSA 1998f), but other food and waterborne diseases, as well as skin infections and conjunctivitis (PAHO 1998b; SENAMHI 2004). In other regions, such as the northern highlands landslides destroyed homes and killed livestock (UNDRO 1998). During these events public health responses were limited because of downed bridges and roads. In addition there were reports of population displacement and refugees, which may have potentially increased cholera exposure (PAHO 1998b). Although elevated temperatures may have contributed to *V. cholerae* reproduction and subsequent cholera incidence in Lima, contaminated water supplies via rains and floods may have been a more important factor in other places in Peru.

Alternatively, rainfall deficit may have played a role in cholera transmission. For example, in Loreto, which was discussed earlier, low river levels were associated with cholera risk in places of poor water and sanitation infrastructure (MINSA 1995b; 1998b). Under these circumstances, exposure to cholera may have occurred because persons were limited to marginal water supplies (e.g., polluted river water) for drinking, cooking and hygienic purposes.

3.6 Social Dimensions

Glantz (2005) in describing the factors that resulted in the outcomes of Hurricane Katrina stated, “The combination of psychological, financial, and political factors—together with a direct hurricane hit, the breakdown of the levees, and the subsequent cascade of disasters underscored the vulnerabilities of the poor, the elderly, children, and racial minorities.” This statement illuminates the notion that underlying climate-related hazards are often, social, economic and political factors that contribute to disasters, such as famines, population displacement, and epidemics (Sen 1981; Watts and Bohle 1993; Glantz 2003: 253; Davis 2001: 279). Although the 1990s were associated with several El Niños, it was also a time during which Peru was addressing complex emergencies—unrelated to El Niño (UNDRO 1990a; 1990b), a multitude of socioeconomic and infrastructure problems, as well as civil unrest (e.g., terrorism) (Nash 1991; Youngers 2000). This was the setting of the cholera epidemic in the early 1990s.

Preceding the epidemic, the Peruvian government was addressing two humanitarian crises. The first was an earthquake in northeast Peru, which affected 70,000 and injured 1500 people in May 1990 (UNDRO 1990b). The second was an agricultural state of emergency declared across 13 departments (out of 25) in June 1990. Reportedly over 2 million subsistence farmers in the highlands were gravely affected by an ongoing drought and cold extremes experienced in 1989; and food and water supplies were in decline (UNDRO 1990a). When cholera emerged in 1991, approximately 45.0% of the country's population did not have access to clean water and 59.0% were without sanitation services. In rural areas, conditions were much worse; there, less than one-third of the population had access to clean water and other basic services (PAHO 1991a). In addition, Peruvians were affected by economic reforms implemented by the then elected President Alberto Fujimori (Nash 1991; Youngers 2000). As a result, public infrastructure and services were reduced including those in the health sector (Cueto 2003). Ultimately, these events may have aggravated the pre-existing living conditions of a population, who lacked immunity to cholera, increasing their exposure and susceptibility to disease transmission.

3.7 Summary

In this chapter, I highlighted several factors of ENSO, which are important to understand cholera transmission in Peru and warrant further investigation. These potential avenues of research are: El Niño's association with cholera may vary by the definition applied; there is evidence that El Niño's role might have been critical only after the onset of the outbreak; La Niña may have contributed to a reduction in cholera incidence; there is a need for studies in other areas of Peru given that El Niño-cholera studies were limited to Lima; rainfall extremes may have been an important factor in transmission; and social factors of vulnerability may have enhanced the severity of impacts on cholera transmission. Each of these factors will be considered in this dissertation study.

3.8 Research Questions, Hypotheses and Objectives

As stated earlier, the goal of my dissertation research is to reconstruct the temporal and spatial associations among ENSO, social vulnerability and cholera incidence in Piura, Peru from 1991 to 2001 in order to better understand El Niño's impact on the cholera epidemic in Peru. My overarching research questions are: (1) What was the impact of ENSO on cholera incidence in Piura; and (2) How did social vulnerability influence this relationship?

The research hypotheses are:

- Hypothesis 1 (H1): There was a temporal association between ENSO, climate and cholera cases in Piura in the 1990s. Furthermore, these associations were stronger after 1992 compared to the onset of the epidemic in 1991.
- Hypothesis 2 (H2): The spatial variability of the ENSO-climate-cholera associations in Piura in 1997-98 will be explained by the spatial distribution of social vulnerability. Moreover, the level of social vulnerability within districts in Piura will either antagonize or buffer the effects of ENSO and climate on cholera incidence.

The following objectives will address my research questions and hypotheses:

1) Develop a conceptual framework that characterizes the potential ecological pathways and vulnerability conditions of cholera transmission in Piura;

2) Characterize the temporal associations between ENSO, climate and cholera cases in Piura from 1991 to 2001;

3) Construct a social vulnerability index (SVI) that characterizes social vulnerability to cholera in Piura in 1997-98;

4) Characterize the spatial and temporal associations between ENSO, climate and cholera incidence by district in Piura for 1997-98 and estimate the degree to which social vulnerability influenced this relationship;

5) Reflect on the findings from this study using a climate and development ethics perspective in order to better formulate recommendations.

CHAPTER 4: RESEARCH DESIGN

In this chapter I present the research design of my dissertation project including the research approach, theoretical concepts and conceptual framework that guide and inform this study. I also provide a description of the study area and population. I conclude with the data and methods I employed to complete each research objective .

4.1 Approach, Concepts and Framework

In this dissertation research, I used a *climate affairs* approach (Glantz 2003) to develop a conceptual framework that integrates ENSO science and knowledge about cholera impacts and interactions with theories of disease ecology and vulnerability from the subfields of health and medical geography (Mayer 2000; Meade and Erickson 2005) and human-environment geography (Cutter 2003; Turner et al. 2003; Zimmerer and Bassett 2003) to explain cholera transmission. From an ethical viewpoint, this study is guided by an ethics of climate and development, two emerging subfields in philosophy (See section 6.5 for the ethical geographies of this study). The framework is further informed by cholera research (Stock 1991; Cueto 2003; Nelson et al. 2009); climate-cholera studies (refer to Chapter 2); and climate and society research (Glantz 2001; Caviedes 2001; CCB 2010). Furthermore, my dissertation fieldwork conducted in the summers of 2008 and 2009 in Lima and Piura, Peru was central to this project because it grounded the conceptual framework and informed my research questions and hypotheses.

4.1.1 Climate Affairs Approach

C*limate affairs* is a holistic approach to understanding the many facets of climate (e.g., averages, extremes, variability and change) and how ecosystems and societies interact with climate phenomena at multiple scales (Glantz 2003). The concept emphasizes the importance and necessity of the contributions of physical, biological, social sciences, and humanities to the understanding of the impacts of air and sea interactions in the equatorial Pacific Ocean and worldwide (CCB 2010). It is principally grounded in ENSO/climate science and knowledge, ecosystem-societal impacts and vulnerability, and ethics and equity research and was therefore, an ideal lens by which to reexamine ENSO's link with the cholera epidemic in Peru and understand its potential impact(s) on cholera transmission in Piura, Peru in the 1990s. The concept evolved from the climate-society oriented research and collaborative activities of Dr. Michael H. Glantz, which began in 1974 at the Environmental and Societal Impacts Group (ESIG), a former program of the National Center for Atmospheric Research (NCAR), and which later came to fruition as a research, training and education initiative in 2003. A large segment of climate affairs-related activities and publications were centered on ENSO including an El Niño Affairs program for Latin American countries (http://ccb.colorado.edu/enos/). Currently, it continues to be implemented through the Consortium for Capacity Building (CCB) at the University of Colorado, Boulder.

Figure 4.1 illustrates how a climate affairs approach, geographic concepts, ethics and fieldwork were integrated into the research design of this study. A description of the approach, theoretical concepts and conceptual framework developed to explain cholera transmission in Piura will follow.

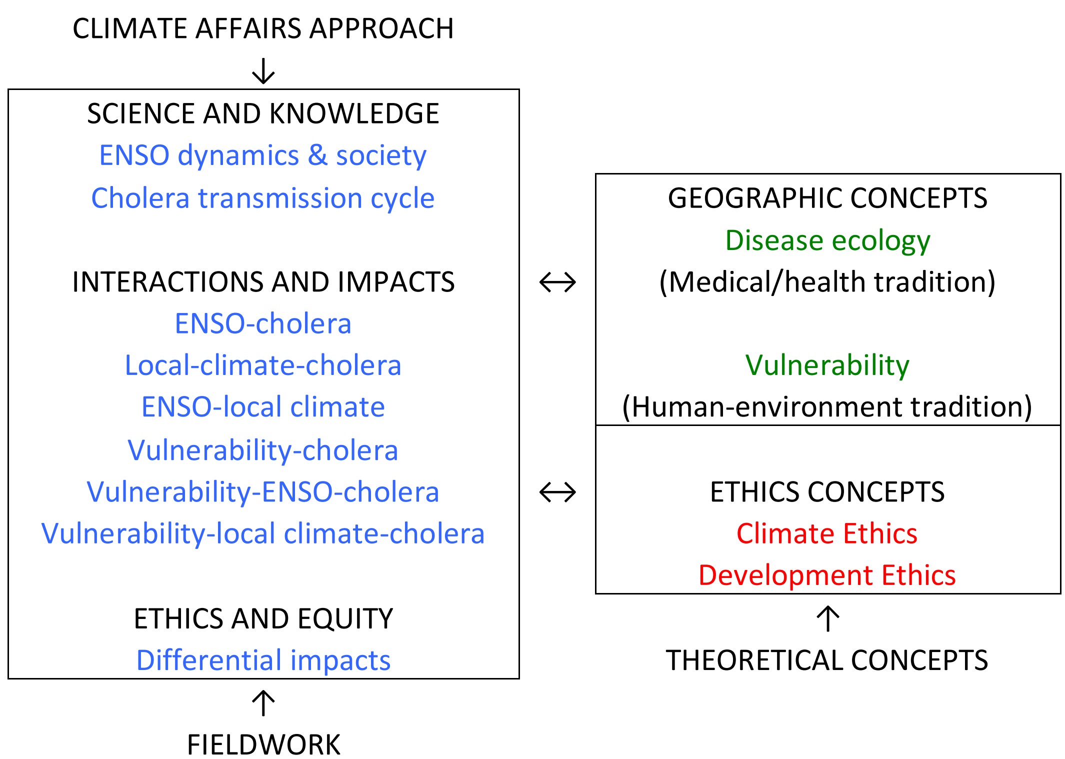


Figure 4.1 Climate Affairs as an Integrating Approach and Concept.

4.1.2 Theoretical Concepts

Disease Ecology

Disease ecology explains infectious disease transmission through the interactions among biological agents (pathogens and vectors/reservoirs), population (human hosts) and environment (Wilson 2003). Transmission occurs when an infectious agent enters the human host through ingestion, respiration, absorption or sexual contact. Environmental conditions and changes may contribute to the risk of exposure to infection (e.g., via ecological changes in landscape and aquatic environments). Infectious disease transmission can also occur through the migration of an infected person or a biological agent (e.g., mosquito or tsetse fly). Who and how a population becomes exposed to an agent and disease also varies by preexisting conditions: population susceptibility, including genetics, previous exposure (immunity) to the agent, and prior health status. From a medical geographic perspective, the concept of disease ecology incorporates the notion of 'place' and considers transmission using a human-ecological model within social, economic, cultural, built, and physical environments (Meade and Erickson 2005). 'Place' is a key theme in medical and health geographies (Kearns and Moon 2002). It is critical to the understanding of cholera ecology and transmission in this dissertation because it emphasizes understanding the characteristics and contextual setting of a 'place' in which human-cholera interactions may have occurred and subsequent transmission may have taken place. Importantly, 'place' refers to the composition of a society (i.e., its people) and the context of the society (Macintyre et al. 2002), e.g., social determinants as stated earlier (WHO 2008).

Vulnerability

Audy (1965) defined health as a process of adaptability or ability to defend or recover from afflictions or hazards. Although he was referring to the susceptibility of a population, his definition suggested that a 'place' is not only an environment where a population becomes exposed to a biological hazard; it is also a setting where the susceptibility of a population to transmission or a health hazard is influenced by a population's capacity to cope and respond when exposed. While culture is an important factor that influences human behavior and response to disease (Roundy 1979), it is also important to consider the underlying conditions and processes that make people, places and societies susceptible to harm from an external hazard (Wisner et al. 2004: 167-200). From this orientation, disease ecology and susceptibility of a population are linked to the geographic theoretical concept of *vulnerability*. Like disease ecology, 'place' is an important tenet of vulnerability research (Cutter 2003). Patterns of vulnerability vary by the processes and hazards that exist in a place and region (Hewitt 1997). The "geography of risk" is differential within and between societies (Hewitt 1997: 28), where some subpopulations are more susceptible to harm and cope less than others (Cutter and Finch 2008). To date multiple conceptions of vulnerability have emerged; importantly, risk-hazards (Kates 1971; Burton et al. 1993), disasters (Hewitt 1997; Lewis 1999), and human ecology (Watts and Bohle 1993). The work of Glantz (1981; 2001) and Caviedes (1973; 1982; 1984; 1985) have also contributed to this concept, particularly with respect to El Niño impacts. More recently, vulnerability has been used in climate-society research (Vogel 2001; Liverman et al. 2006; Adger 2006) and coupled human-environment systems-thinking (Turner et al. 2003).

In the past, geographers have utilized the concepts of disease ecology and vulnerability to understand global to local interactions that influence emerging infectious diseases (e.g., diarrheal disease and HIV/AIDS in Africa). For example, in Mozambique, Collins (1998) investigated diarrheal disease in coastal areas in relation to population displacement and international development policies and found that transmission was indirectly associated with global development programs influenced by multi-lateral institutions. Structural changes led to impacts via land-use changes on the local environment, which contributed to heightened disease incidence (Collins 1998: xiii-xiv). Similarly, in sub-Saharan Africa, Mayer (2005) demonstrated that HIV/AIDS was associated with SAPs, which led to reduced health services and treatment (Mayer 2005). In Ghana, Oppong (1998) attributed the diffusion of HIV in subpopulations to population vulnerability influenced by a national economic crisis that preceded an epidemic (Oppong 1998). These studies in Africa illustrate that although HIV and diarrheal disease (including cholera) are distinctly different infectious diseases, they share a commonality: both are associated with a population's vulnerability indirectly influenced by global and local development.

4.1.3 Conceptual Framework

In this study, the particular conception of vulnerability that I integrated with disease ecology was social vulnerability. Social vulnerability is characterized as social factors and processes that contribute to a population's susceptibility to harm in relation to an environmental hazard (Cutter 2006). According to Wisner et al. (2004), these factors are the root causes of vulnerability in society. Social vulnerability and the concept of vulnerability are often associated with deprivation and disparities between subpopulations (Cutter et al. 2003). Measuring social vulnerability is challenging, but factors such as urban/rural, basic needs infrastructure (water, housing and sanitation), and level of education can be utilized in geostatistical models to understand the temporal-spatial relationships of such phenomenon (Cutter and Finch 2008). Using social vulnerability, the human ecology of cholera transmission can be examined in three dimensions: 1) exposure pathways to cholera transmission, 2) population sensitivity or resistivity to cholera, and 3) capacities to cope with/respond to or recover from cholera (i.e., resilience) (Turner et al. 2003). As such, cholera can be viewed as both a hazard to society and an outcome from an external hazard/stressor (Wisner et al. 2003), e.g., associated with basic needs deprivation or extreme climate impacts. In this study, the disease ecology of cholera and social vulnerability to cholera were situated within a broader framework of vulnerability adapted from Turner et al. (2003).

Figure 4.2 is the conceptual framework adapted from Turner et al. (2003) to situate my study within the climate affairs perspective. It illustrates the ecological interactions and conditions that contributed to cholera transmission in the subregion of Piura at global, national and local levels. The elements highlighted in white boxes represent the factors that are empirically modeled in this study. Disease-ecological vulnerability is composed of conditions and processes that are human-environment coupled (Turner et al. 2003) and social-environmentally produced (Zimmerer and Bassett 2003: 3). Furthermore, interactions and impacts depend on the spatial and temporal scale(s) of analysis (Vincent 2007). According to the framework, cholera incidence emerges from "place"-based interactions among population (e.g., demographics and health), local climate teleconnections, social environment (e.g., social organization, culture, politics, microeconomics), infrastructure environment (roads, bridges, health system infrastructure), and physical environment (land, weather, and water). Pathogens and vectors are also included (e.g., *V. cholerae* and other disease agents that persist in Piura). ENSO is an environmental factor that is cross-scalar with global, national and local impacts. It influences local climate teleconnections, which has associated impacts on human-pathogen-environment interactions in Piura.

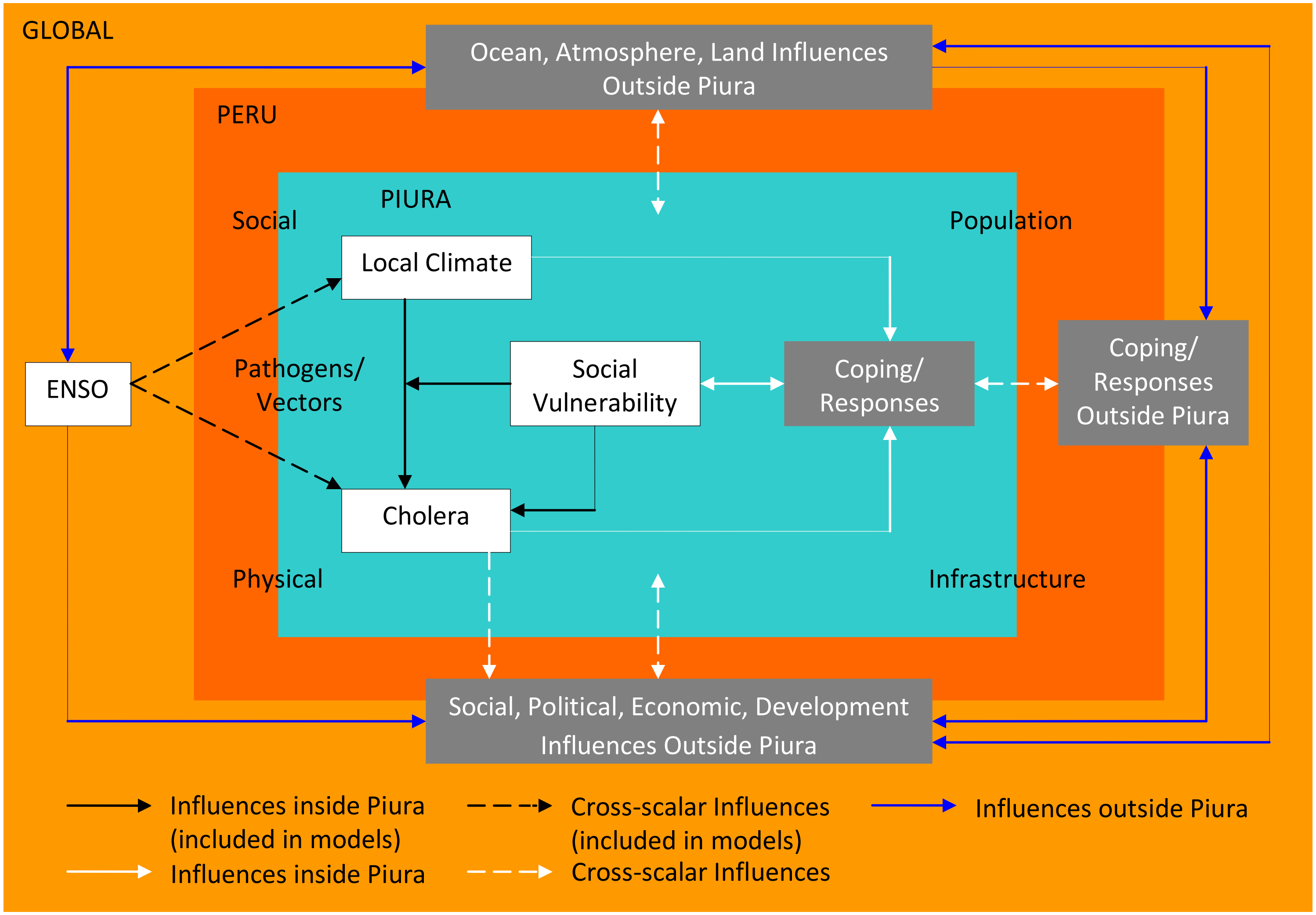


Figure 4.2 Conceptual Framework adapted from Turner et al. (2003).

Figure 4.3 shows ENSO impacts on the cholera transmission cycle in Piura. The impact of ENSO can occur through direct and indirect impacts on *V. cholerae* and its reservoirs in the ocean, coast and inland environments. ENSO can directly impact *V. cholerae* and its reservoirs in the ocean through ocean-atmosphere interactions (e.g., changing marine conditions or coastal intrusion via storm surges). Through local climate teleconnections, ENSO can indirectly influence the reproduction of *V. cholerae* in aquatic inland environments (e.g., temperature changes). Local climate can also influence the transport of *V. cholerae* into contact with humans via rainfall and flooding. Even if *V. cholerae* are not present, humans can introduce the bacteria into the local environment by migration of infected persons and through contaminated water from a passing ship's ballast. Potential exposure and transmission occurs when a susceptible population comes into contact with *V. cholerae* by ingestion of contaminated water or food. Preexisting conditions (e.g., genetic susceptibility, immunity, health and nutritional status) influence whether a person becomes symptomatically or asymptomatically infected. Cholera can potentially spread when an infected person defecates and introduces *V. cholerae* into a local aquatic environment (i.e., municipal water supply or river water). Cholera can also spread if the water or food becomes contaminated within a household by an infected person. When local climate conditions become favorable for the proliferation of *V. cholerae*, the amplification of transmission by human-feacal spread becomes a potential pathway in which exposure and transmission increase among a population.

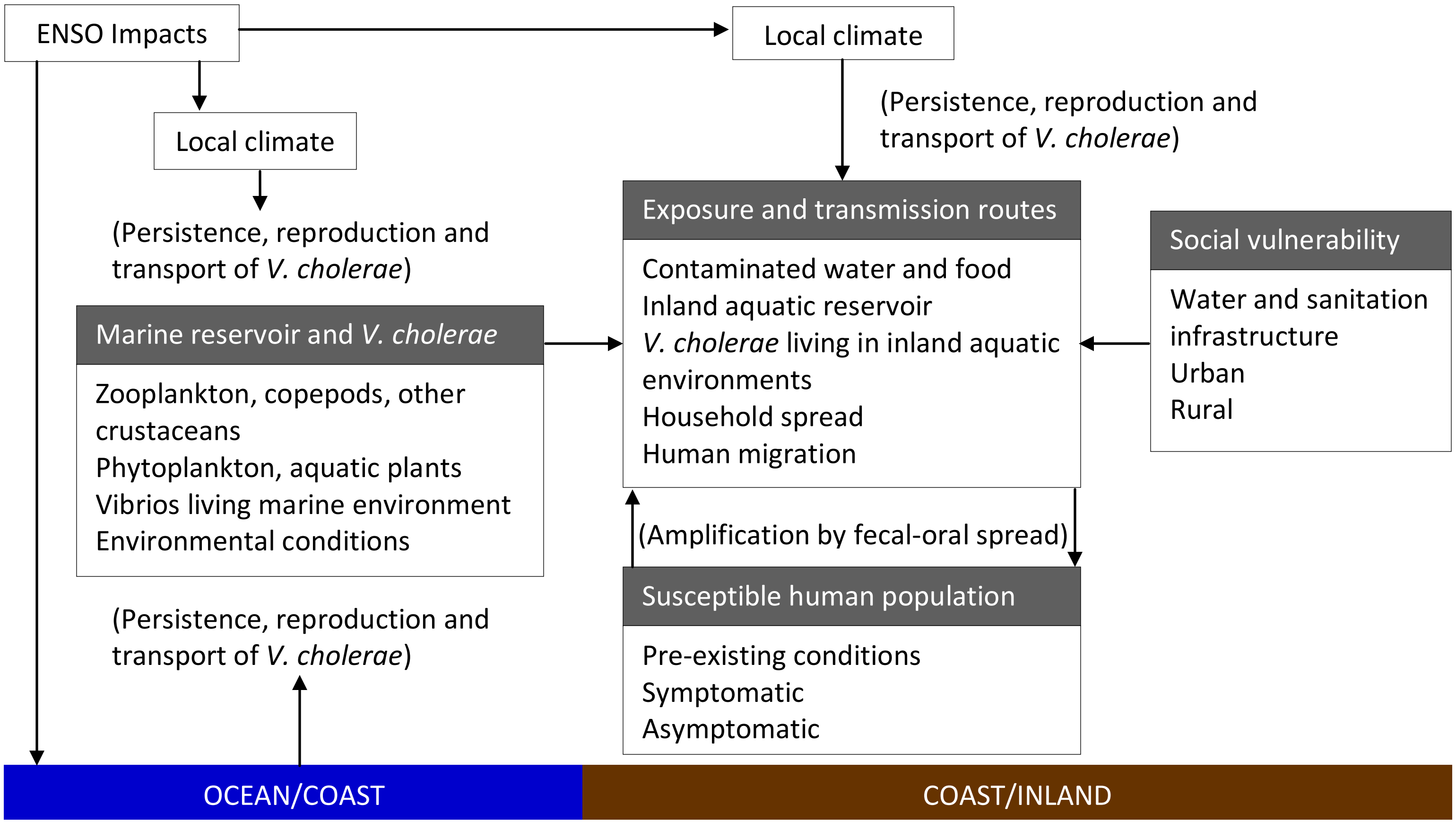


Figure 4.3 ENSO Impacts on the Cholera Transmission Cycle.

Adapted from Lipp et al. (2002) and Nelson et al. (2009).

However, ENSO and local climate impacts on cholera transmission are contingent on the social vulnerability to cholera in Piura. Cholera transmission may either be enhanced or buffered depending on the level of social vulnerability within Piura (e.g., access to water and sanitation infrastructure and living in urban versus rural areas). Once a person is infected the ability to recover depends on the subsequent coping/responses (e.g., local actions, access to healthcare, and public health responses) in Piura and outside Piura (e.g., Peruvian civil defense, multi-lateral aid and assistance, and NGOs). The framework also recognizes that cholera transmission and vulnerability in Piura may have also been influenced by a broader context of national and global pressures (Oppong 1998; Farmer 1999; Mayer 2000; Wisner et al. 2004: 184-185), such as macroeconomic policies (e.g., associated with SAPs), terrorism (e.g., Shining Path guerrillas), war (e.g., Ecuador border conflict), and an energy crisis (e.g., oil supply and demand fluctuations related to the first Gulf War) (PAHO 1991a; Nash 1991; El Tiempo 1991b; Youngers 2000; Cueto 2003). As such, my conceptual framework acknowledges political ecology (e.g., Zimmerer and Bassett [2003]), but also recognizes that examining the links between subregion and district-level cholera incidence in Piura and global development (and other large-scale social forces) goes beyond the scope of this study.

4.2 Study Area and Population

The study area is the health subregion of Piura in the Department of Piura, located on the northern coast of Peru (approximately 900 km from Lima). The department comprises of an area of 20,238 km^2 with two well-defined land features, including a low-lying savannah (3-meter elevation) on the coast and mountainous forests (2,709- meter elevation) in the east. On the coast the climate is semi-arid and in the mountains it is subtropical. The climate is dominated by the Humboldt Current, conditions in the equatorial Pacific Ocean basin and the Andes Mountains, which lay in the east. It has one important river, the River Piura, which is seasonal (Institute of National Statistics and Information [INEI] 2000).

Figure 4.4 and **4.5** show monthly average temperatures and rainfall totals at the Miraflores meteorological station in the capital city of Piura. [12] The average annual temperature in Piura is 24.0°C with an average annual maximum and minimum of 31.0°C and 19.0°C. Average temperatures do not vary so much compared to rainfall total which is highly seasonal (December to May). Piura typically receives less than 50 millimeters (mm) of rainfall annually, except during El Niño years when rainfall has been recorded to be over 25 times the average total (Woodman 1998).

[12] I used the capitol city average because it is widely used by officials in Piura and represents the dataset which I am employing in this study.

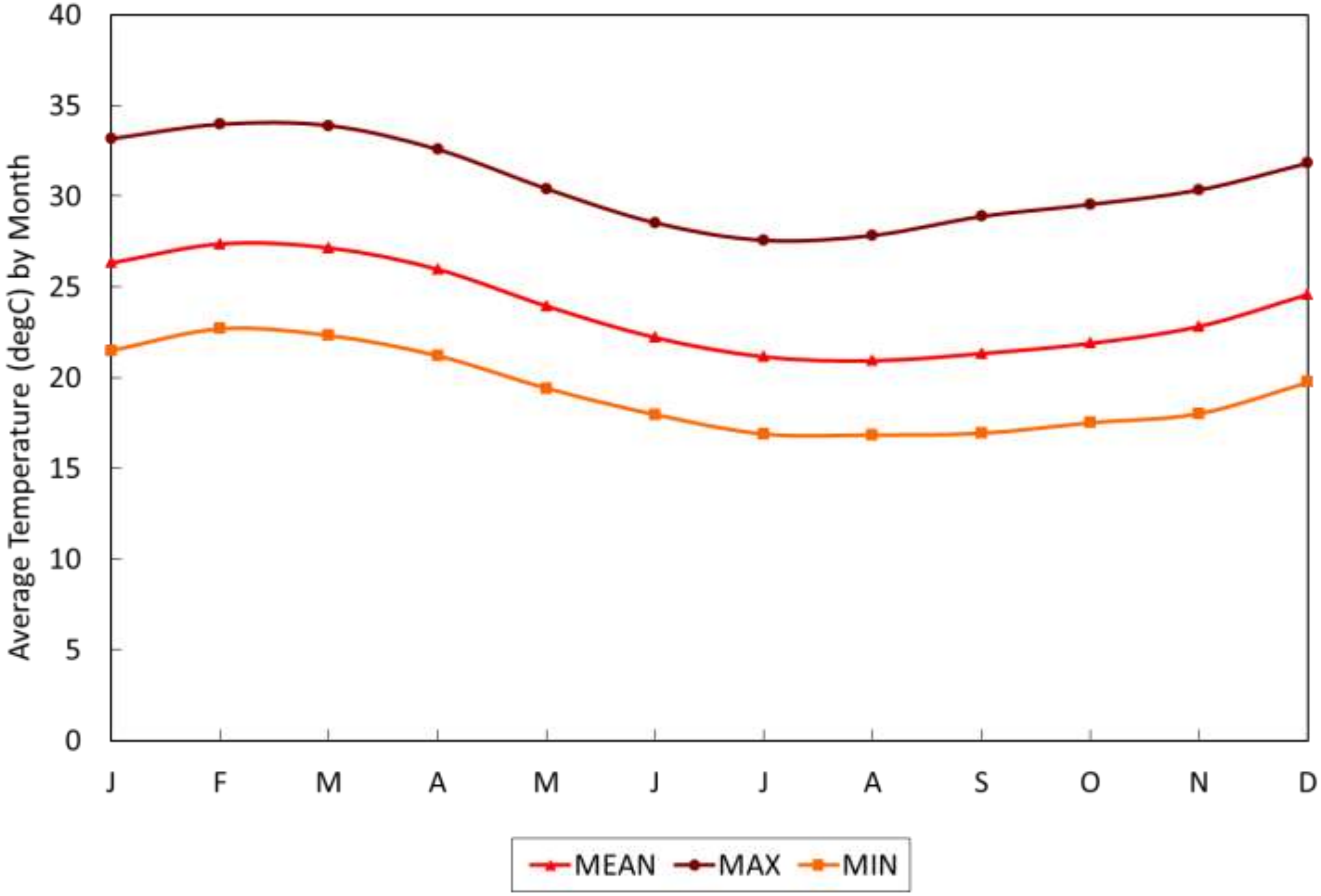


Figure 4.4 Monthly Average Temperature (°C) at Miraflores station, Piura for 1971 to 2000.

Source: UDEP 2008

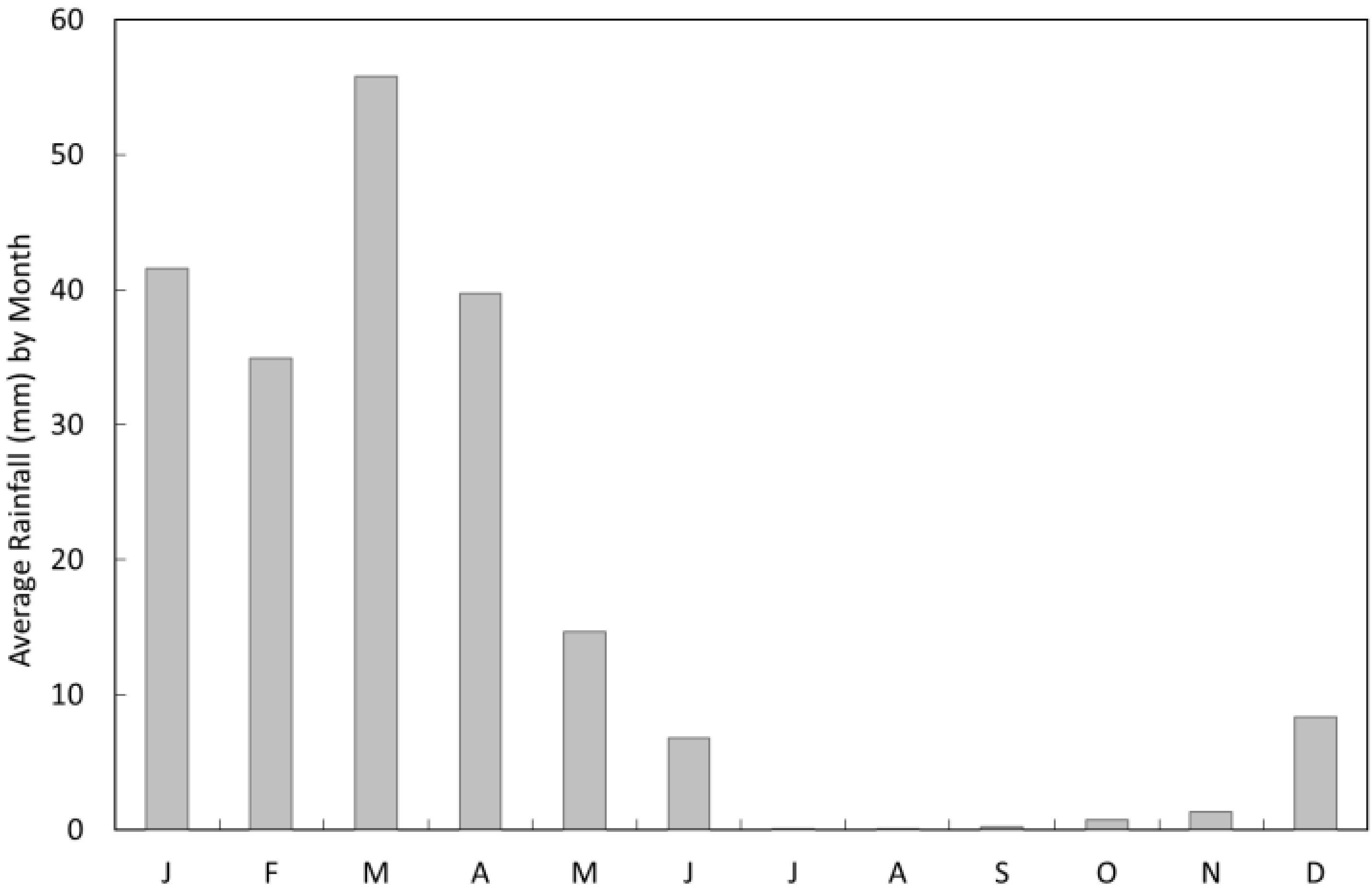
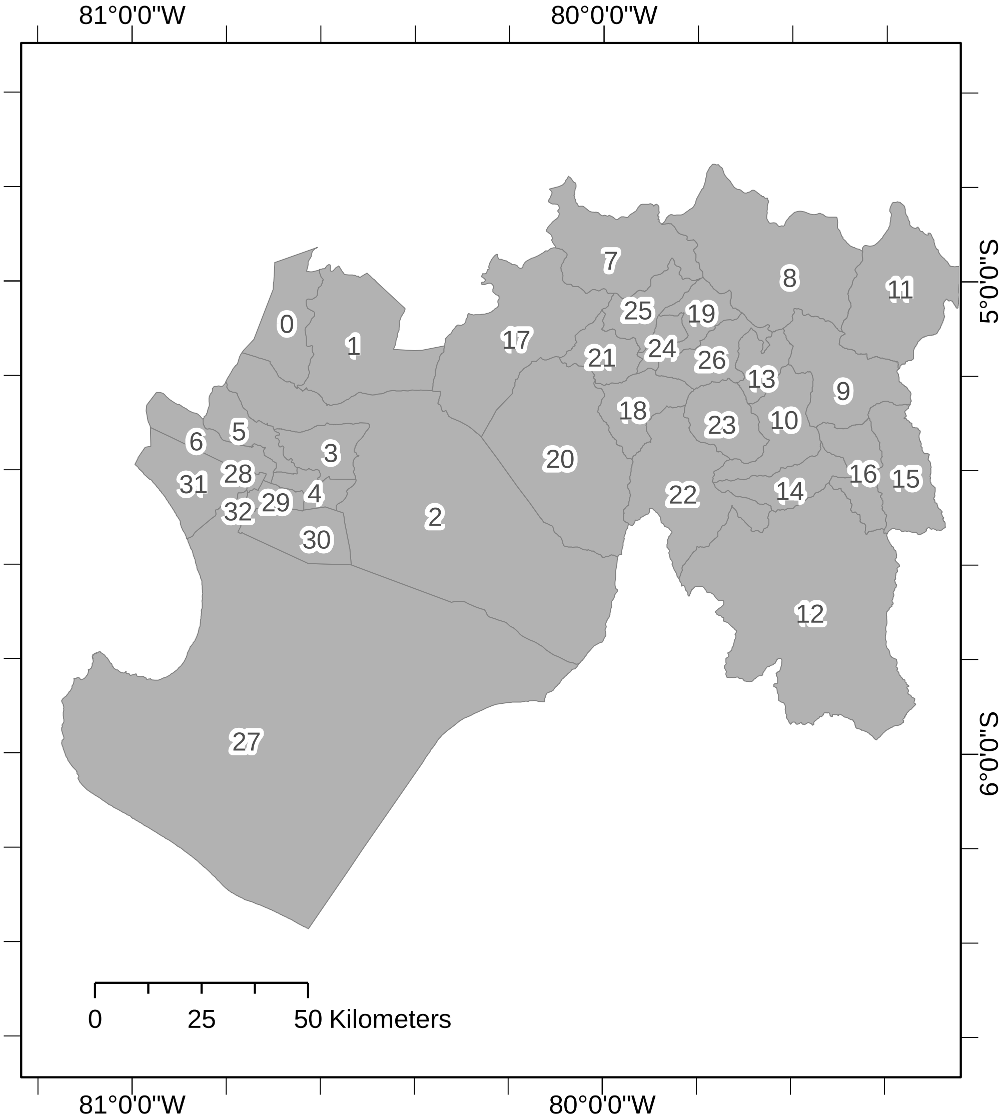


Figure 4.5 Monthly Average Rainfall (mm) at Miraflores station, Piura for 1971 to 2000.

Source: UDEP 2008.

Figure 4.6 is a district-level map of the subregion of Piura. It is one of two health subregions. Piura consists of thirty-three of sixty-four districts in the Department of Piura. In 1998, it had an estimated 847,257 habitants (56.0% of the Department's total population) representing 42 habitants per km^2 (INEI 2000). Fifty-one percent of residents lived in urban areas near the coast. The main sectors of employment were agriculture, fisheries and mining (INEI 1996). Forty-eight percent of the population was dependent (i.e., dependency ratio = 0.5) with most of that dependency attributed to children under the age of 15 years (INEI 1993).



District	ID	District	ID	District	ID
PIURA	0	EL CARMEN DE LA FRONTERA	11	SALITRAL1	22
CASTILLA	1	HUARMACA	12	SAN JUAN DE BIGOTE	23
CATACAOS	2	LALAQUIZ	13	SANTA CATALINA DE MOSSA	24
CURA MORI	3	SAN MIGUEL DE EL FAIQUE	14	SANTO DOMINGO	25
EL TALLAN	4	SONDOR	15	YAMANGO	26
LA ARENA	5	SONDORILLO	16	SECHURA	27
LA UNION	6	CHULUCANAS	17	BELLAVISTA DE LA UNION	28
FRIAS	7	BUENOS AIRES	18	BERNAL	29
PACAIPAMPA	8	CHALACO	19	CRISTO NOS VALGA	30
HUANCABAMBA	9	LA MATANZA	20	VICE	31
CANCHAQUE	10	MORROPON	21	RINCONADA LLICUAR	32

Figure 4.6 Map of the Subregion of Piura by District (ID).

Development indicators in Piura suggest that basic needs are unmet for some segments of the population. Illiteracy affected 25.0% of population (i.e., adults 15 years +) in 1993. Importantly, water and sanitation infrastructure was not accessible to 27.0% and 71.0% of the population (INEI 1993). The impact of basic needs unmet on subpopulations was evident in the subregion's health reports. There were high rates of infant mortality (17.0 per 1000 live births) and maternal mortality (89.0 per 1000). Moreover, 31.0% of diarrheal disease cases were associated with dehydration (INEI 1997).

Piura's health capacity in 1997 was 57 laboratories and 199 health centers including 3 major hospitals (INEI 2001). It is part of Peru's health system that encompassed (at the time) three organizations: Ministry of Health (87.0% of hospital infrastructure and 87% of primary healthcare), Peruvian Institute of Social Security (ESSALUD), and the private sector, which mainly provides ambulatory services. The latter is a sector for wealthy Peruvians. Although the Ministry of Health was responsible for most healthcare services to Peruvians, only a small percentage used those services (e.g., 13.0% of those contributing to ESSALUD via employment and 9.8% of those with private insurance). In many rural areas, communities did not have access to healthcare; health care was mainly available in cities (Department for International Development Health Systems [DFID] 1999). As part of a health reform in 1995, primary health care was extended by forming 'Local Committees for Health Administration' (CLAS), which is administered by local communities and funded by the treasury to expand healthcare to underserved communities (DFID 1999). Despite this effort, which was part of a larger national initiative called the Basic Health-for-All Program during the mid-1990s, it was reported that the poorest (by poverty rates) sections of the Peru had the least resources and human capital (PAHO 1998).

4.3 Data and Methods

I primarily used secondary data collected from various institutions in Peru in Piura and Lima, online sources and various literatures (documents and sources are described in Objective 1). A description of these data per objective will follow.

4.3.1 Objective 1: Develop a conceptual framework that characterizes the potential ecological pathways and conditions of cholera vulnerability and transmission in Piura

Objective 1 Data and Methods

In the first objective, I developed a conceptual framework to explain cholera vulnerability and transmission in Piura, Peru. The framework was presented in detail in the previous sections. Developing the framework was a reflexive process guided by a climate affairs approach and grounded in theoretical concepts of disease ecology and vulnerability and fieldwork in the cities of Lima and Piura, Peru where I collected data, information and documents in the Spanish language. In order to collect these data I obtained an IRB (#X08-724 with exemption status) from Michigan State University in order to consult with and document anecdotes from officials at a number of Peruvian institutions to learn more about the cholera outbreaks in the 1990s, El Niño impacts, and the type and quality of the data I collected. A list of the types of questions I asked officials and a copy of a consent form are found in **Appendix 2**. I also took many field notes where I documented my observations and also reflected on them. These experiences and exchanges with the people in Piura provided me with 'revealing points' that helped me to connect important pieces of information and refine my framework (Emerson et al. 1995: 144-167). These revelations were important because they helped me ground my research questions and hypotheses. Thus, I was better informed about Piura and how cholera transmission occurred and El Niño's impact. I also collected archival materials (e.g., newspapers, 1991 to 1993), newsletters, journal articles, and health bulletins from various sources, including the library at University of Piura (UDEP), University of the Pacific in Lima, INEI in Piura, the Ministry of Health in Piura, International Institute of Nutrition in Lima, Institute of Peruvian Studies, Department of Fisheries at the National University of Agriculture – La Molina in Lima, Center of Research and Advocacy for Farmers in Piura (CIPCA), Applied Geography Research Center at the Pontifical Catholic University of Peru, PAHO, and GTZ, a German non-governmental organization in Piura. In addition I visited and used archives and materials at the Consortium for Capacity Building (CCB) and the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. I consulted closely with Dr. Michael H. Glantz about the El Niño materials I collected during fieldwork, and I gained anecdotal knowledge from him about ENSO and society during the 1990s.

4.3.2 Objective 2: Characterize the temporal associations between ENSO, climate and cholera cases in Piura from 1991 to 2001

Objective 2 Data

a) Cholera

I collected data on cholera cases for Piura during fieldwork in Peru from three sources:

(1) The Department of Epidemiology at the Ministry of Health in Lima, Peru – These data were provided in a spread sheet and consisted of weekly reports for the time period (1991 to 2002).

(2) The Department of Epidemiology at the Ministry of Health and the International Institute of Nutrition in Lima, Peru – Weekly Epidemiology Bulletins (hard copies and disk) for the time period (1991 to 2004).

(3) The Ministry of Health for the Subregion Piura in Piura, Peru (MINSA Piura). These data were provided in a spread sheet and consisted of weekly reports for the time period (1991 to 2006).

These data included both laboratory confirmed cases, suspected (clinically confirmed) cases and laboratory-negative cases. It was important to determine if the data collected from these three sources were consistent so that I could select the most 'reasonable' dataset to use in my research. I found that the cholera data among these sources were generally in agreement from 1991 to 1998. After 1998, cholera data among these sources were not in agreement. In summary, I decided to use the cholera data from source (3) for the time period 1991 to 2001. The total number of cases in the

Piura dataset that I used in this research was (n= 38,040). These weekly data were then aggregated to cholera-case counts per month. Lastly, these time series data were square-root transformed, a standard procedure used in wavelet analyses.

b) Sea Surface Temperature (SST)

Monthly SST index, mean and standardized anomaly data for 1971 to 2002 were obtained for the following Niño Regions: Niño 3.4 (5°North-5°South) (120-170°West) and Niño 1+2 (0-10°South) (90°West-80°West). These data were downloaded from the Center for Climate Prediction (http://www.cpc.ncep.noaa.gov/data/indices/). Niño index data are 3-month running averages of SST anomaly (e.g., December, January, February; January, February, March, etc.). A Niño 1+2 index was not available via the webpage so an index was calculated using the standardized anomaly data. Both indices were used to define and identify ENSO events in the first part of this objective. Niño 3.4 was used for comparative purposes because it is a widely used global climate indicator of ENSO conditions, and correlates strongly with rainfall in northern coastal Peru (Lagos et al. 2008). I also obtained monthly SST mean and anomaly data for Paita for 1971 to 2001 from the University of Piura (UDEP). Paita is a coastal port located 3 meters above sea-level and SST data from Paita is used to monitor SST off the coast of the Department of Piura ([05°04' 57"South] [81°06' 57"West]). Sea surface temperature anomalies (SSTA) data were based on the period 1971 to 2000. SSTA data were used to assess patterns and associations between climate and cholera. In this study the Niño SSTA parameters represent global SST conditions in the central and eastern equatorial Pacific and the Paita parameter represents local SST conditions off the coast of Piura, Peru.

c) Temperature and Rainfall

Monthly temperature data (mean, maximum and minimum values) and rainfall data (total mm) for the Miraflores station for 1971 to 2001 were obtained from UDEP. Miraflores is a meteorological station located in the district of Castilla, which shares the eastern border of the district Piura and is in the subregion of Piura ([05° 10'South] [80°37'West]; altitude = 30 meters above sea level). A minimal number of values were missing from the Miraflores datasets so I replaced those values with data from another meteorological station called CORPAC, also located in Castilla ([05°12'South] [80°36']; altitude = 49 meters above sea level). For each temperature parameter, standardized anomalies were calculated by subtracting the monthly mean for the base period (1971 to 2000) from the mean from a particular month and then dividing by the monthly standard deviation calculated for the base period. This procedure removed the annual cycle. For rainfall, the data were normalized using square-root transformation.[13] In this study temperature maximum anomaly (TMAXA), temperature mean anomaly (TMEANA), temperature minimum anomaly (TMINA), and rainfall parameters represented the local climate conditions in the subregion of Piura.

Table 4.1 is a summary of statistics for cholera cases and the global and local climate parameters (anomalies) described in this objective. I found that rainfall and cholera case data were highly skewed even after performing square-root transformation. In order to address this potential problem, I calculated standardized

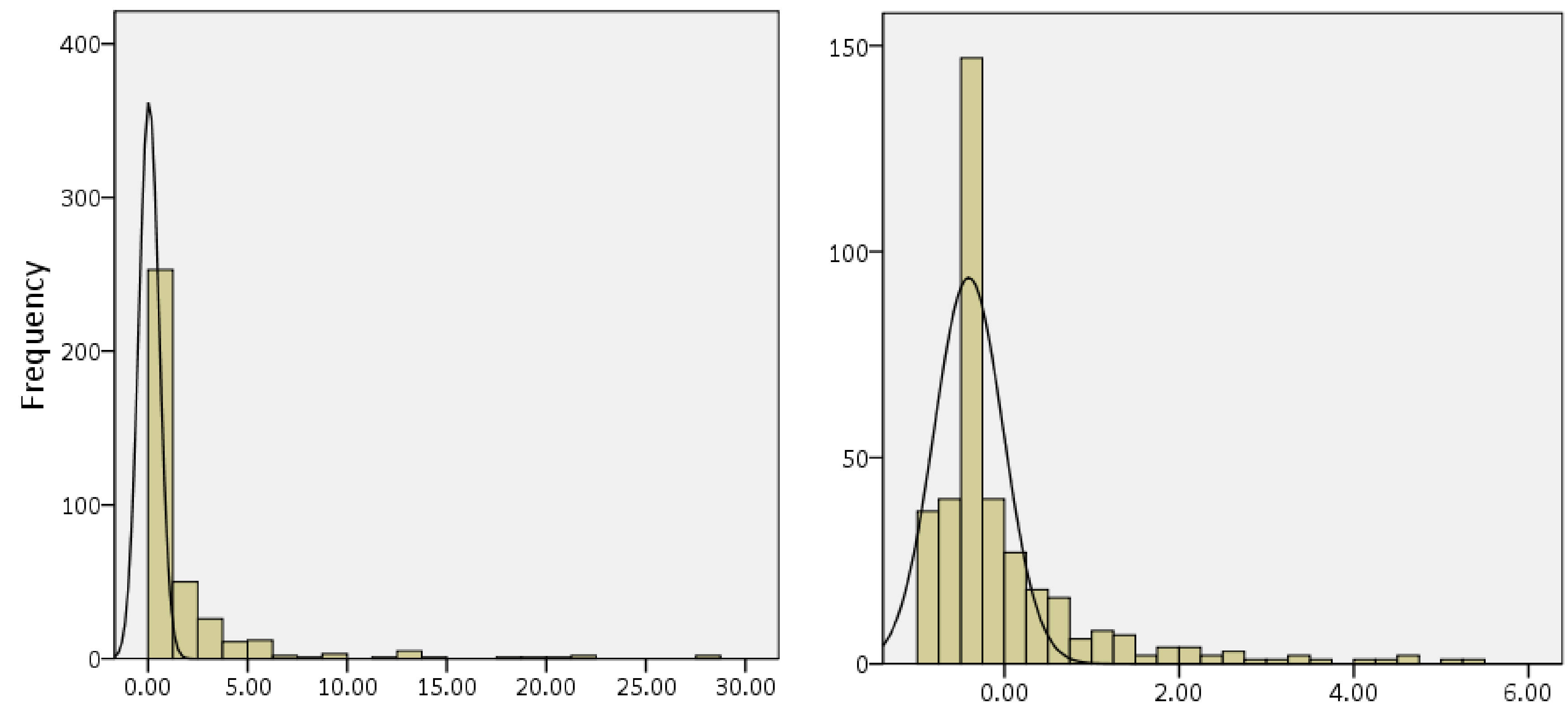
[13] This procedure is typically used to remove extremes in wavelet studies that examine climate and disease relationships.

anomalies using base periods of 1971 to 2000 and 1991 to 2001. Using this procedure there was an improvement in the frequency distribution of rainfall and cholera (**Figures 4.7** and **4.8**).

Table 4.1 Summary of Statistics for Cholera and Global and Local Climate Parameters for the years 1971 to 2001

Variable	N	Minimum	Maximum	Mean	Mean Std. Error	Std. Deviation
Cholera Cases*	132	0.0	10591.0	288.181	104.622	1202.0168
NIÑO 1+2 SSTA (°C)	372	-2.1	4.5	0.011	0.0630	1.2150
NIÑO 3.4 SSTA (°C)	372	-2.1	2.5	-0.004	0.0479	0.9233
Paita SSTA (°C)	372	-1.5	3.9	-0.001	0.0505	0.9735
TMAXA (°C)	372	-2.8	3.6	-0.032	0.0517	0.9978
TMEANA (°C)	372	-2.2	4.1	0.004	0.0505	0.9746
TMINA (°C)	372	-2.4	4.2	0.002	0.0504	0.9713
Rainfall (mm)	372	0.0	778.4	17.031	4.04415	78.0007

*Cholera data is for the time period 1991 to 2001



(a) (b)

Figure 4.7 Histograms of (a) Rainfall (square-root transformed) (mm) by month; and (b) Rainfall (square-root transformed) Anomaly (mm) by month.

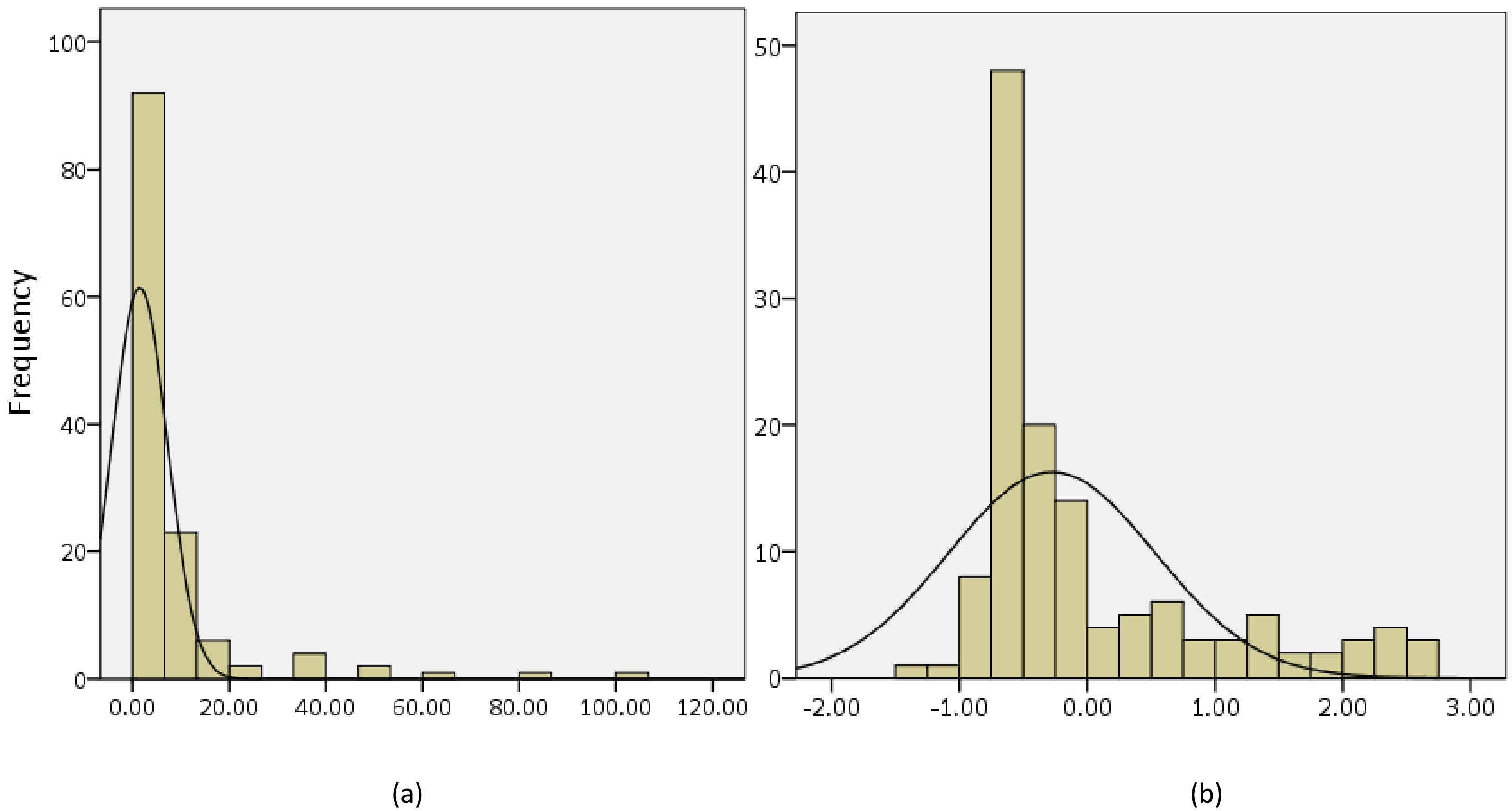


Figure 4.8 Histograms of (a) Cholera Cases (square-root transformed) by month and (b) Cholera Cases (square-root transformed) Anomaly by month.

Objective 2 Methods

a) Defining ENSO

In the first part of Objective 2, I adopted the current definition of ENSO used by NOAA to estimate ENSO events (2010). The purpose of this procedure was to identify ENSO events per region so that I can interpret and explain the ENSO background in the results and discussion. El Niño (warm phase) and La Niña (cold phase) events are defined as periods during which the values of the Niño 3.4 index exceeded a threshold of +/-0.5 (°C) for at least 5 consecutive seasons. This definition was also applied to the Niño 1+2 index in order to estimate ENSO events in that Niño region. Impacts on the northern coast of Peru are of concern, and therefore, Niño 1+2 is important because of its proximity to the Peruvian Coast and sensitivity to ocean-atmosphere changes in the eastern and central Pacific Ocean.[14]

Niño region indices were compared according to ENSO phase by identifying the number of events, duration of events by months, percentage of months (number of phase months/total number of months for the study time period), and timing of events (beginning and end months). Neutral phase periods (non-El Niño or La Niña months) were also identified. These estimates were studied in relation to cholera cases.

b) Wavelet Analyses

Wavelet analyses was used to characterize the temporal properties of each time series (i.e., cholera and climate variables independently) and quantify associations in

[14] Although Trenberth (1997) found that Niño 3.4 was closely associated with historical studies of ENSO, he recommended the use of criteria that "suits" the region.

time frequency space between the following times series: (a) Niño 3.4 SSTA and cholera; (b) Niño 1+2 SSTA and cholera; (c) Paita SSTA and cholera; (d) TMAXA and cholera; (e) TMEANA and cholera; (f) TMINA and cholera; and (g) Rainfall and cholera. The time period of analysis between cholera and climate associations is 1990 to 2001. In the climate time series analysis (univariate), I considered the time period 1971 to 2000. The longer time period gave me a better estimation of climate temporal patterns. However, when I discuss cholera in reference to these associations I focused on 1990 to 2001, which is relevant to the cholera epidemic in Peru.

The wavelet approach was chosen because it is commonly used in geophysical studies to examine how phenomena (e.g., ENSO and Artic Oscillation) may vary at localized time scales and at different time intervals (Torrence and Compo 1998; Grinsted et al. 2004). More recently wavelet analyses have been used to examine non-stationary associations (i.e., transient temporal properties) between climate and infectious diseases (Cazelles et al. 2007) including cholera (Koelle et al. 2005; Constantin de Magny et al. 2007), dengue (Cazelles et al. 2005; Johansson et al. 2009) and Leishmaniasis (Chaves and Pascual 2006).

This study used three types of wavelet analyses: (a) wavelet transform (univariate); (b) wavelet coherence (bivariate); and (c) cross-wavelet transform (bivariate).

(a) **Wavelet transform** was used to examine the temporal properties of each times series in order to identify time scales of power (i.e., frequency and also referred to as periodicity) across different time intervals. Power increases from blue to red in the wavelet power spectrum. Each scale is denoted by years and represents horizontal slices of the variance across different time intervals (also referred to as bands) (Torrence and Webster 1999). I identified those areas (i.e., time intervals and scales) with the greatest power that are statistically significant (95.0% confidence) and outside the cone of influence (COI), where edge effects at the beginning and end of the times series may be interpreted but are not influential (Torrence and Compo 1998). The average power and scales across the local wavelet spectra that are statistically significant (95.0% confidence) were estimated using a measure called 'global wavelet power spectrum' (GWS).

(b) **Wavelet coherence** was used to estimate localized correlations between two time series and to identify time scales and intervals where the time series co-varied. Coherence increases from blue (low) to red (high) correlation. I was looking for areas (i.e., time intervals and scales) with the greatest coherence that are statistically significant (95% confidence) and outside the cone of influence (COI). In addition to estimating correlations, coherence was also used estimate the direction of the relationship (a range from 'in phase' as positive to 'out of phase' as negative) and whether one time series leads or lags the other in this association. The phase of coherence is indicated by arrows, as follows: north (climate lags by 90° or an estimated 6 months); south (climate leads by 90° or an estimated 6 months); east (climate and cholera in phase at 0° or an estimated zero months); and west (climate and cholera out of phase at 180° or an estimated zero months).

(c) **Cross-wavelet transform** was used to assess whether localized time scales and intervals that co-varied also shared high power or frequency. The cross-wavelet transform is important because it helps to assess whether the phase (denoted by arrows) is consistent across scales. If arrows vary or conflict (e.g., in and out or lag and lead) throughout a scale, it may suggest that the association is coincidental (Grinsted et al. 2004). Therefore, the phase direction and the time lag or lead was interpreted carefully and supported with additional methods.

(d) In this study, I also used cross-correlation analysis to support my interpretations of the phase direction and time association between two times series as outlined above.

The wavelet analyses were performed in Matlab R2009a (Matlab 2010) using scripts by Torrence and Compo (1998) and Grinsted et al. (2004). Examples of these scripts are provided in **Appendix 3.** Cross-correlation analysis was performed using SPSS GRADPACK 17.0 (SPSS 2009).

4.3.3 Objective 3: Construct a social vulnerability index (SVI) that characterizes social vulnerability to cholera in the subregion of Piura in 1997-98

Objective 3 Data

Demographic, socioeconomic, and infrastructure data at the district level (n = 33) for the subregion of Piura were obtained from the census bureau (INEI) in Piura and from the INEI webpage (http://www.inei.gob.pe/). These datasets included census and basic needs information for 1993.[15] I chose this year because it is widely used and more recent data were unavailable.[16] After reviewing the data, I discovered that the basic needs data were incomplete; therefore I chose to use the census bureau data. This dataset included 93 variables that were percentages (e.g., percent of population that had access to potable water via water trucks, etc.). Thirteen variables were selected for the social vulnerability index (SVI) based on theoretical and empirical associations with cholera risk and transmission. **Tables 4.2** and **4.3** show a summary of statistics for these variables and correlations with cholera. Overall these variables included information on education, housing for use as proxy indicators of broader social conditions, water and sanitation infrastructure and urban because cholera in Peru was characterized as an urban epidemic (PAHO 1991; Salazar-Lindo et al. 2008).

[15] Basic need data in Peru is a composite measure using select census data to characterize social and infrastructure poverty.

[16] District level data in Peru was not collected periodically until 2005.

Table 4.2 Description of Variables used in Principal Components Analysis

Variable	Description
ELEM_EDUC	Percentage of population that has only elementary education
ILLITERATE	Percentage of population that is adults (defined as 15 yrs+) that cannot read or write
IMPROV_HSING	Percentage of population that live in improvised housing
KITCHEN_NONE	Percentage of population without kitchen in household
KITCHEN_SHARE	Percentage of population that shares a kitchen
KITCHEN_YES	Percentage of population with exclusive kitchen in household
BATHRM_NO	Percentage of population without bathroom in household
URBAN	Percentage of population that lives in urban area
WATER_OTHER	Percentage of population whose source of water is listed as other
WATER_PUMP	percentage of population whose source of water is a public water pump
WATER_RIVER	percentage of population whose source of water comes is a local river
WATER_TRUCKS	percentage of population whose source of water comes from water trucks
WATER_WELL	Percentage of population whose source of water is a public well

Table 4.3 Summary of Statistics for Variables and Pearson's Correlations with Cholera

Variables	N	Mean	Std. Dev	Correlation with Cholera
Cholera incidence for 1997-98 (per 1000)	33	1.77	1.03	1.00
ELEM_EDUC (%)	33	69.12	10.40	-0.47
ILLITERATE (%)	33	24.64	12.02	-0.63
IMPROV_HSING (%)	33	1.52	3.19	0.36
KITCHEN_NONE (%)	33	15.85	7.12	0.19
KITCHEN_SHARE (%)	33	3.00	2.24	0.59
KITCHEN_YES (%)	33	81.24	7.28	-0.38
BATHRM_NO (%)	33	71.55	21.94	-0.18
URBAN (%)	33	51.03	37.20	0.71
WATER_OTHER (%)	33	5.33	13.30	0.44
WATER_PUMP (%)	33	7.33	7.19	0.12
WATER_RIVER (%)	33	41.64	32.95	-0.65
WATER_TRUCKS (%)	33	4.24	11.63	0.28
WATER_WELL (%)	33	12.73	10.74	0.06

N indicates the number of districts.

Objective 3 Methods

a) Principal Components Analysis

The SVI was constructed following a method by Cutter et al. (2003). Variables were explored for multicolinearity. A correlation matrix of these variables is displayed in **Table 4.4**. In order to address multicolinearity, the SVI input variables were reduced into orthogonal dimensions using principal components analysis (PCA) in SPSS GRADPACK 17.0 (SPSS 2009). The PCA settings were rotated using varimax and sorted. Dimensions that accounted for at least 5.0% of the total variance were extracted. Factors within the dimensions were selected based on a loading value (0.5 or above), theory, and literature review. For example, although a factor may not have obtained a loading value of 0.5, inclusion of the factor in the SVI was contingent on findings from theoretical and empirical studies about cholera transmission (discussed in the literature review). Factor scores for each observation (district) derived from the PCA analysis were saved. Scores represent how influential a variable is in a pattern by the weight assigned in the PCA (Rummel 1967). Each dimension was given equal weight for simplification. Scores for each dimension were then summed and divided by the number of dimensions. Scores were mapped using ArcGIS version 9.2 (ESRI 2010) to illustrate the spatial patterns of vulnerability for the SVI and individual dimensions (SVI factors, hereafter) by districts. District scores for SVI and SVI factors were also mapped and ranked in ascending order (low vulnerability to high vulnerability) for comparison purposes.

Table 4.4 Correlation Matrix for Variables used in Principal Components Analysis

	pw3[1]	pw4[2]	pw5[3]	pw6[4]	pw7[5]	ed3[6]	k1[7]	k2[8]	k3[9]	urban[10]	how5[11]	bth5[12]	illit_a[13]
pw3	1.000	0.136	0.076	*-0.503*	-0.129	-0.306	-0.196	0.258	0.115	*0.456*	0.328	-0.354	0.004
pw4	0.136	1.000	0.003	-0.335	-0.022	0.278	-0.231	0.359	0.140	0.127	-0.082	-0.036	0.206
pw5	0.076	0.003	1.000	-0.239	-0.042	0.020	*-0.457*	0.274	0.377	0.322	0.194	0.095	-0.306
pw6	*-0.503*	-0.335	-0.239	1.000	-0.312	*0.542*	*0.459*	*-0.721*	-0.237	*-0.928*	*-0.477*	*0.414*	*0.556*
pw7	-0.129	-0.022	-0.042	-0.312	1.000	-0.157	-0.124	0.220	0.053	0.347	-0.052	0.149	-0.298
ed3	-0.306	0.278	0.020	*0.542*	-0.157	1.000	0.106	-0.340	0.012	*-0.578*	*-0.629*	*0.758*	*0.688*
k1	-0.196	-0.231	*-0.457*	*0.459*	-0.124	0.106	1.000	-0.177	*-0.952*	*-0.511*	-0.348	-0.033	0.231
k2	0.258	0.359	0.274	*-0.721*	0.220	-0.340	-0.177	1.000	-0.130	*0.662*	0.394	-0.352	*-0.411*
k3	0.115	0.140	0.377	-0.237	0.053	0.012	*-0.952*	-0.130	1.000	0.304	0.228	0.146	-0.090
urban	*0.456*	0.127	0.322	-0.928	0.347	*-0.578*	*-0.511*	*0.662*	0.304	1.000	*0.523*	-0.379	*-0.668*
how5	0.328	-0.082	0.194	*-0.477*	-0.052	*-0.629*	-0.348	0.394	0.228	*0.523*	1.000	*-0.426*	*-0.494*
bth5	-0.354	-0.036	0.095	*0.414*	0.149	*0.758*	-0.033	-0.352	0.146	-0.379	*-0.426*	1.000	0.396
illit_a	0.004	0.206	-0.306	*0.556*	-0.298	*0.688*	0.231	*-0.411*	-0.090	*-0.668*	*-0.494*	0.396	1.000

[1]WATER_PUMP, [2]WATER_WELL, [3]WATER_TRUCKS, [4]WATER_RIVER, [5]WATER_OTHER, [6]ELEM_EDUC, [7]KITCHEN_YES, [8]KITCHEN_SHARE, [9]KITCHEN_NO, [10]URBAN, [11]IMPROV_HSING, [12]BATHRM_NO, and [13]ILLITERATE

4.3.4 Objective 4: Characterize the spatial and temporal associations between ENSO, climate and cholera incidence by district in Piura for 1997-98 and estimate the degree to which social vulnerability influenced this relationship

Objective 4 Data

a) Cholera

Cholera data by district (n=33) per week for January 1997 to December 1998 in Piura were obtained from the Department of Epidemiology at the Ministry of Health in Lima, Peru. I aggregated these data to a monthly scale using cholera case-counts in 1997 to 1998 and monthly cholera case-counts for 1998.[17] In addition population estimates by district for 1998 were obtained from the INEI webpage. I then calculated cholera incidence rates (herein referred to as, cholera incidence) at two scales (total cholera incidence for 1997 to 1998 and monthly cholera incidence in 1998) by dividing the total number of cholera cases by the estimated population in 1998. The total cholera case-counts for 1997 to 98 and monthly cholera case-counts for 1998 were square-root transformed for analytical analyses. The reasoning for the two scales of data is explained in the subsequent methods section.

b) SVI

The SVI and SVI factors by district (n = 33) estimated in the previous section were also utilized in this objective.

[17] Because 1997 was a year with less than 50 cholera cases in the subregion, I decided to sum 1997 and 1998 cases by district.

c) Climate

Monthly values of global and local sea surface temperature anomalies (Niño 3.4, 1+2 and Paita); local temperature anomalies (TMAXA, TMEANA and TMINA) and rainfall for 1997 to 1998 in Piura (obtained from datasets described in section 4.3.2.1) were also utilized in this objective. From these data, a new set of time series were created with 1 to 7 month lag associations. The temporal lag implied that climate may have led cholera by 1 to 7 months. In total there were 8 time series (0 to 7 month lags) for each of the climate parameters. Each time series had 0 to 7 month lags with a total of 12 months.

Objective 4 Methods

After examining the data that I collected while I was in Peru, I realized that my data had issues related to sample size and scale mismatch. First, the sample size (n=33 districts) was too small to fully estimate the modifying (indirect) effect(s) of social vulnerability on the cholera and ENSO, climate relationships, as outlined in my Objective 4 in my proposal. Second, I only had climate data from one meteorological station and therefore, I did not have informaton on the climate variablility across the district. Instead I decided to use the monitoring data to study the climate and cholera relationship in separate models for each district.[18] Third, I wanted to estimate the effect of SST on cholera at a district-level. However, since SST is based on parameters in

[18] After consulting with Prof. Norma Ordinola, my collaborator at the University of Piura, I decided to use the data at the Miraflores station located in the city of Piura. Although reliable, the data were only representative of climate in districts along the low lying coast and may not capture climatic conditions further inland or at higher elevations (personal communication June 2009).

the equatorial Pacific Ocean, obtaining a measure of SST variability at a district-level is not possible. I, therefore, examined the effect(s) of each hazard (e.g., social vulnerability and climate) on cholera incidence by district in separate models and then descriptively compared the mapped-spatial patterns in coefficients from those models.

In the first part of this objective, I examined the spatial relationships between cholera incidence (1997-1998) and SVI and SVI factors at the district level (n=33). In the second part, I examined the temporal relationships between cholera incidence and global and local climate variables by district (n=33) and month (n=12) in 1998. This estimated the potential temporal impact of climate (monthly) on cholera across districts in Piura.

a) Objective 4 Methods Part 1

Unadjusted global (ordinary least squares regression [OLS]) and local (geographically weighted regression [GWR]) models were estimated to assess the effect of SVI or SVI factors on cholera incidence (dependent variable) in the subregion of Piura at the district level. The OLS regression analysis estimated the strength of association (r^2) and level of significance (p-values) in these relationship(s) across the study area. Subsequently, local GWR models were estimated to visualize and explore the spatial variation in model coefficients (i.e., intercepts and slopes) and residual-error terms. The results from the global and local models were compared in order to assess how localized cholera incidence was in each region (in constrast to being evenly distributed across the subregion). GWR is a spatial regression technique that accounts for spatial autocorrelation in the data; therefore in this objective it was used to characterize non-stationary spatial associations, where the relationships between variables vary by location (Fotheringham et al. 2002). All models were estimated using OLS and GWR functions in the Spatial Statistics tool in ArcGIS (v.9.3.1) (ESRI 2010).

b) Objective 4 Methods Part 2

OLS regression analyses estimated the association(s) between cholera incidence and global and local climate parameters for <u>each</u> district in Piura. Bivariate analyses were conducted where the monthly cholera incidence was the dependent variable and global sea surface temperature (Niño 3.4 SSTA and Niño 1+2 SSTA), local sea surface temperature (Paita SSTA), local temperature (TMAXA, TMEANA and TMINA), and local rainfall were explanatory variables. Temporal lag associations from zero to 7 months were explored. I identified the strength of climate association (r-squared) and significance (p-value) by district, variable and time lag. All OLS analyses were performed in Matlab R2009a (Matlab 2010). The districts with the strongest association(s) in cholera incidence and climate parameters and temporal lags (strongest teleconnections) were then joined into one table and mapped in ArcGIS version 9.2 (ESRI 2010) to explore the spatial variation of the climate-cholera relationships.

4.3.5 Objective 5: Reflect on the findings from this study using a climate and development ethics perspective in order to better formulate recommendations

Objective 5 Approach

In this objective, I wrote a reflective statement that draws on the ethics of climate and development literatures to address the moral questions that underlie my research questions and research process. In this coda, my goal was to use the methodological contributions of the study presented as a starting point for suggestions about approaches to ethical issues in interdisciplinary research and policy around climate and health, and broader societal issues pertaining to global climate change and global development. I refer to these ethical challenges as 'ethical geographies'. I addressed challenges pertinent not only to cholera and development, but climate and development as well. The notions of "climate ethics" and "climate justice" have been developing since the 1990s due to growing concerns about extreme weather and a changing climate. A particular concern for public health practitioners is that impacts will be disproportionately felt in developing countries, where currently, large segments of their populations are deprived of basic human needs. This statement links these ethical concerns with those in global development. In addition questions were considered that arose during the research process, such as trade-offs and "useability" of the research (Glantz 2001a: 7). Trade-off refers to the opportunity costs incurred by the collaborators and others that have assisted the researcher in this project. "Useability" refers to the potential benefits of the research to society that includes its application (Glantz 2001a: 7) and credibility and communicability of the conclusions to society (Brown and Doberneck 2009). Specifically I referred to literatures on climate ethics and justice (Jamieson and Glantz 2000; Glantz 2003; Jamieson 2010), ethics of global development (Gasper 2004; Crocker 2008), and the capability approach (Nussbaum 2000; Sen 1999; 2009; Esquith and Gifford 2010) to address the ethical geographies in my coda. This statement was used to inform the recommendations that I present in the concluding chapter of this dissertation research.

CHAPTER 5: RESULTS

In this chapter, I present key results for Objectives 2, 3, and 4. First I compare ENSO events by Niño region. I then discuss the wavelet analysis, which estimated the temporal associations between climate parameters and cholera cases in the subregion of Piura from 1991 to 2001. Following the temporal analysis, I present the SVI by district in Piura and the analysis estimating the spatial associations between (a) SVI and cholera incidence (1997-98) and (b) climate parameters and cholera incidence in 1998.

5.1 ENSO Events by Niño Index (Objective 2)

Figures 5.1 and **5.2** are time plots of the Niño 3.4 and 1+2 region indices. An ENSO event was defined as a period during which the values of the indices (3-month running means for SSTA) in a given Niño region exceeded a threshold of +/-0.5 (°C) for at least 5 consecutive months.

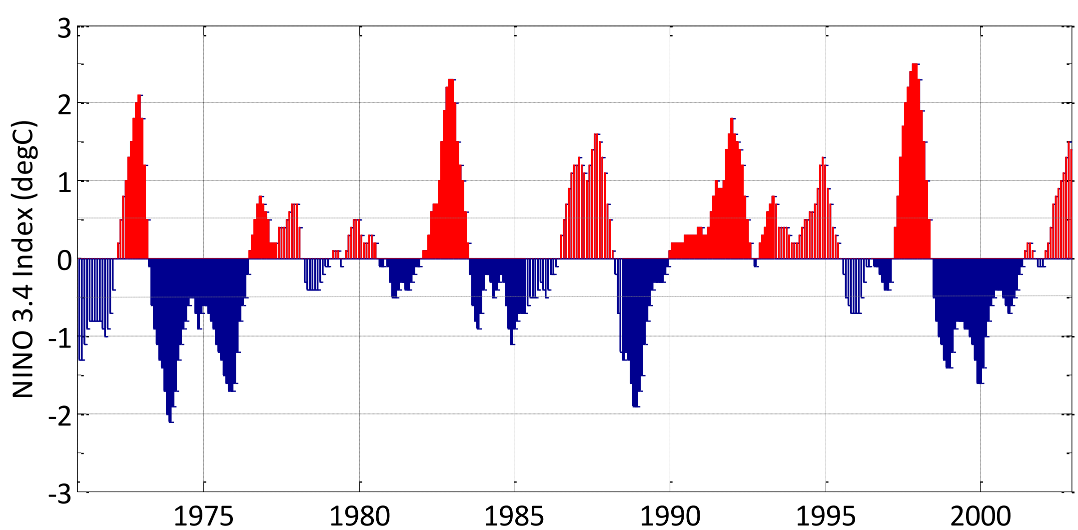


Figure 5.1 Niño 3.4 Index from 1971 to 2001 at ±0.5 (°C) threshold (gray dotted lines).

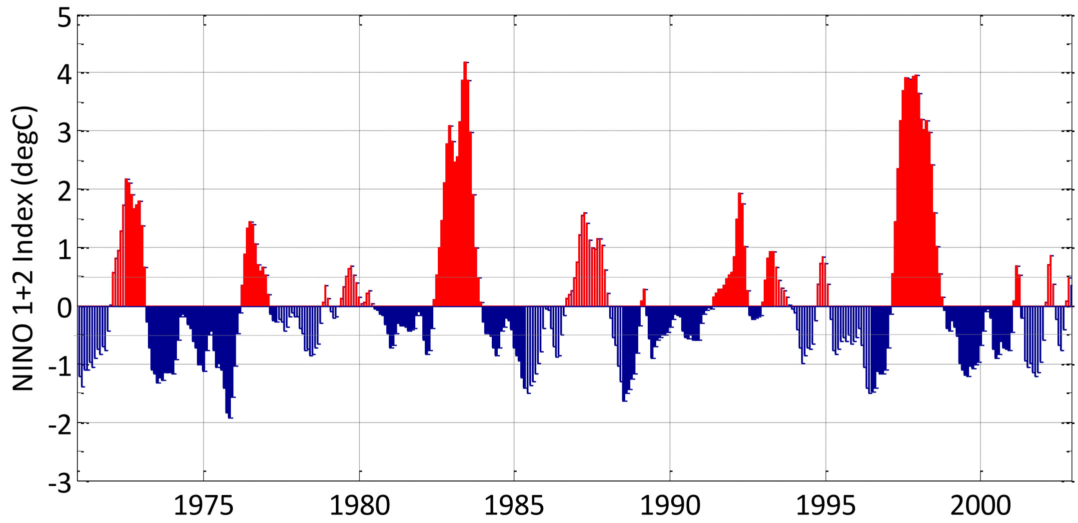


Figure 5.2 Niño 1+2 Index from 1971 to 2001 at ±0.5 (°C) threshold (gray dotted lines).

Tables 5.1 and **5.2** compare El Niño (red) and La Niña (blue) events according to the Niño 3.4 and 1+2 Indices for 1990 to 2001. The 2 regions illustrate different Niño signature patterns. For the entire period, 39 months were assigned to El Niño and 36 months were assigned to La Niña in the Niño 3.4 region. This suggests that ENSO events were in mode 52.0% (75 of 144 months) of the time in the central equatorial Pacific Ocean. This comprises of 3 El Niños and 3 La Niñas. On the eastern end of the equatorial Pacific Ocean, the Niño 1+2 region shows that La Niñas appear to be the dominant mode. Fifty-nine months were assigned to La Niña, while only 27 months were El Niño. In contrast to the Niño 3.4 region, that consisted of 2 El Niños and 7 La Niñas. Here, an El Niño or La Niña event was underway 60.0% (86 of 144 months) of the time.

Table 5.1 Comparison of El Niño (red) and La Niña (blue) events according to the Niño 3.4 Index from 1990 to 2001

	J	F	M	A	M	J	J	A	S	O	N	D
1990	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4
1991	0.4	0.3	0.3	0.4	0.6	0.8	1.0	0.9	0.9	1.0	1.4	1.6
1992	1.8	1.6	1.5	1.4	1.2	0.8	0.5	0.2	0.0	-0.1	0.0	0.2
1993	0.3	0.4	0.6	0.7	0.8	0.7	0.4	0.4	0.4	0.4	0.3	0.2
1994	0.2	0.2	0.3	0.4	0.5	0.5	0.6	0.6	0.7	0.9	1.2	1.3
1995	1.2	0.9	0.7	0.4	0.3	0.2	0.0	-0.2	-0.5	-0.6	-0.7	-0.7
1996	-0.7	-0.7	-0.5	-0.3	-0.1	-0.1	0.0	-0.1	-0.1	-0.2	-0.3	-0.4
1997	-0.4	-0.3	0.0	0.4	0.8	1.3	1.7	2.0	2.2	2.4	2.5	2.5
1998	2.3	1.9	1.5	1.0	0.5	0.0	-0.5	-0.8	-1.0	-1.1	-1.3	-1.4
1999	-1.4	-1.2	-0.9	-0.8	-0.8	-0.8	-0.9	-0.9	-1.0	-1.1	-1.3	-1.6
2000	-1.6	-1.4	-1.0	-0.8	-0.6	-0.5	-0.4	-0.4	-0.4	-0.5	-0.6	-0.7
2001	-0.6	-0.5	-0.4	-0.2	-0.1	0.1	0.2	0.2	0.1	0.0	-0.1	-0.1

Table 5.2 Comparison of El Niño (red) and La Niña (blue) events according to the Niño 1+2 Index from 1990 to 2001

	J	F	M	A	M	J	J	A	S	O	N	D
1990	-0.4	-0.2	-0.1	-0.2	-0.2	-0.4	-0.5	-0.6	-0.5	-0.6	-0.6	-0.6
1991	-0.3	-0.1	-0.1	0.0	0.0	0.2	0.2	0.3	0.3	0.4	0.5	0.5
1992	0.6	0.8	1.5	1.9	1.8	1.0	0.3	-0.2	-0.2	-0.2	-0.2	-0.2
1993	0.1	0.4	0.8	0.9	0.9	0.7	0.4	0.3	0.3	0.2	0.0	-0.1
1994	-0.1	-0.4	-0.7	-1.0	-0.9	-0.7	-0.7	-0.7	-0.2	0.4	0.7	0.8
1995	0.7	0.4	-0.2	-0.8	-0.8	-0.7	-0.6	-0.5	-0.6	-0.5	-0.7	-0.6
1996	-0.5	-0.4	-0.7	-1.0	-1.4	-1.5	-1.5	-1.4	-1.1	-1.2	-1.2	-1.1
1997	-0.7	-0.1	0.6	1.5	2.4	3.2	3.7	3.9	3.9	3.9	3.9	4.0
1998	3.6	3.2	3.0	3.2	3.0	2.4	1.6	1.0	0.6	0.2	-0.1	-0.4
1999	-0.4	-0.3	-0.4	-0.5	-1.0	-1.1	-1.2	-1.2	-1.0	-1.1	-1.0	-1.0
2000	-0.7	-0.4	-0.1	-0.1	-0.2	-0.7	-0.9	-0.8	-0.6	-0.7	-0.7	-0.8
2001	-0.5	0.1	0.7	0.5	-0.2	-0.9	-1.0	-1.0	-1.1	-1.2	-1.1	-1.0

Tables 5.3 and **5.4** display the timing of ENSO events with the duration of months per ENSO event from 1990 to 2001. From 1990 to 1995 there is a marked contrast between the two Niño Indices. The difference in the number of El Niño/ La Niña months and their timing is notable. There were a total of 26 El Niño months and 4

months assigned to La Niña in the Niño 3.4 region. The first El Niño began in May 1991 and lasted until July 1992. Another event took place from May 1994 to March 1995. One La Niña event was qualified from September 1995 into the summer season of 1996. In contrast, the Niño 1+2 region was assigned 8 months as El Niño and 21 months as La Niña. The only El Niño event in this region began in November 1991 and ended June 1992. A La Niña preceded this warm event beginning in July 1990 and lasted 6 months. The next La Niña events qualified in March 1994 for 6 months and April 1995 for 9 month.

Table 5.3 Niño 3.4 Index: Timing of El Niño and La Niña events from 1990 to 2001

El Niños				
Year	Begin	Year	End	Duration (months)
1991	May	1992	Jul	15
1994	May	1995	Mar	11
1997	May	1998	May	13
La Niñas				
Year	Begin	Year	End	Duration (months)
1995	Sep	1996	Mar	7
1998	Jul	2000	Jun	24
2000	Oct	2001	Feb	5

Table 5.4 Niño 1+2 Index: Timing of El Niño and La Niña events from 1990 to 2001

El Niños				
Year	Begin	Year	End	Duration (months)
1991	Nov	1992	Jun	8
1997	Mar	1998	Sep	19
La Niñas				
Year	Begin	Year	End	Duration (months)
1990	Jul	1990	Dec	6
1994	Mar	1994	Aug	6
1995	Apr	1996	Jan	10
1996	Mar	1997	Jan	11
1999	Apr	2000	Jan	10
2000	Jun	2001	Jan	8
2001	Jun	2002	Jan	8

Compared to the first half of the time period, the two Niño indices show fewer differences in El Niño/La Niña patterns from 1996 to 2001. Except for 1996 during which the Niño 3.4 region contrasts the Niño 1+2 region by the number of La Niña months (e.g., 3 versus 11), the subsequent years show both regions follow similar dominant ENSO modes including the extreme El Niño in 1997-98 followed by several La Niña months until 2001. In the Niño 3.4 region an El Niño began in May 1997 lasting 13 months, while the Niño 1+2 region qualifies El Niño earlier (March) and lasts longer (19 months). In June 1998 there is an abrupt switch of modes from warm to cold in the Niño 3.4 region. In the following month a La Niña qualified and persisted for 2 years (ending June 2000). Another La Niña qualified in October 2000 and ended February 2001. In the Niño 1+2 region there is a neutral period of 6 months before a 10-month La Niña begins in April 1999. This episode was followed by two La Niñas in June 2000 and June 2001. These tables demonstrate the need to clarify the definition of ENSO in climate and health studies.

5.2 Cholera Cases by Niño Index and ENSO Event (Objective 2)

Tables 5.5 and **5.6** show a comparison of ENSO months and cholera cases. When comparing ENSO events/periods by index with the occurrence of cholera in Piura by month, an interesting observation is revealed. According to both Niño indices, cholera was more likely to occur in a neutral month than an ENSO event month. In fact, although Niño 3.4 and 1+2 indices had different ENSO patterns, particularly in the first half of the decade, it can be discerned that cholera emerged during a neutral period preceded by neutral months in the Niño 3.4 region and La Niña months in the Niño 1+2 region. Overall, in the Niño 3.4 region, cholera was reported during 43 neutral months compared to 35 El Niño months and 32 La Niña months. In the Niño 1+2 region, cholera was found in 51 neutral months, while cholera was only reported in 22 El Niño months and 35 La Niña months.

Table 5.5 Comparison of ENSO months and cholera cases using the Niño 3.4 Index from 1990 to 2001

	J	F	M	A	M	J	J	A	S	O	N	D
1990												
1991	81	6804	10591	4360	1181	308	243	40	13	23	0	0
1992	96	230	1582	2838	2202	684	89	41	53	55	62	58
1993	118	65	168	130	99	46	10	33	61	81	162	181
1994	353	143	98	98	43	3	0	4	1	1	3	2
1995	17	20	26	50	61	7	12	7	2	8	3	0
1996	3	10	1	4	0	1	0	2	3	2	1	0
1997	3	4	3	0	0	1	0	2	1	2	5	4
1998	156	1472	1534	559	252	59	44	30	7	9	9	16
1999	1	19	12	12	4	2	2	5	1	1	0	3
2000	1	3	3	7	2	0	0	1	0	2	1	0
2001	1	0	1	7	0	0	0	0	0	0	0	0

Table 5.6 Comparison of ENSO months and cholera cases using the Niño 1+2 Index from 1990 to 2001

	J	F	M	A	M	J	J	A	S	O	N	D
1990												
1991	81	6804	10591	4360	1181	308	243	40	13	23	0	0
1992	96	230	1582	2838	2202	684	89	41	53	55	62	58
1993	118	65	168	130	99	46	10	33	61	81	162	181
1994	353	143	98	98	43	3	0	4	1	1	3	2
1995	17	20	26	50	61	7	12	7	2	8	3	0
1996	3	10	1	4	0	1	0	2	3	2	1	0
1997	3	4	3	0	0	1	0	2	1	2	5	4
1998	156	1472	1534	559	252	59	44	30	7	9	9	16
1999	1	19	12	12	4	2	2	5	1	1	0	3
2000	1	3	3	7	2	0	0	1	0	2	1	0
2001	1	0	1	7	0	0	0	0	0	0	0	0

5.3 Wavelet Transform Analyses (Objective 2)

The aim of this section is to examine the temporal patterns of cholera cases and global and local climate parameters from 1991 to 2001. **Figure 5.3** is cholera case anomaly in Piura from 1991 to 2001. The time plot shows that cholera case anomaly peaked in 1991, 1992, 1994, and throughout 1998. **Figures 5.4** to **5.10** show time plots of global and local climate parameter anomalies from 1975 to 2001. The most notable peaks across most climate series were in 1982-83 and 1997-98 during the strongest El Niños of the twentieth century. The latter El Niño event coincided with a rise of cholera in Piura and throughout Peru. Prior to the 1997-98 El Niño, there were several peaks observed in the first half of the 1990s for all climate parameters. Understanding these temporal patterns using wavelet analysis is the focus of the next sections.

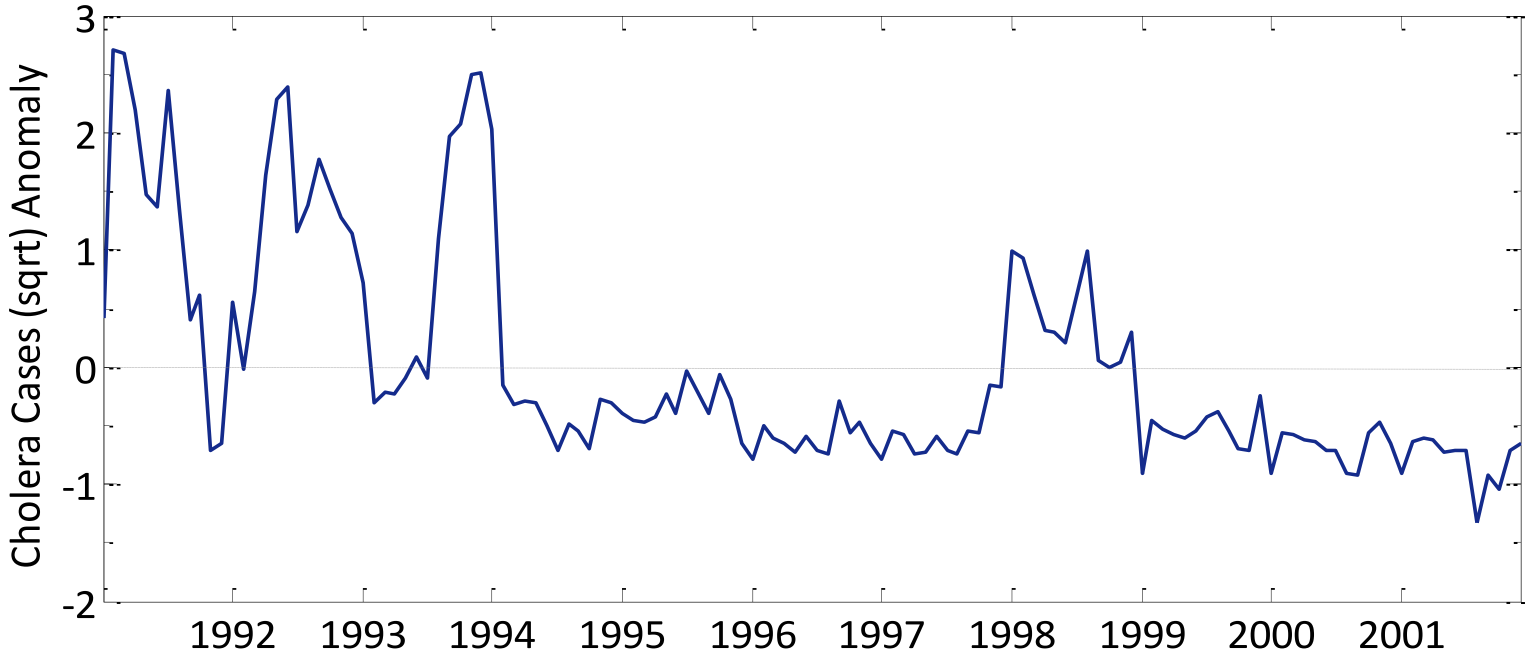


Figure 5.3 Cholera Cases (square-root transformed) Anomaly from 1991 to 2001.

The gray dotted line indicates the mean.

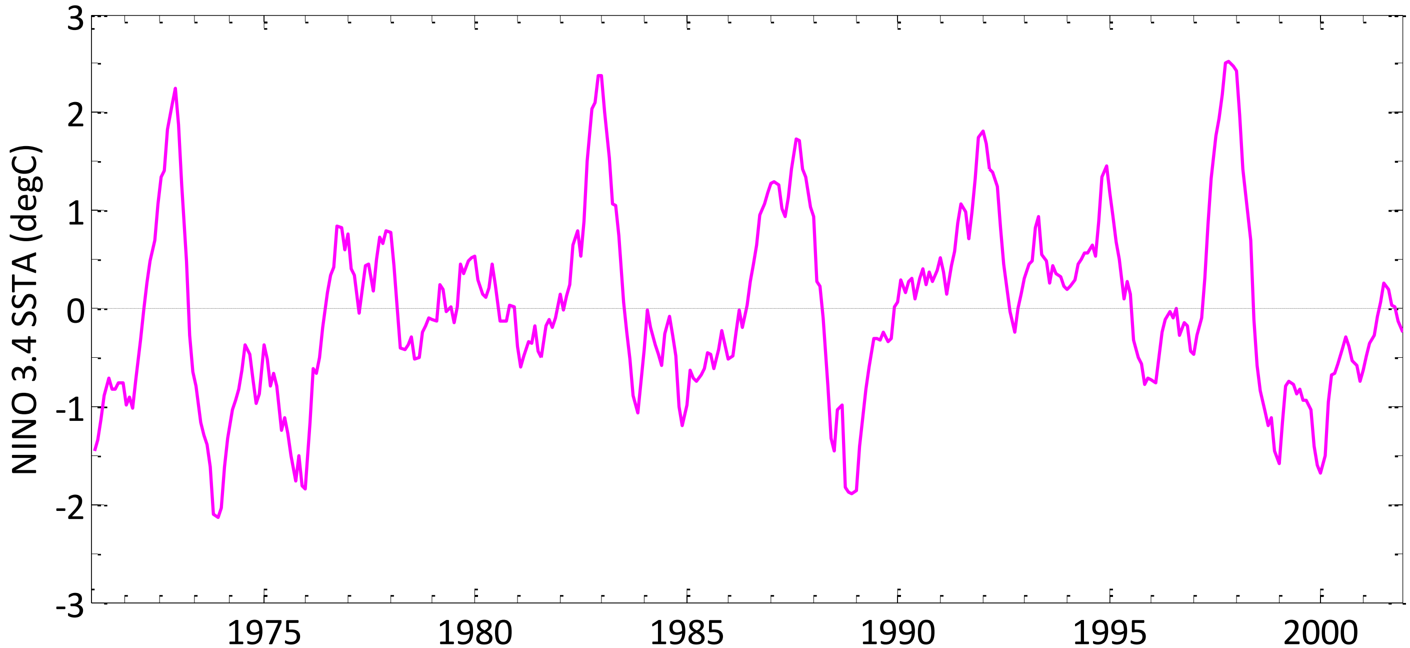


Figure 5.4 Niño 3.4. Sea Surface Temperature Anomaly (SSTA) (°C) from 1971 to 2001.

The gray dotted line indicates the mean.

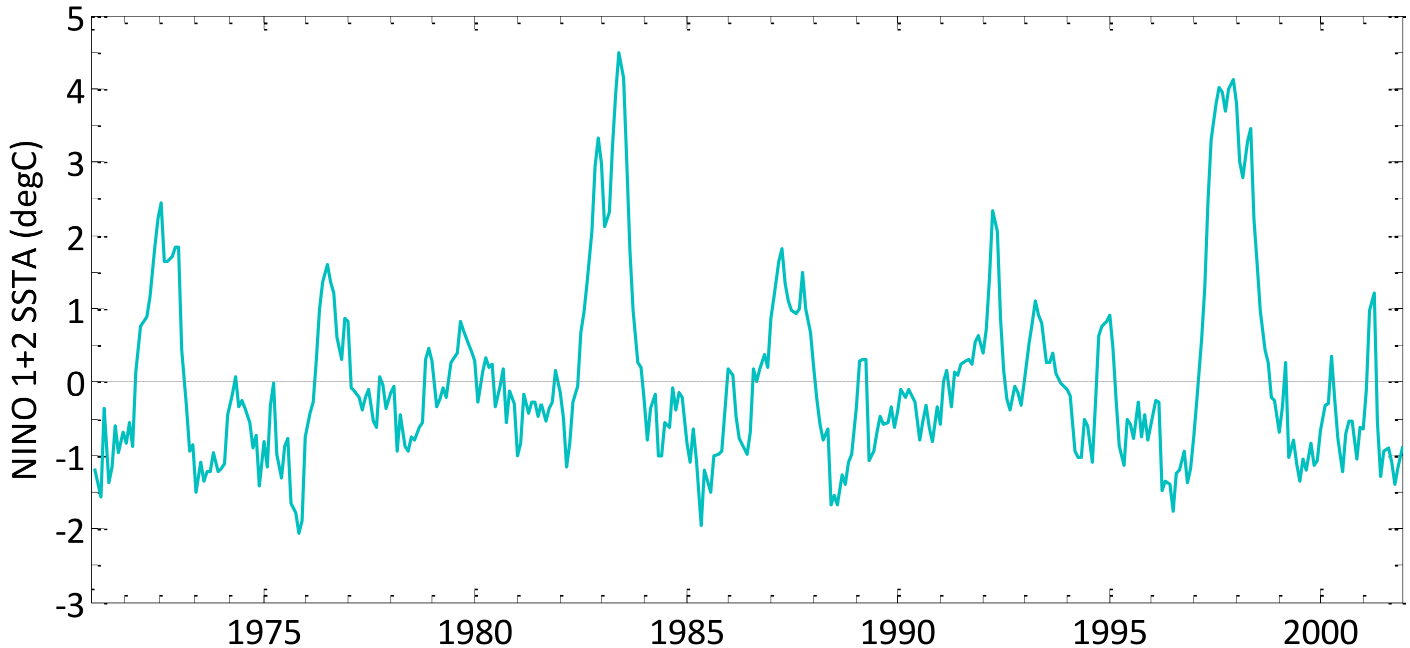


Figure 5.5 Niño 1+2 Sea Surface Temperature Anomaly (SSTA) (°C) from 1971 to-2001.

The gray dotted line indicates the mean.

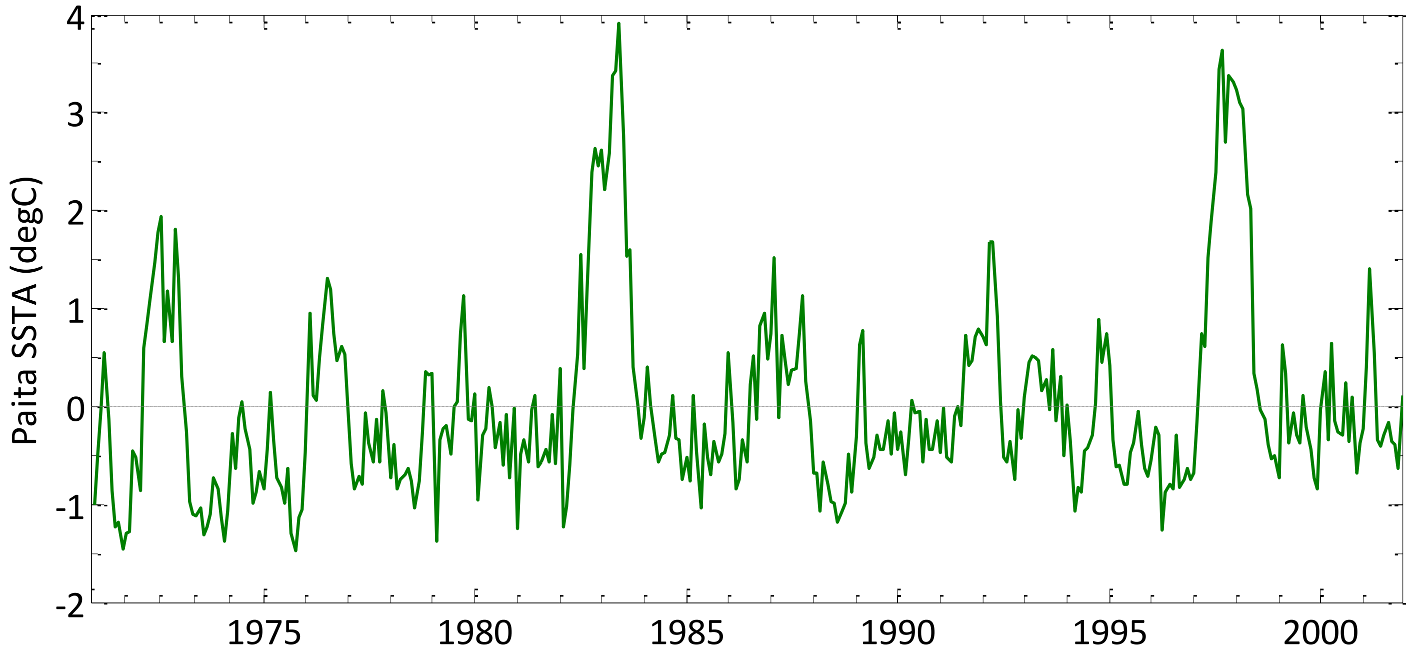


Figure 5.6 Paita Sea Surface Temperature Anomaly (SSTA) (°C) from 1971 to 2001.

The gray dotted line indicates the mean.

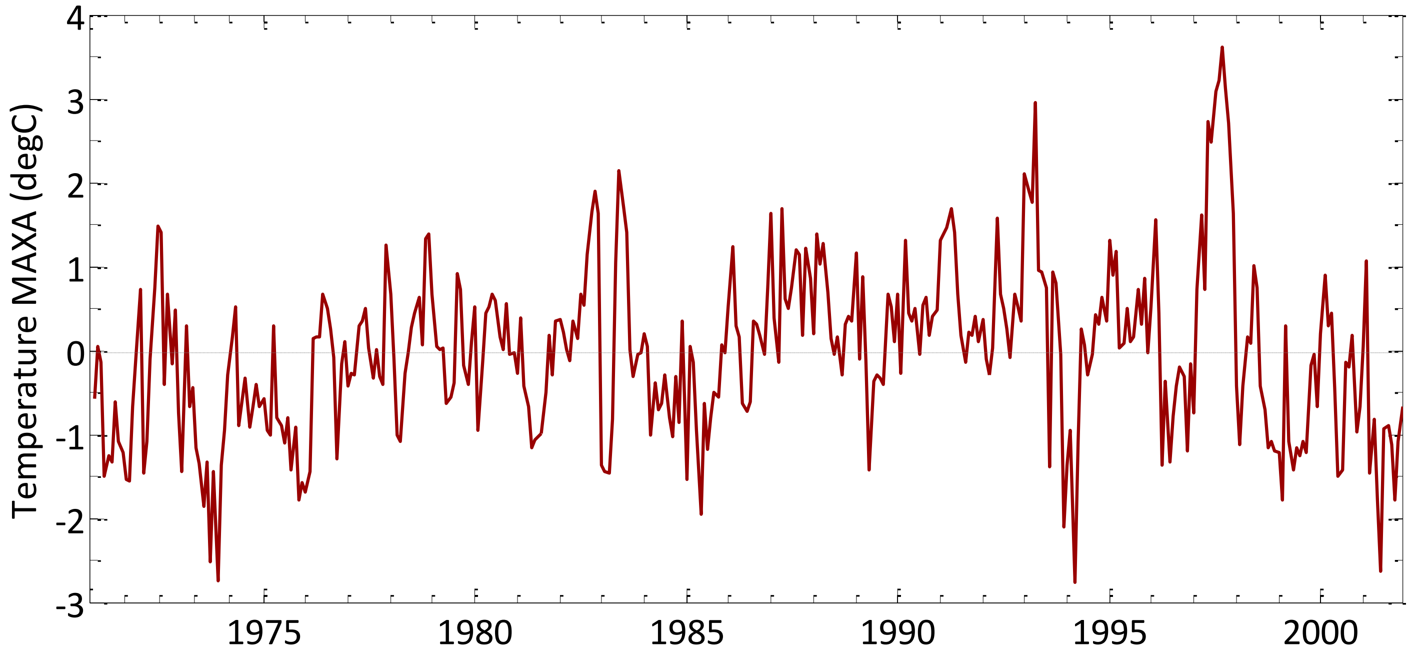


Figure 5.7 Temperature Maximum Anomaly (TMAXA) (°C) in Piura from 1971 to 2001.

The gray dotted line indicates the mean.

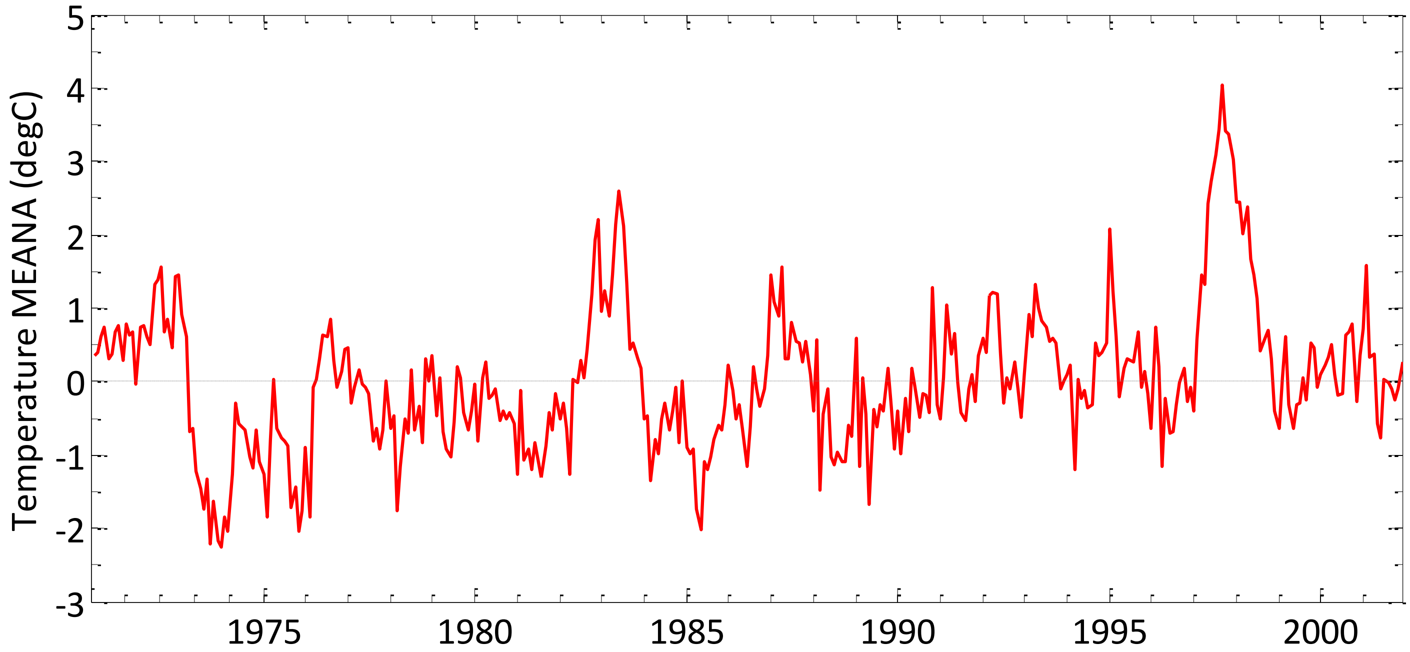


Figure 5.8 Temperature Mean Anomaly (TMEANA) (°C) in Piura from 1971 to 2001.

The gray dotted line indicates the mean.

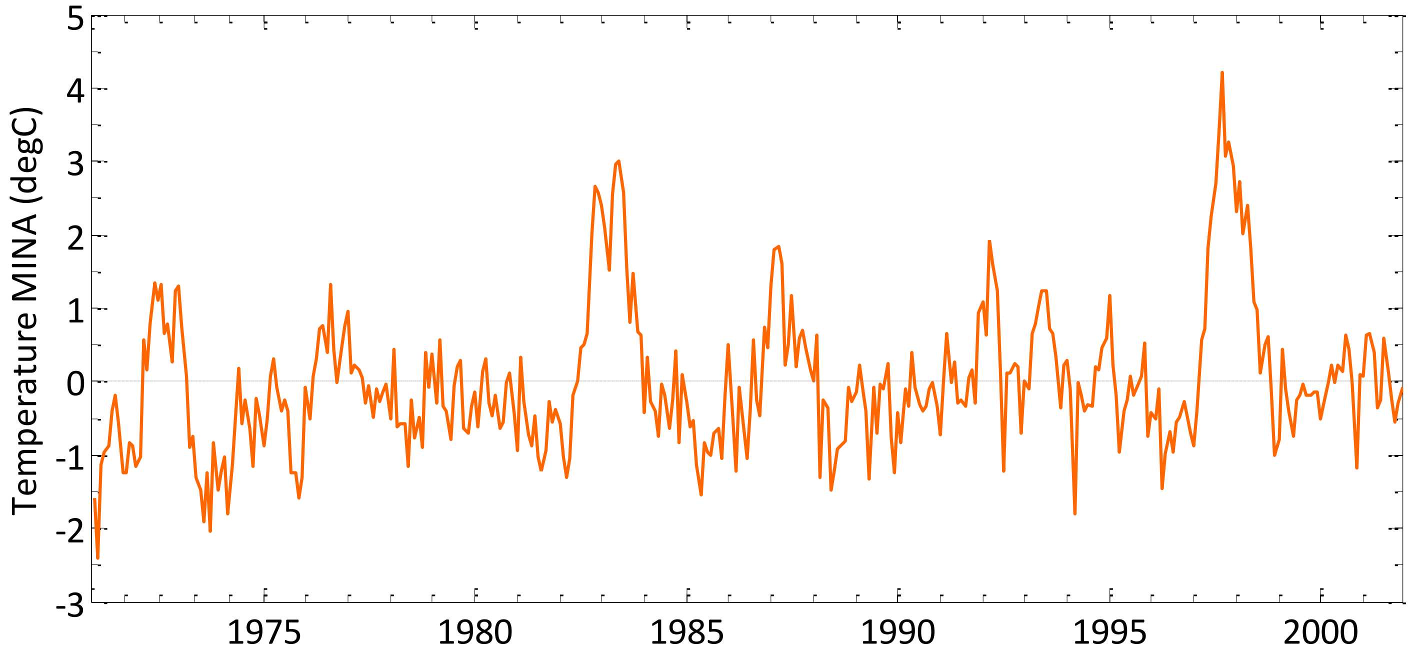


Figure 5.9 Temperature Minimum Anomaly (TMINA) (°C) in Piura from 1971 to 2001.

The gray dotted line indicates the mean.

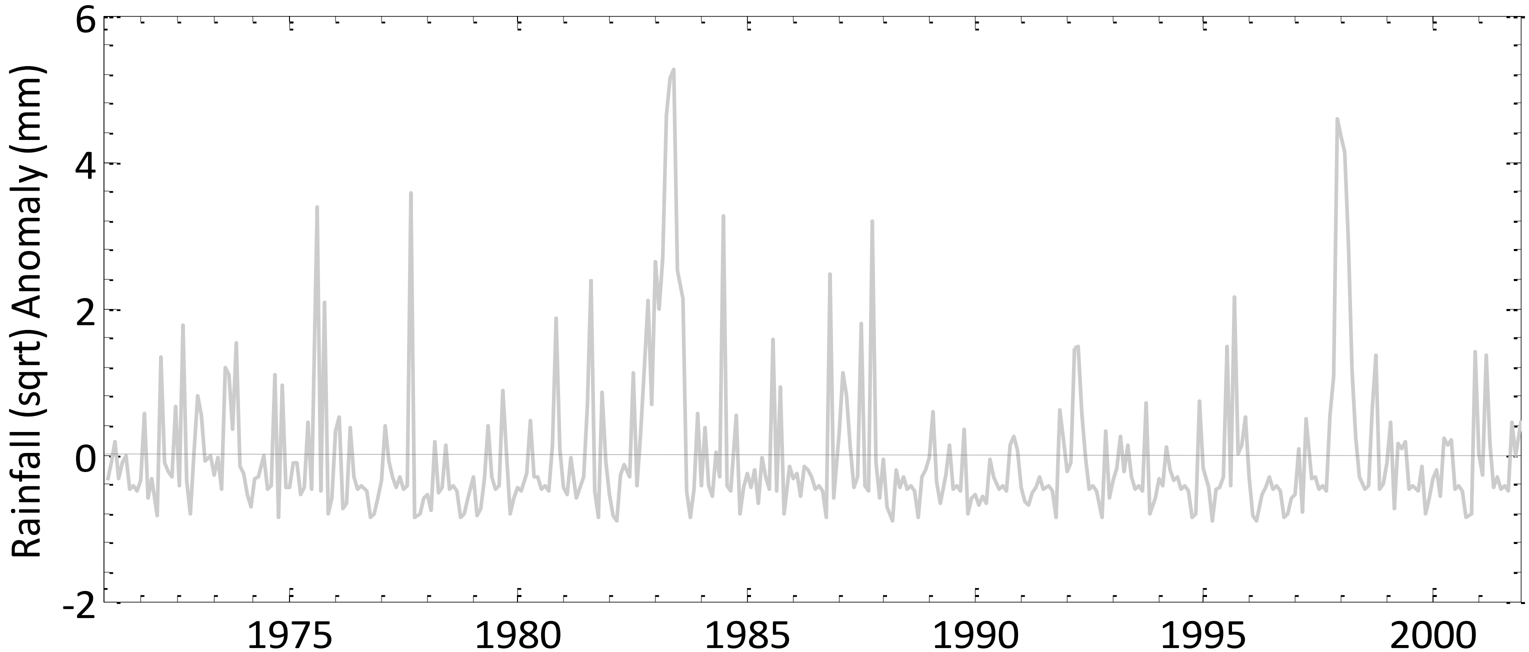


Figure 5.10 Rainfall (square-root transformed) Anomaly (mm) in Piura from 1971 to 2001.

The gray dotted line indicates the mean.

Cholera Cases Anomaly

Figure 5.11 shows the wavelet transform of cholera cases anomaly in Piura. Cholera cases in Piura show high significant power at the 1 – 1.5 yr scale from 1991 until mid-1994. Periodicity at this scale was reliable only after mid-1992 (because data in 1991 were inside the COI). Still it illustrates there was high cholera activity during the initial outbreak. After 1994 until 1998, there was moderate power at a 2 yr scale. Although periodicity was not statistically significant at this time interval, the shape of the spectra is marked during the resurgence of cholera in 1997 to 1998 at low power and at scales less than 1 year. Why cholera activity from 1997 to 1998 does not exhibit high power or is not statistically significant is surprising and interesting given it was the third largest outbreak in Piura. On average the GWS indicated that periodicity of cholera cases during the 1990s was not statistically significant.

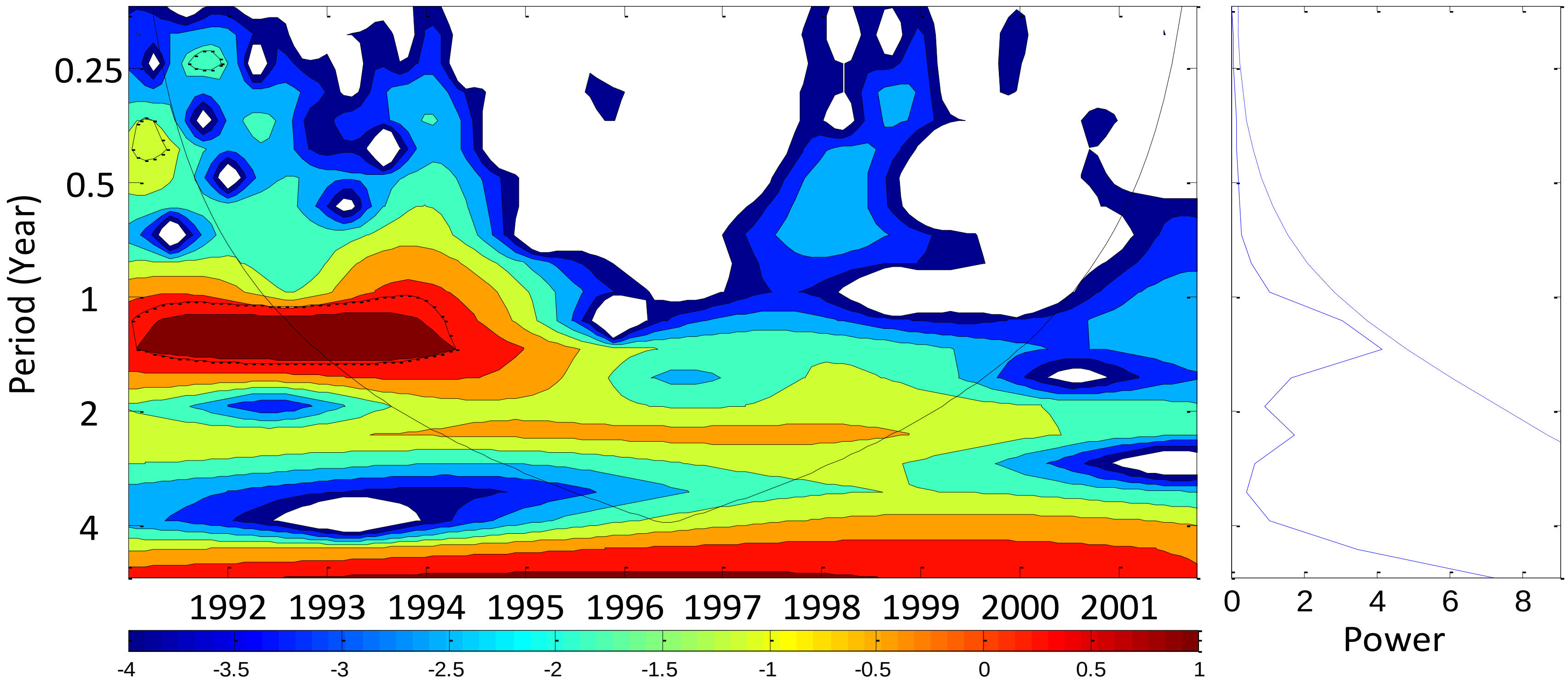


Figure 5.11 Wavelet Transform Analysis of Cholera Cases Anomaly in Piura by month from 1991 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

Sea Surface Temperature Anomaly

The wavelet transform analyses for global and local SSTA are shown in **Figures 5.12** to **5.14.** Before 1991, Niño 3.4 SSTA showed high significant power from 1981 to 1990 at a 4-5 yr scale (**Figure 5.12**). After 1991, although there appears to be high power during the initial cholera outbreak (1991 to 1995), periodicity for Niño 3.4 SSTA was not statistically significant. However, from 1995 to 1998, which includes the resurgence of cholera, there was high significant power for Niño 3.4 SSTA at a 3-4 yr scale. In the Niño 1+2 region, SSTA showed high significant power throughout the 1980s and 1990s at a 4 yr scale (**Figure 5.13**). Periodicity was most notable in 1982-83 and during the resurgence of cholera in 1997-98 at a 2 to 4 yr scale. In Paita, local SSTA showed high significant power before 1986 and from 1995 to 1998 at a 2 to 4 yr scale (**Figure 5.14**). On average the GWS indicated that significant periodicity for Niño 3.4, Niño 1+2, and Paita SSTA was found at scales of 3 to 5 yrs.

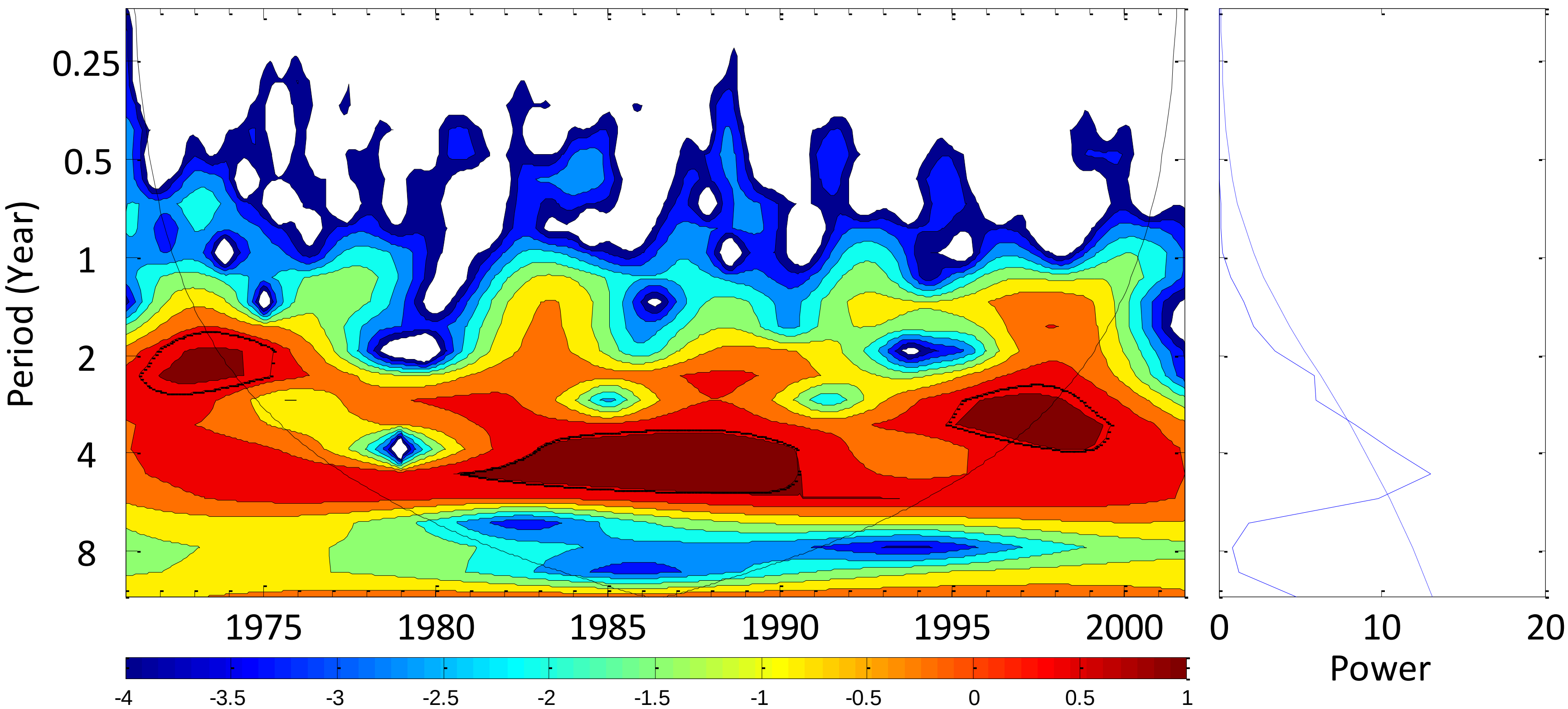


Figure 5.12 Wavelet Transform Analysis of Niño 3.4 Sea Surface Temperature Anomaly (SSTA) (°C) by month from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

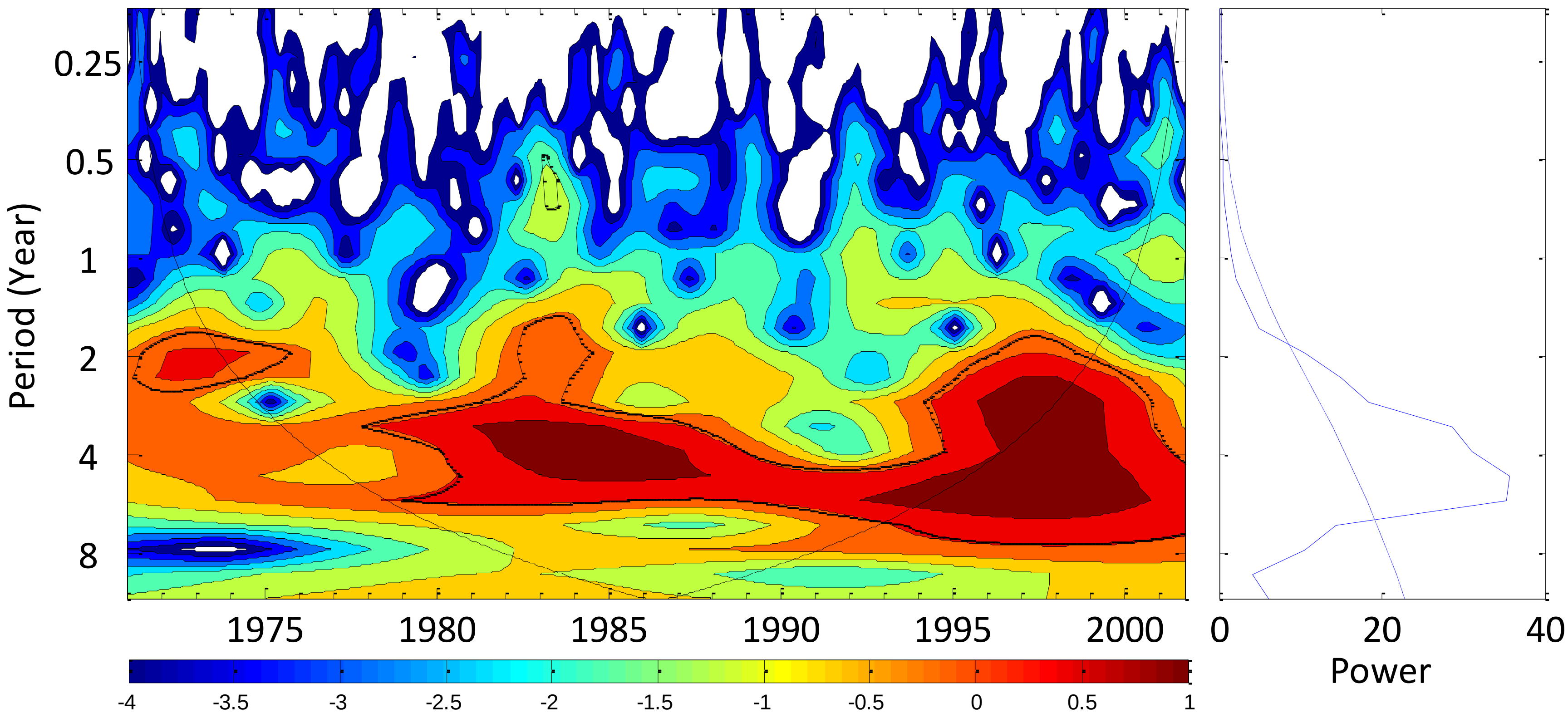


Figure 5.13 Wavelet Transform Analysis of Niño 1+2 Sea Surface Temperature Anomaly (SSTA) (°C) by month from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

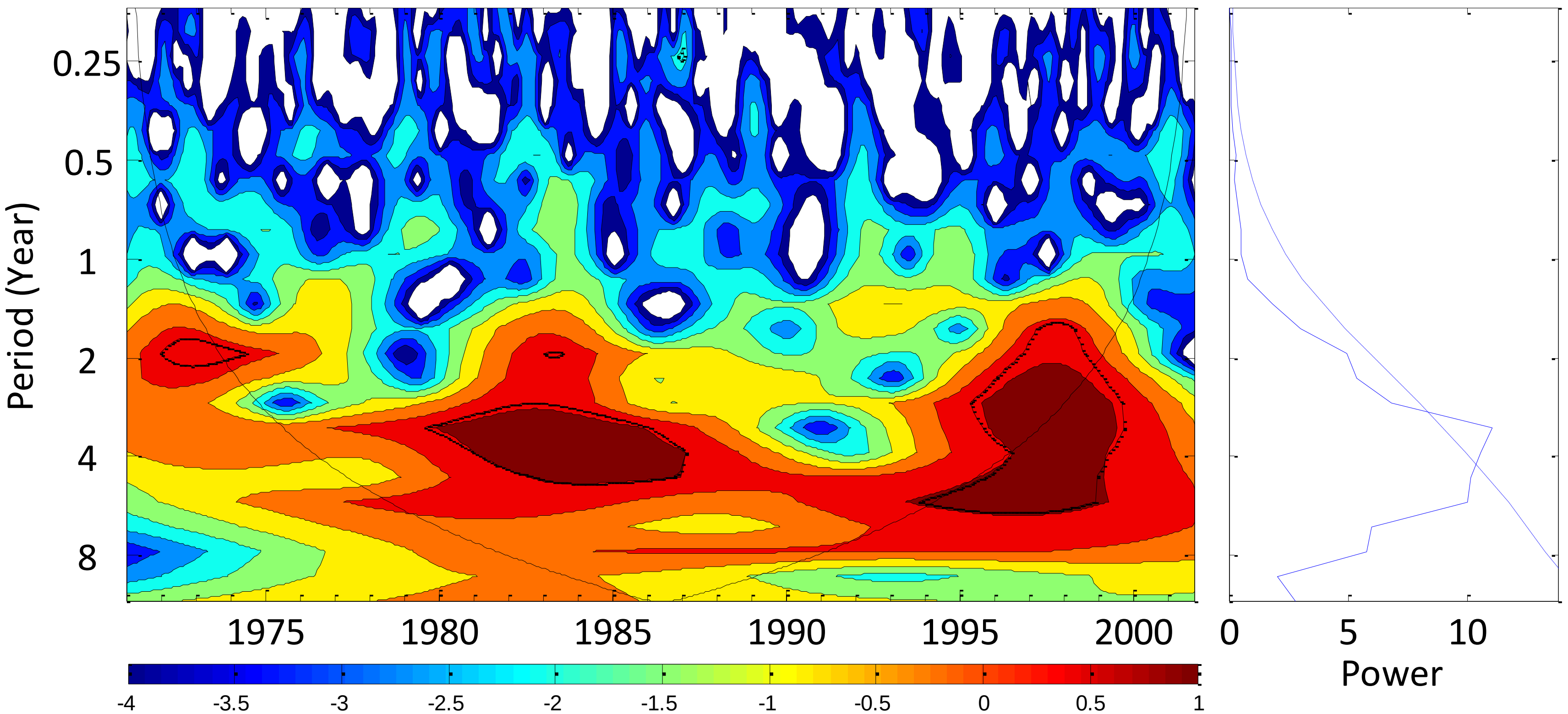


Figure 5.14 Wavelet Transform Analyses of Paita Sea Surface Temperature Anomaly (SSTA) (°C) by month from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

Temperature Anomaly

The wavelet transform analyses of local temperature anomalies are displayed in **Figures 5.15** (TMAXA), **5.16** (TMEANA) and **5.17** (TMINA). Moderate to high significant power was found before the initial cholera outbreak in 1983 at a 1 yr scale for TMAXA and from 1982 to 1987 at a 4 yr scale for TMEANA and TMINA. Significant periodicity for local temperature parameters was not observed during the first half of the 1990s. From 1995 to 1999, however, significant periodicity was found for TMAXA, TMEANA, and TMINA ranging from moderate to high power at scales of 2 to 4 yrs. Significant power was evident among all three parameters during the resurgence of cholera in 1997-98. On average the GWS indicated that significant periodicity for TMAXA was found at a 2 yr scale and at a 4 yr scale for TMEANA and TMINA.

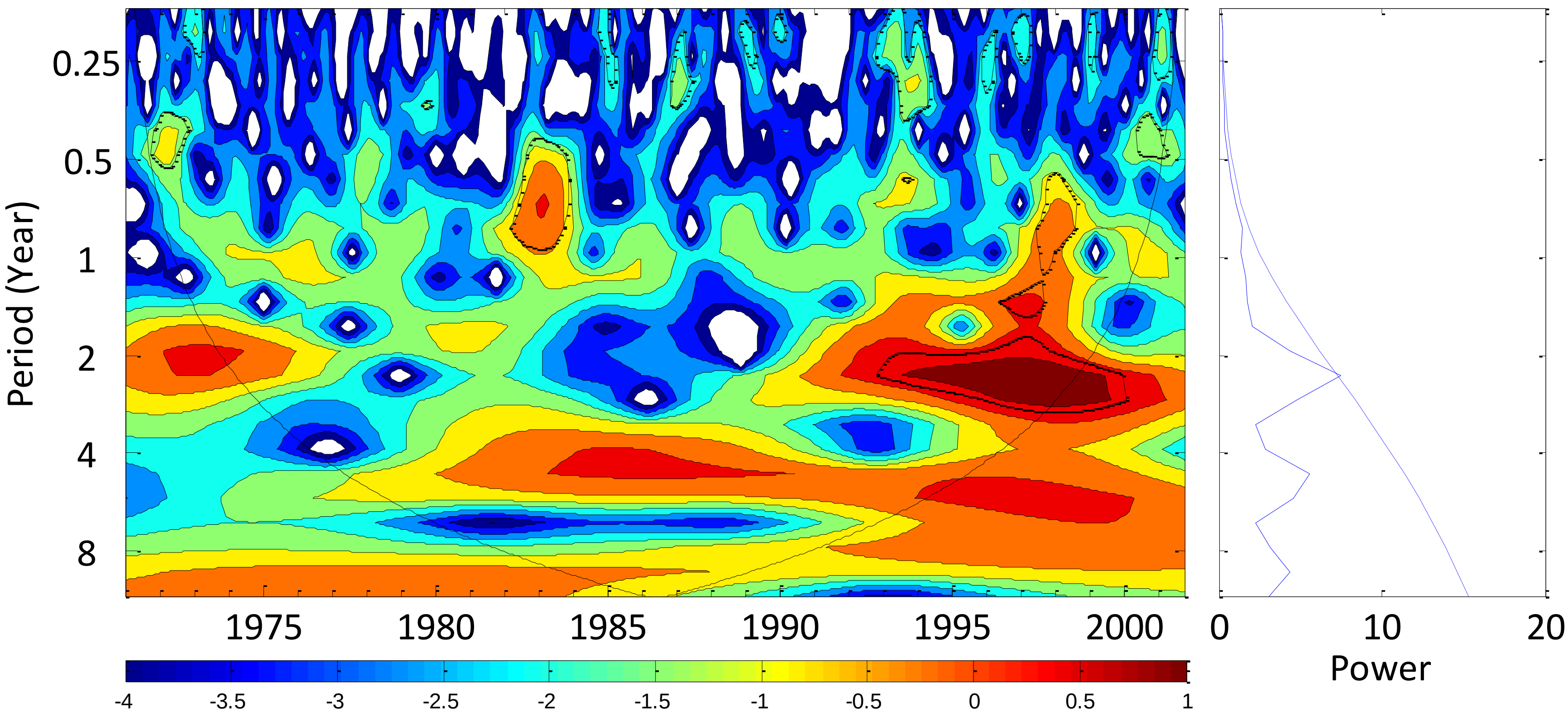


Figure 5.15 Wavelet Transform Analyses of Temperature Maximum Anomaly (TMAXA) (°C) by month in Piura from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

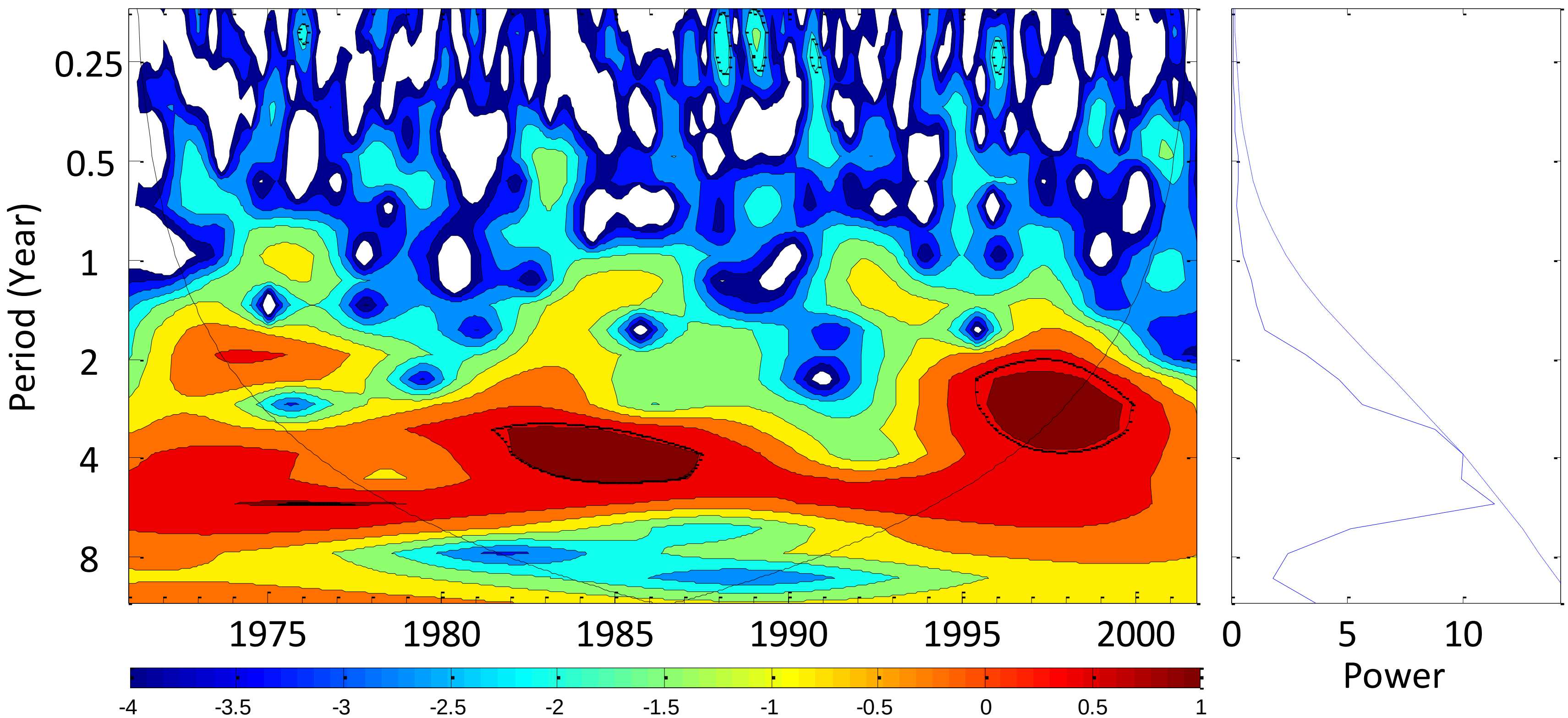


Figure 5.16 Wavelet Transform Analyses of Temperature Mean Anomaly (TMEANA) (°C) by month in Piura from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

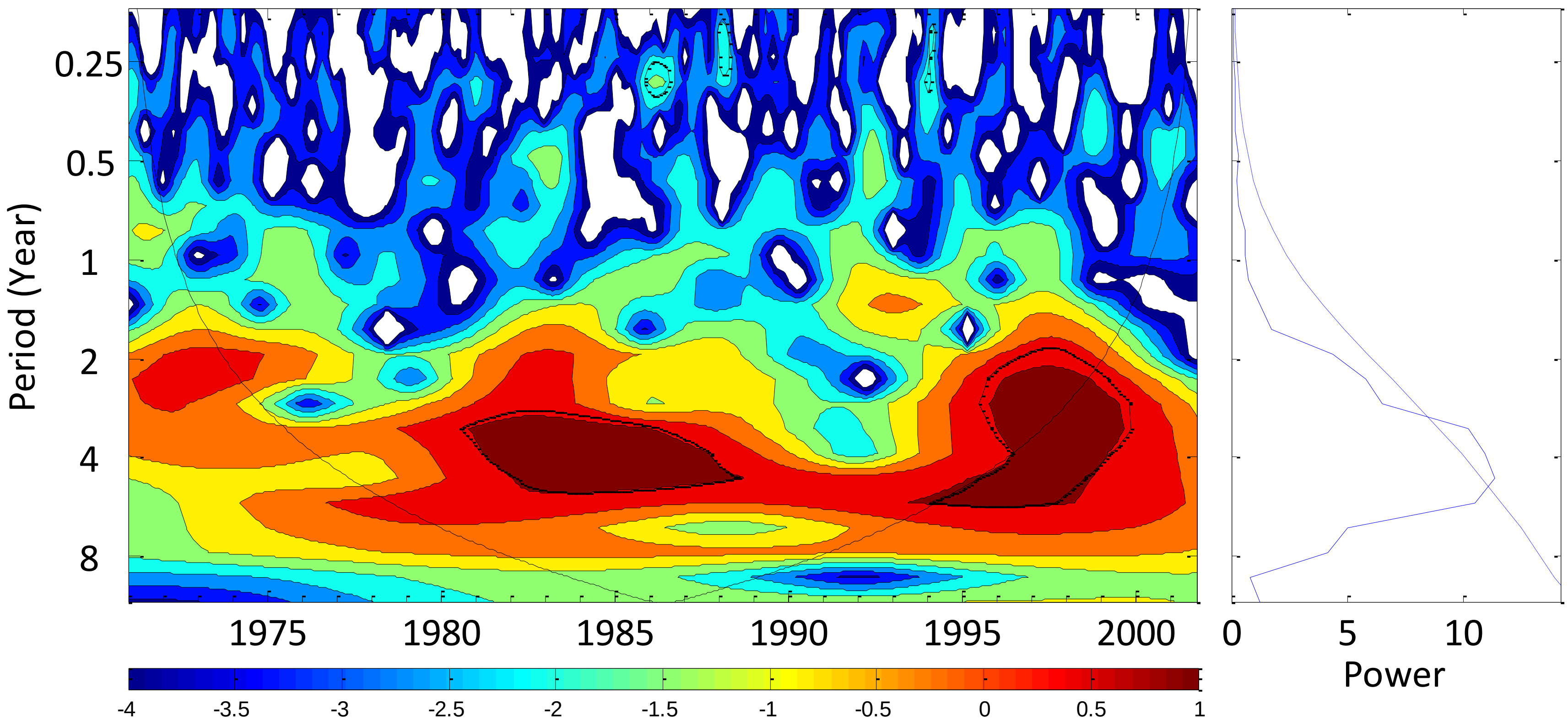


Figure 5.17 Wavelet Transform Analyses of Temperature Minimum Anomaly (TMINA) (°C) by month in Piura from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

Rainfall Anomaly

Figure 5.18 is the wavelet transform of local rainfall anomaly. High significant power was found before the initial cholera outbreak in 1982 to 1984 and during the resurgence of cholera in 1997-98 at multiple scales ranging from .8 to 2 yr scale. There was also high to moderate significant power at several scales less than 1 yr throughout most of the 1980s and in 1996. On average the GWS indicated that significant periodicity for rainfall anomaly was significant at less than 1 yr scale.

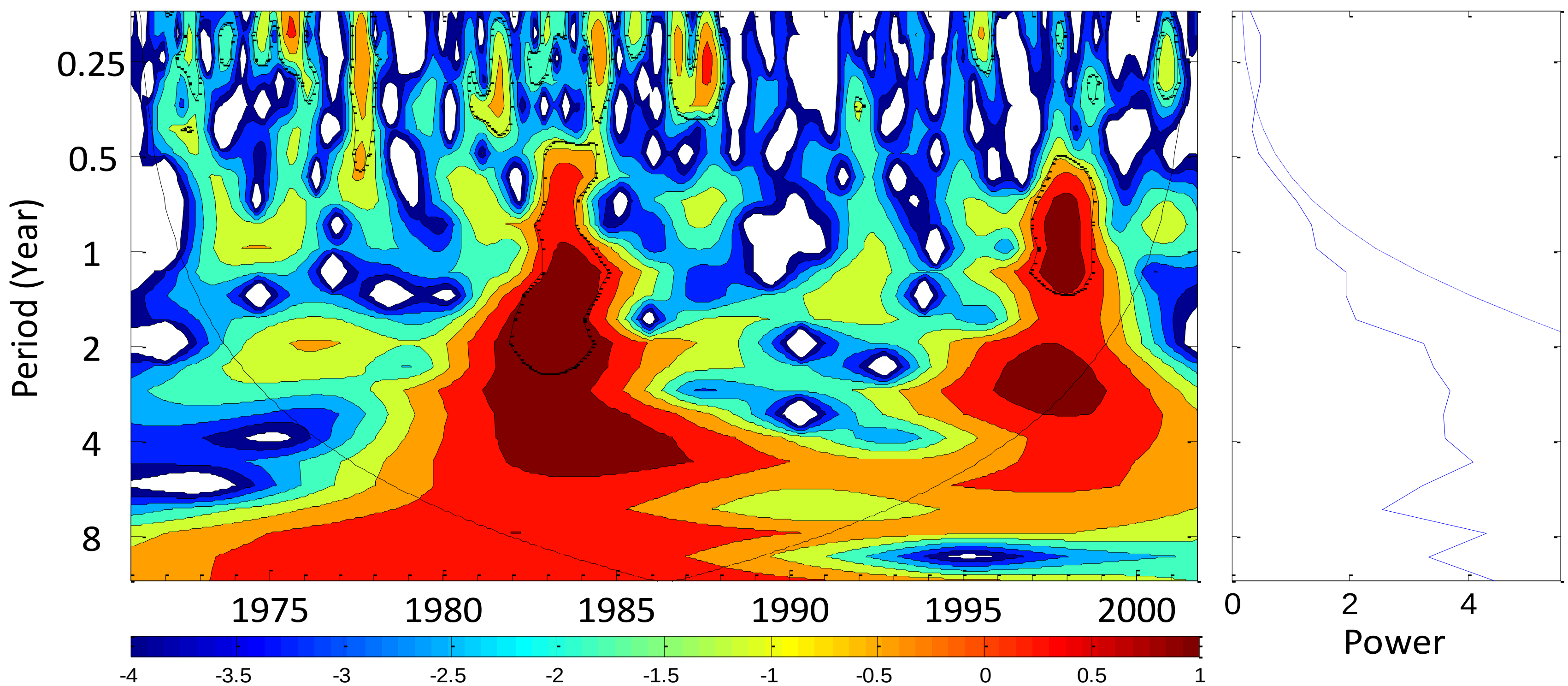


Figure 5.18 Wavelet Transform Analyses of Rainfall Anomaly (mm) by month in Piura from 1971 to 2001.

The left panel represents the wavelet transform by period (scale by year) and across time. Power, indicating periodicity or frequency, increases from blue to red in the wavelet transform, and statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential. The right panel represents the global wavelet power spectrum, an estimate of the average scales and powers; statistical significance (95.0% confidence level) is denoted by the black dashed line across the local wavelet spectra.

5.4 Wavelet Coherence Analyses (Objective 2)

5.4.1 Climate-Cholera Associations

Sea Surface Temperature Anomaly and Cholera Associations

The wavelet coherence between cholera cases anomaly and SSTA were examined first. The analysis shows that moderate to high significant coherence existed between cholera and Niño 3.4 SSTA in mid-1993 and during the resurgence of cholera from 1997 to 1999 at a 1.5 yr scale (**Figure 5.19**). The phase angle suggests that at these time intervals cholera followed Niño 3.4 by angles greater than 90° or approximately more than 6 months.

Figure 5.20 shows the wavelet coherence between cholera cases anomaly and Niño 1+2 SSTA. Moderate significant coherence was found between cholera and Niño 1+2 in 1993-94 at a 1.5 yr scale where SSTA led cholera by 90°. During the resurgence of cholera, Niño 1+2 SSTA led cholera by 2-3 months from 1997 to 1999 at a 2 yr scale. With respect to local sea surface temperature conditions in Piura, moderate significant coherence was found between cholera cases anomaly and Paita SSTA (**Figure 5.21**). Paita SSTA, like Niño 3.4 SSTA, led cholera by more than 6 months in 1993 and 1998 at a scale of 1.5 yr.[19]

[19] The time interval scales were approximately 1993-94 and 1998-99.

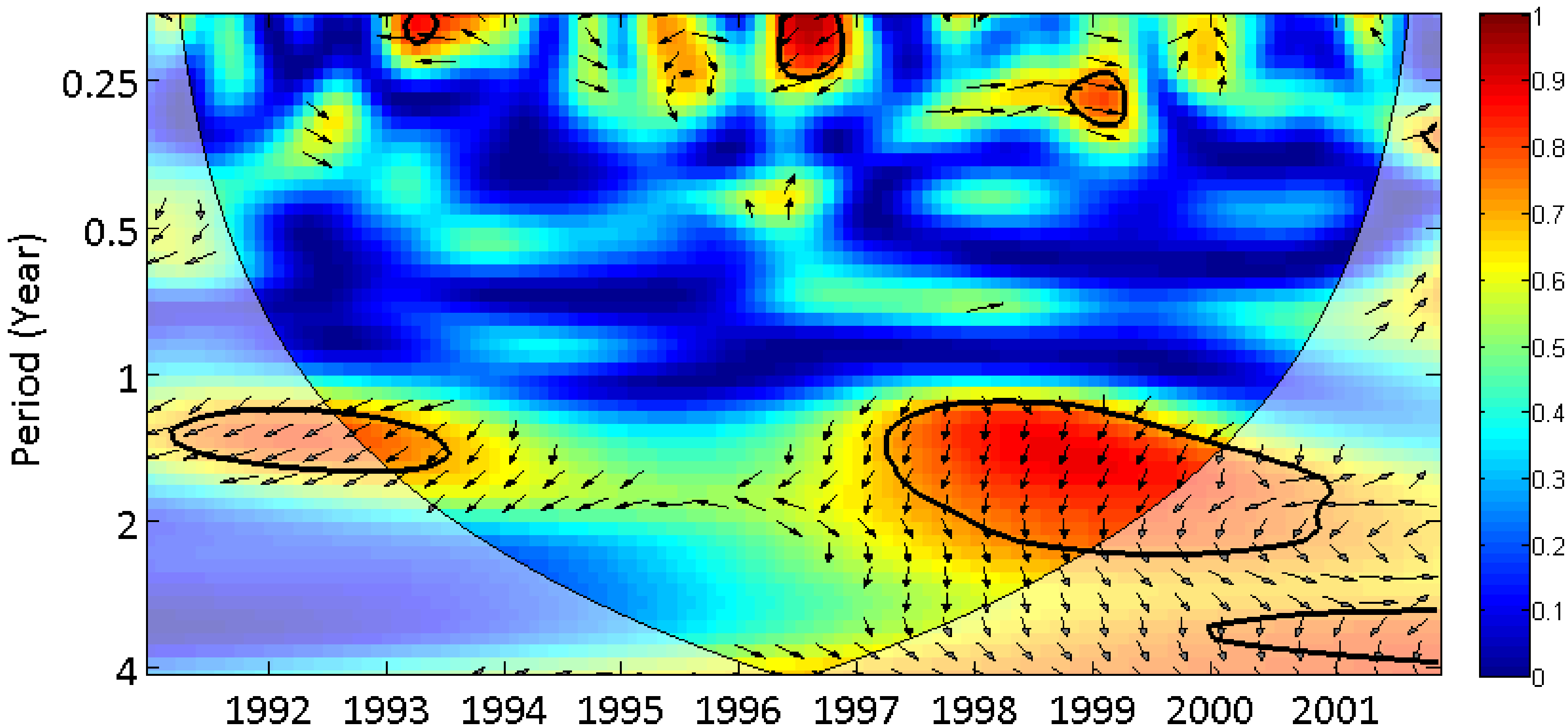


Figure 5.19 Wavelet Coherence of Niño 3.4 Sea Surface Temperature Anomaly (SSTA) and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

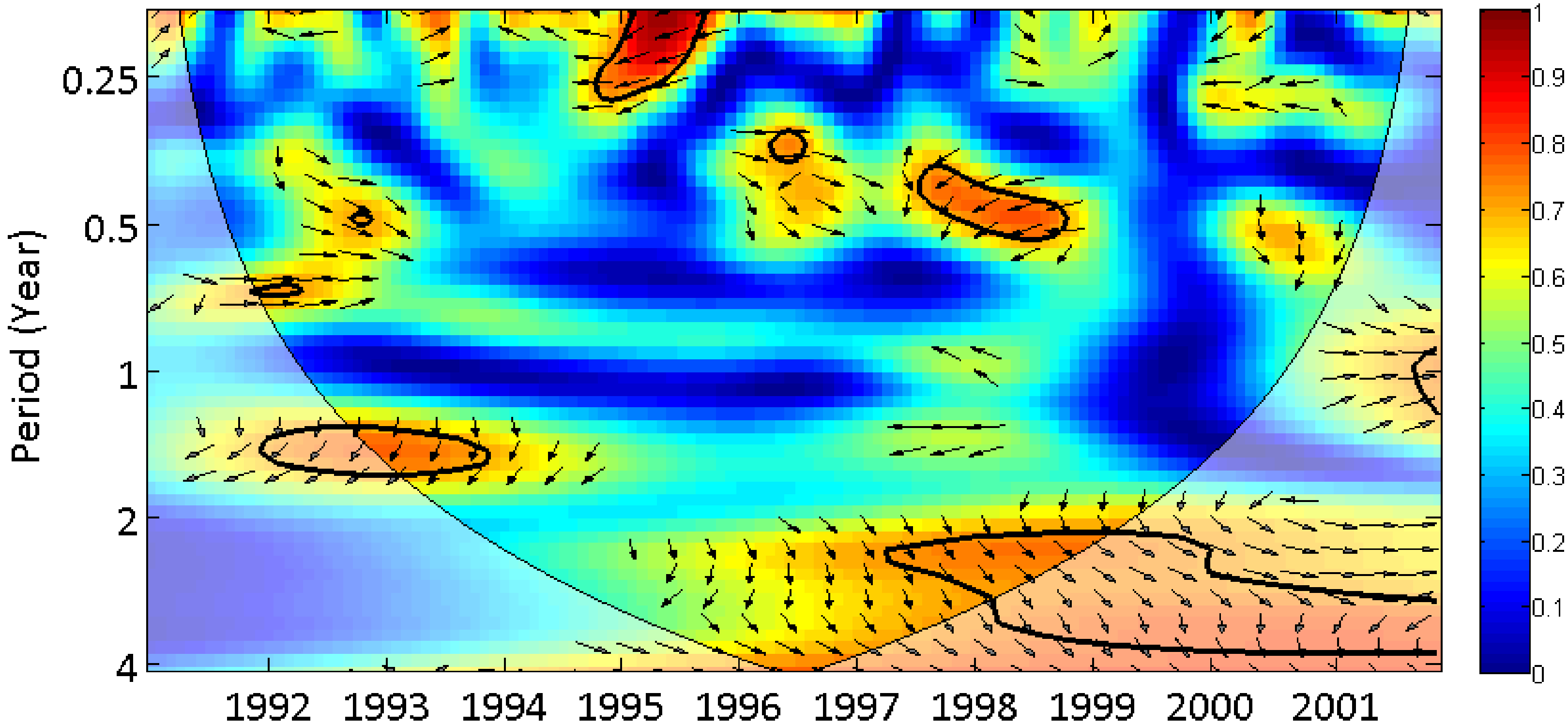


Figure 5.20 Wavelet Coherence of Niño 1+2 Sea Surface Temperature Anomaly (SSTA) and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

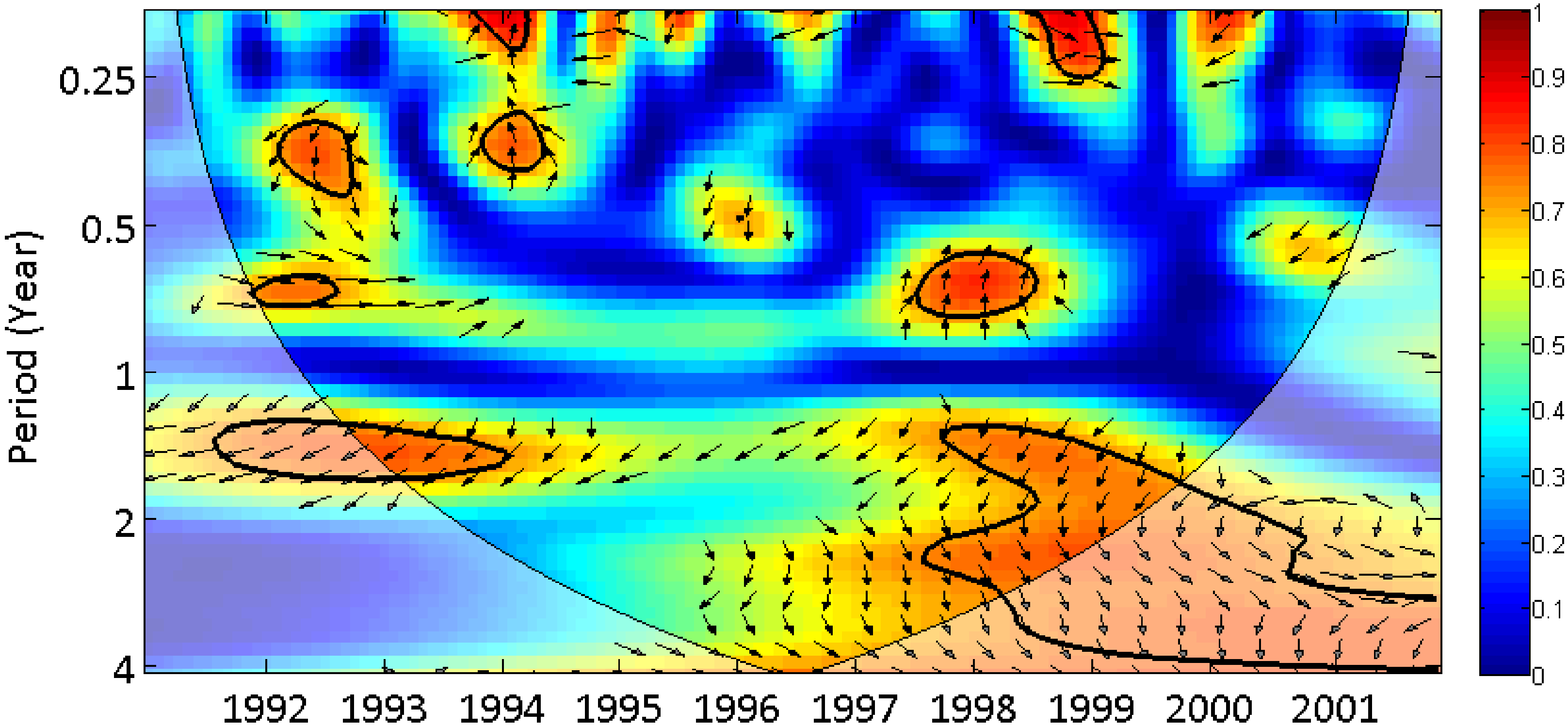


Figure 5.21 Wavelet Coherence of Paita Sea Surface Temperature Anomaly (SSTA) and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

Temperature Anomaly and Cholera Associations

Wavelet coherence analyses between cholera cases anomaly and local temperature anomalies are shown in **Figures 5.22** to **5.24**. High significant coherence was found between cholera and TMAXA throughout the 1990s at the 2-3 yr scale (**Figure 5.22)**. For TMEANA, moderate significant coherence was found with cholera at two time intervals: 1993 to the middle of 1994 at a 1.5 yr scale and from 1995 to 1999 at a 2-3 yr scale (**Figure 5.23)**. Similarly, there was moderate significant coherence between cholera and TMINA from 1993 to 1995 at 1.5 yr scale and from 1996 until 1999 at scales ranging from 1.5 to 2.5 yr scale (**Figure 5.24)**. However, these relationships should be considered with caution because the phase relationships and time lags were unclear in the graphs (Refer to cross-wavelet transform results in section 5.4.2).

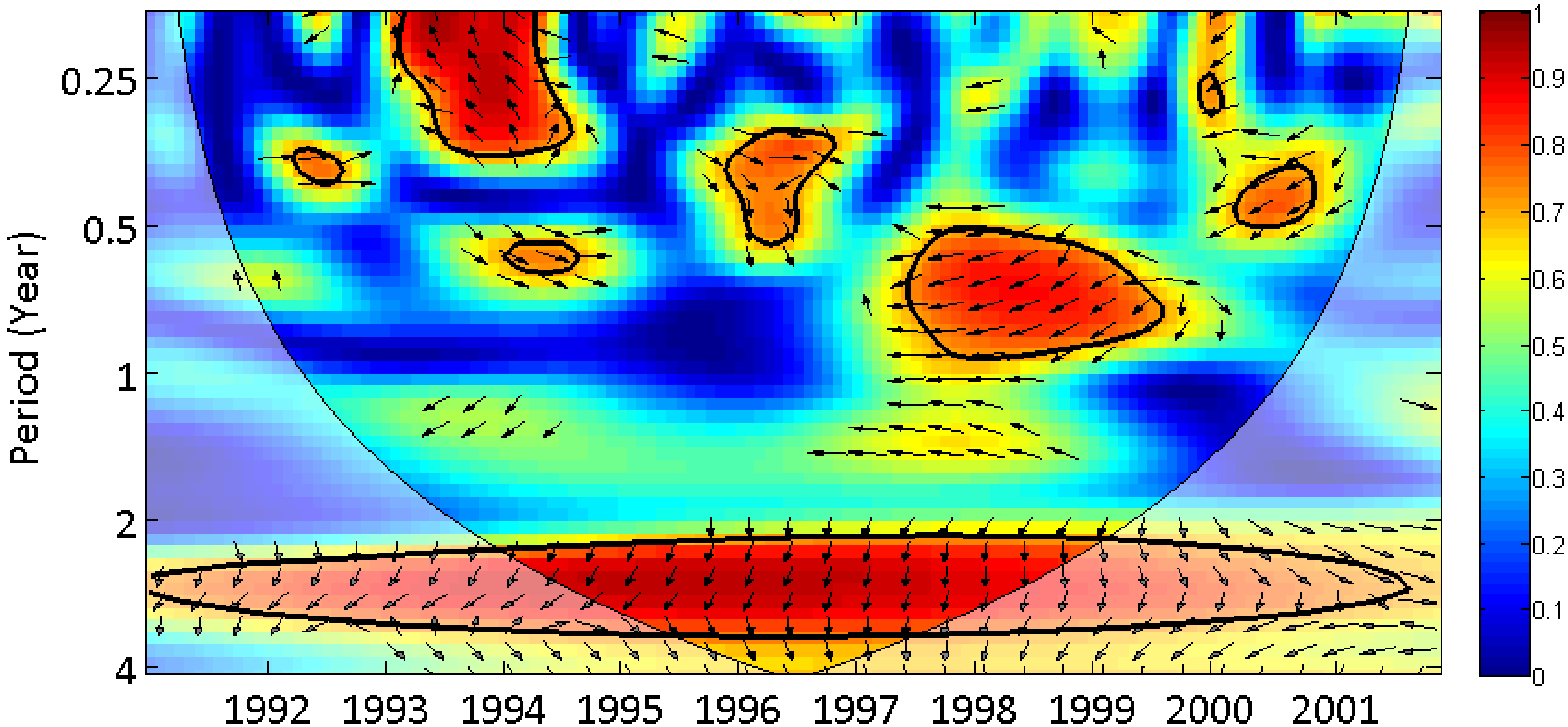


Figure 5.22 Wavelet Coherence of Temperature Maximum Anomaly (TMAXA) and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

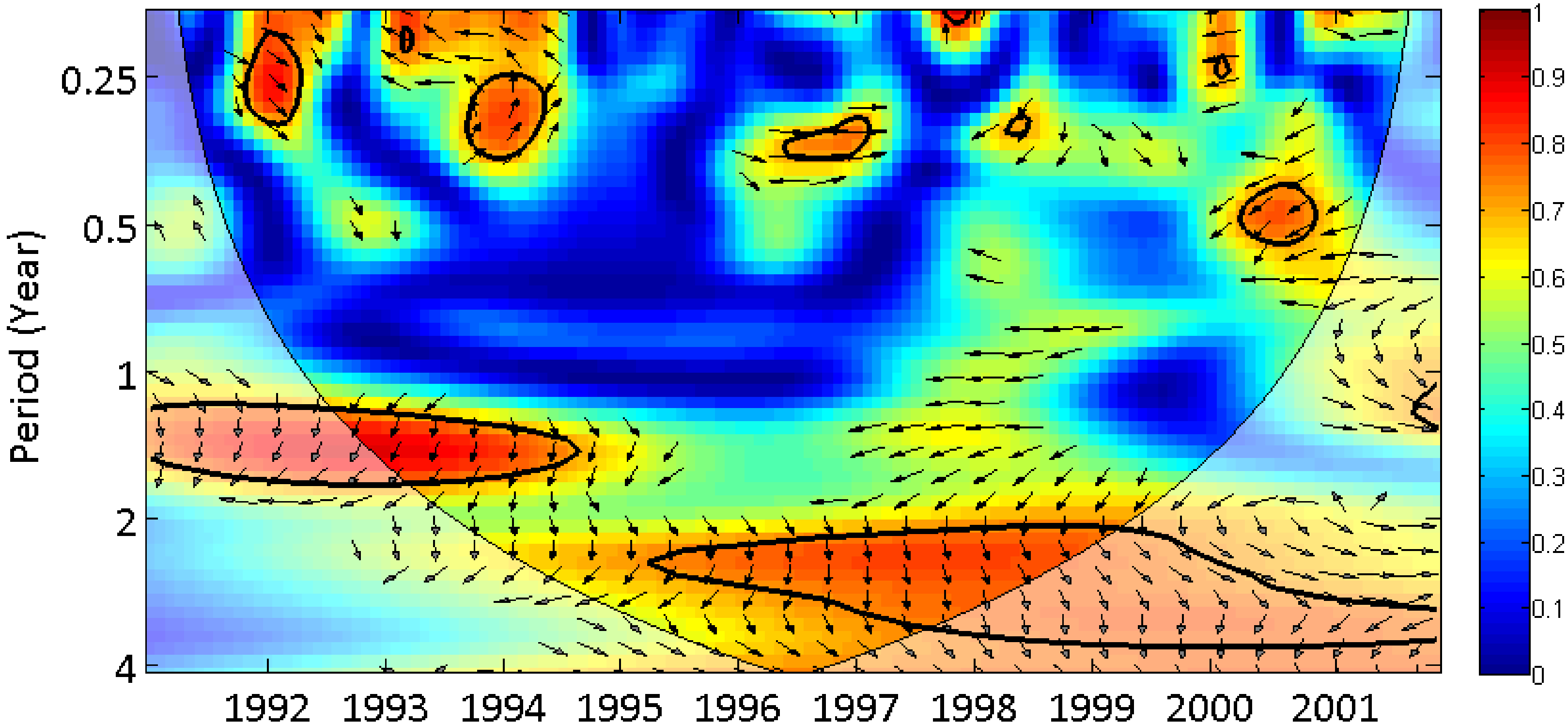


Figure 5.23 Wavelet Coherence of Temperature Mean Anomaly (TMEANA) and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

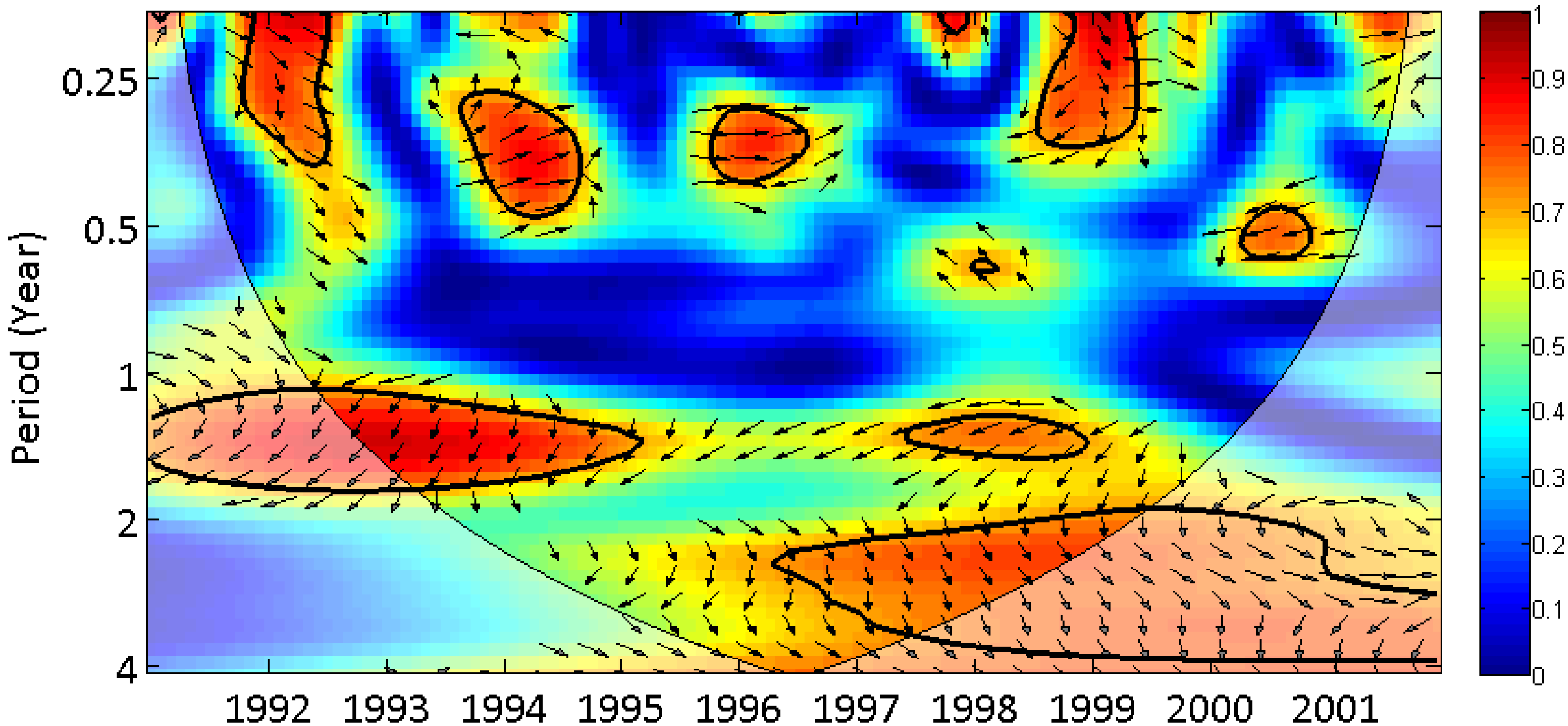


Figure 5.24 Wavelet Coherence of Temperature Minimum Anomaly (TMINA) and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

Rainfall and Cholera Associations

Figure 5.25 is the wavelet coherence between rainfall anomaly and cholera cases anomaly. Moderate to high significant coherence was found during the resurgence of cholera in 1997 until 1999 at multiple scales ranging from 7 months to 2.25 yr. The phase relationship between cholera and rainfall indicated that the phase direction approached in-phase as the scale decreased by month (i.e., lag approached zero as time delay decreased). Rainfall led cholera by approximately zero to one month lag.

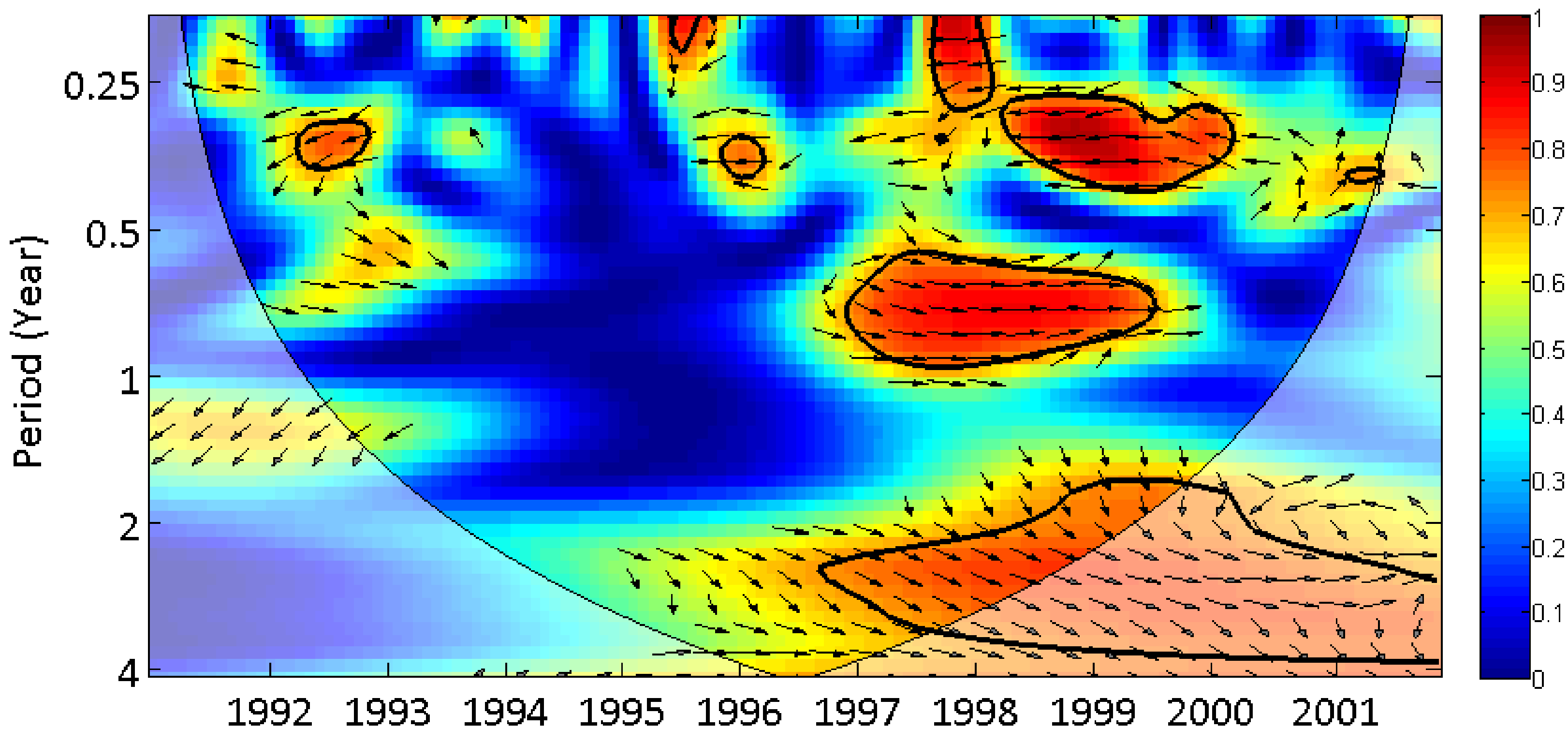


Figure 5.25 Wavelet Coherence of Rainfall Anomaly and Cholera Cases in Piura from 1991 to 2001.

The panel represents the wavelet coherence by period (scale by year). Coherence was estimated from low (blue) to high (red) correlation. The direction (phase) of each coherence and temporal lead/lag (i.e., the phase angle or difference) was indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

5.4.2 Cross-Wavelet Transform: Climate-Cholera

Figures 5.26 to **5.32** show the cross-wavelet transforms of cholera with the global and local climate parameters. In general the cross-wavelet transform analyses indicated that areas with significant coherence at scales greater than 1 yr shared high common power, whereas scales lower than 1 yr shared low common power. It was also found that a strong association could exist between different levels of power (Torrence and Webster 1999). For example, during the resurgence of cholera there was significant high coherence between cholera and rainfall from 1997 to 1999, yet in the cross-wavelet analysis, there was moderate common power. It suggests that correlation in time does not always lead to frequency of occurrence between cholera and climate. Furthermore, the cross-wavelet results revealed that the phase and time relationships between cholera and local temperature (TMAXA, TMEANA and TMINA) were likely coincidental given that the phase arrows in the graphs were inconsistent across the frequency scales where significant coherence was noted (Refer to Grinsted et al. (2004) and associated webpage in References for more on the interpretation of the cross-wavelet).

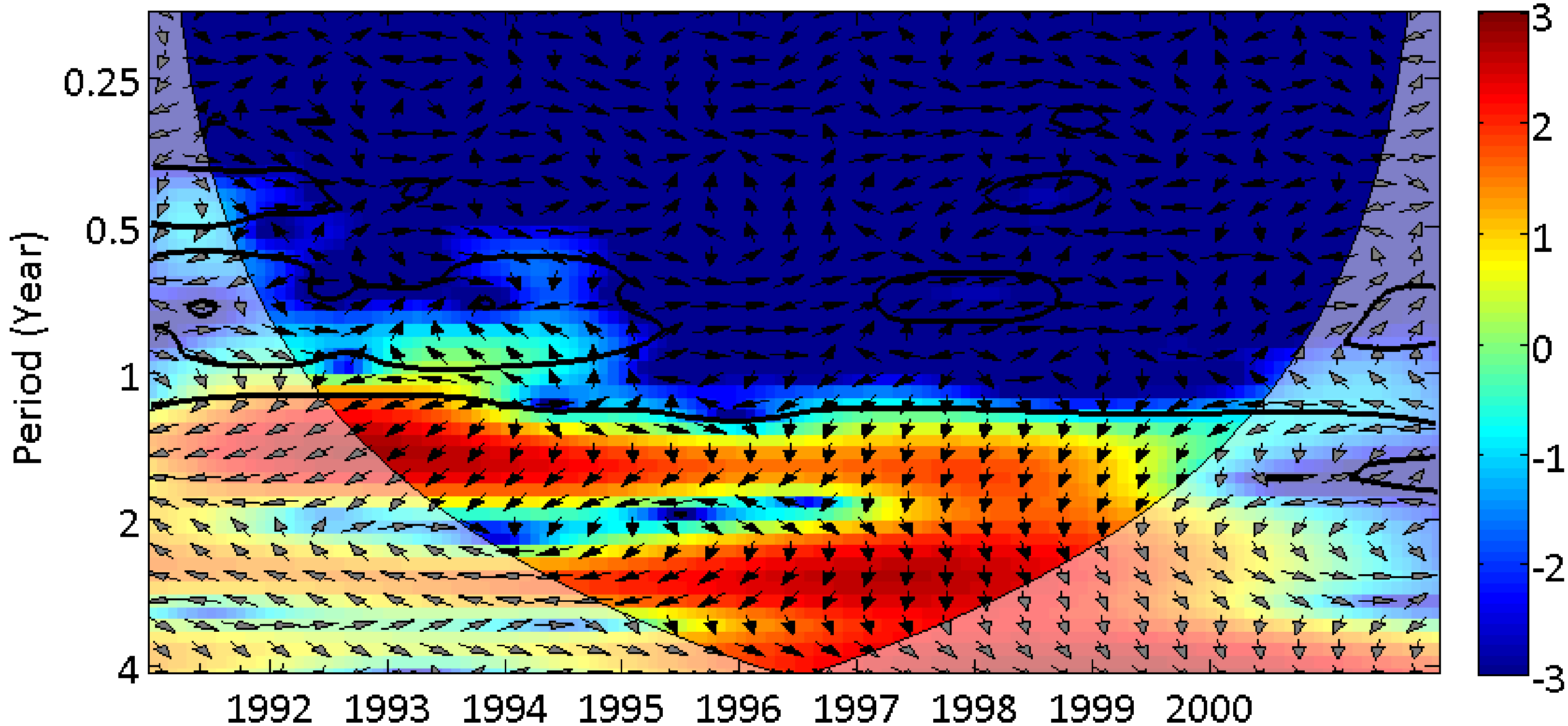


Figure 5.26 Cross-Wavelet of Niño 3.4 Sea Surface Temperature Anomaly (SSTA) and Cholera Cases in Piura from 1991 to 2001.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

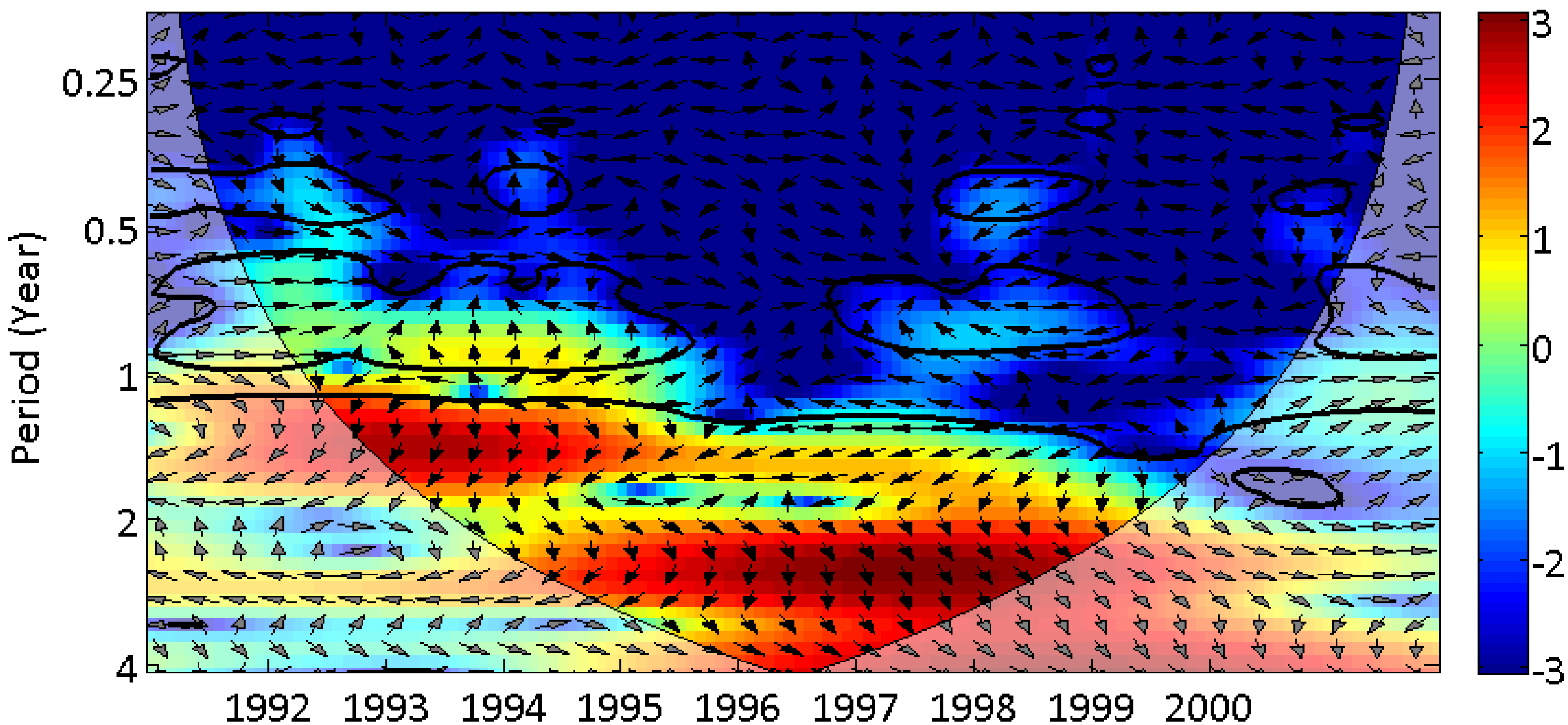


Figure 5.27 Cross-Wavelet of Niño 1+2 Sea Surface Temperature Anomaly (SSTA) and Cholera Cases in Piura from 1991 to 2001.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

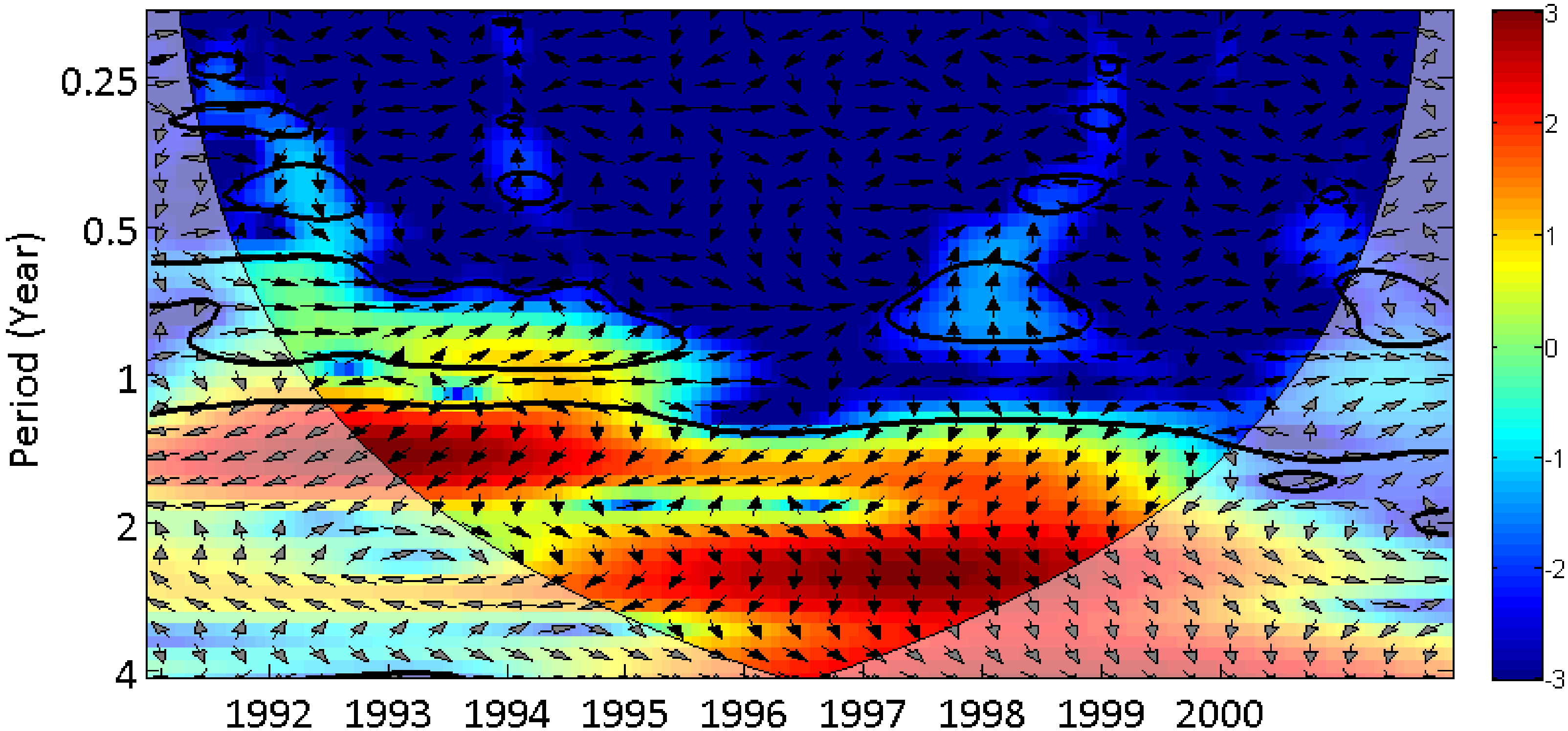


Figure 5.28 Cross-Wavelet of Paita Sea Surface Temperature Anomaly (SSTA) and Cholera Cases in Piura from 1991 to 2001.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

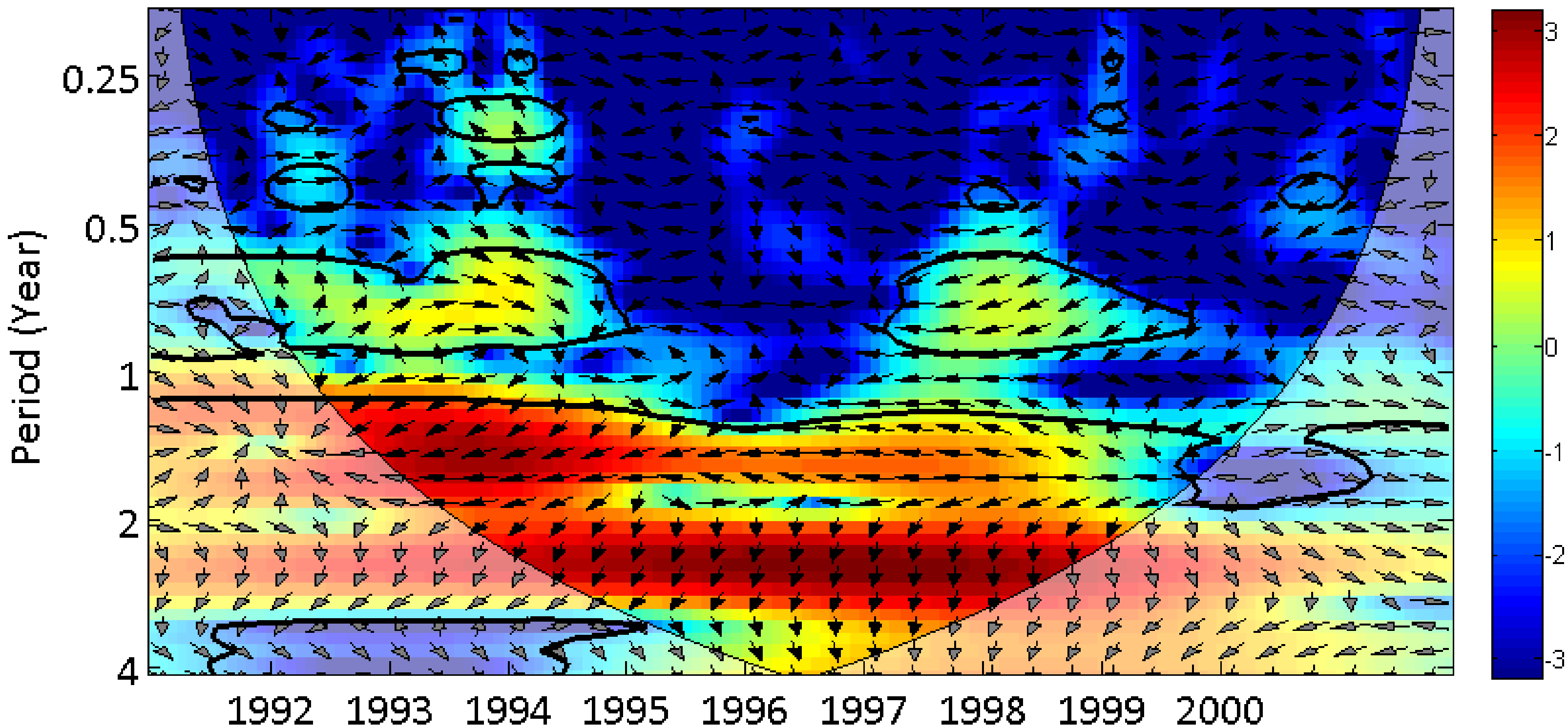


Figure 5.29 Cross-Wavelet of Temperature Maximum Anomaly (TMAXA) and Cholera Cases in Piura from 1991 to 2001.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

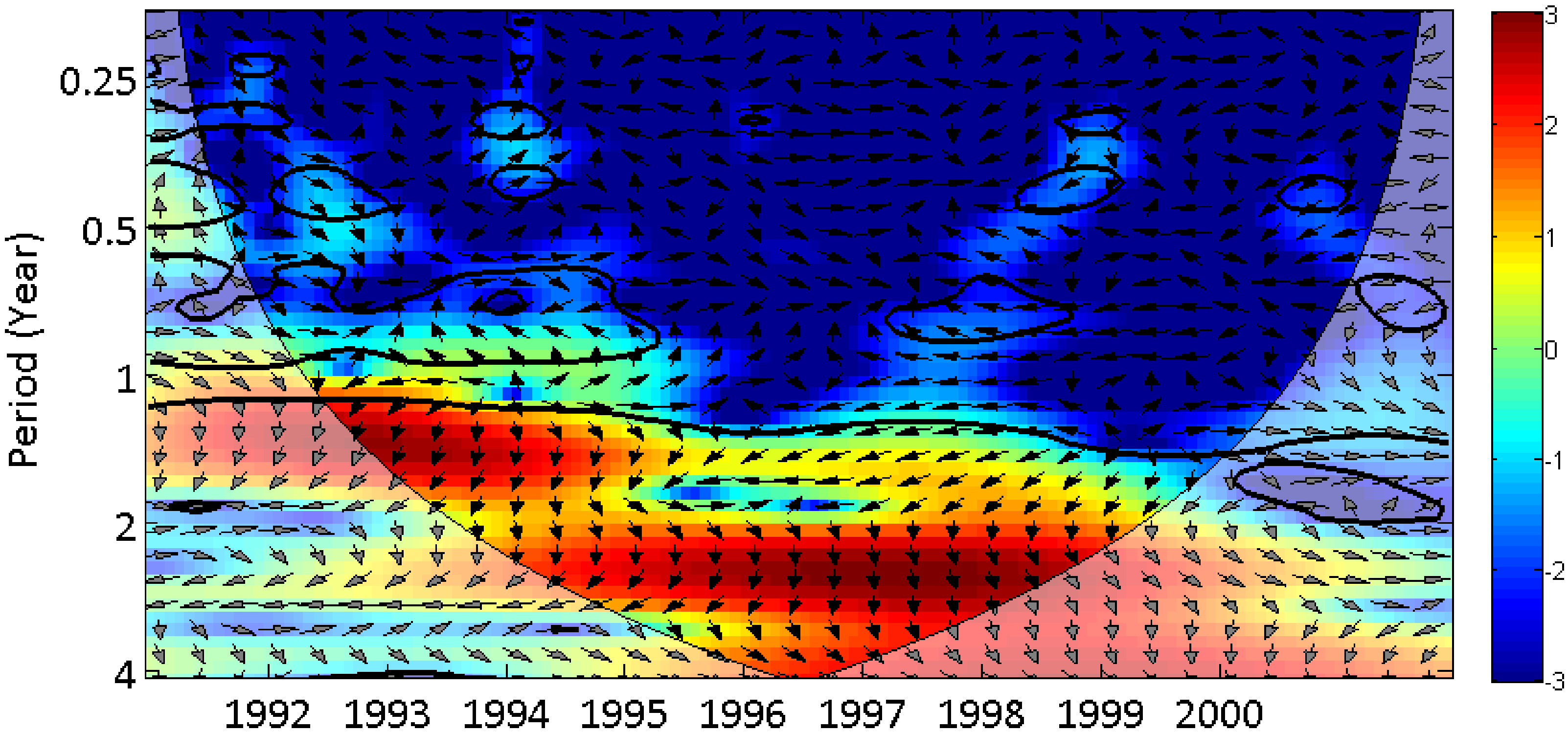


Figure 5.30 Cross-Wavelet of Temperature Mean Anomaly (TMEANA) and Cholera Cases in Piura from 1991 to 2001.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

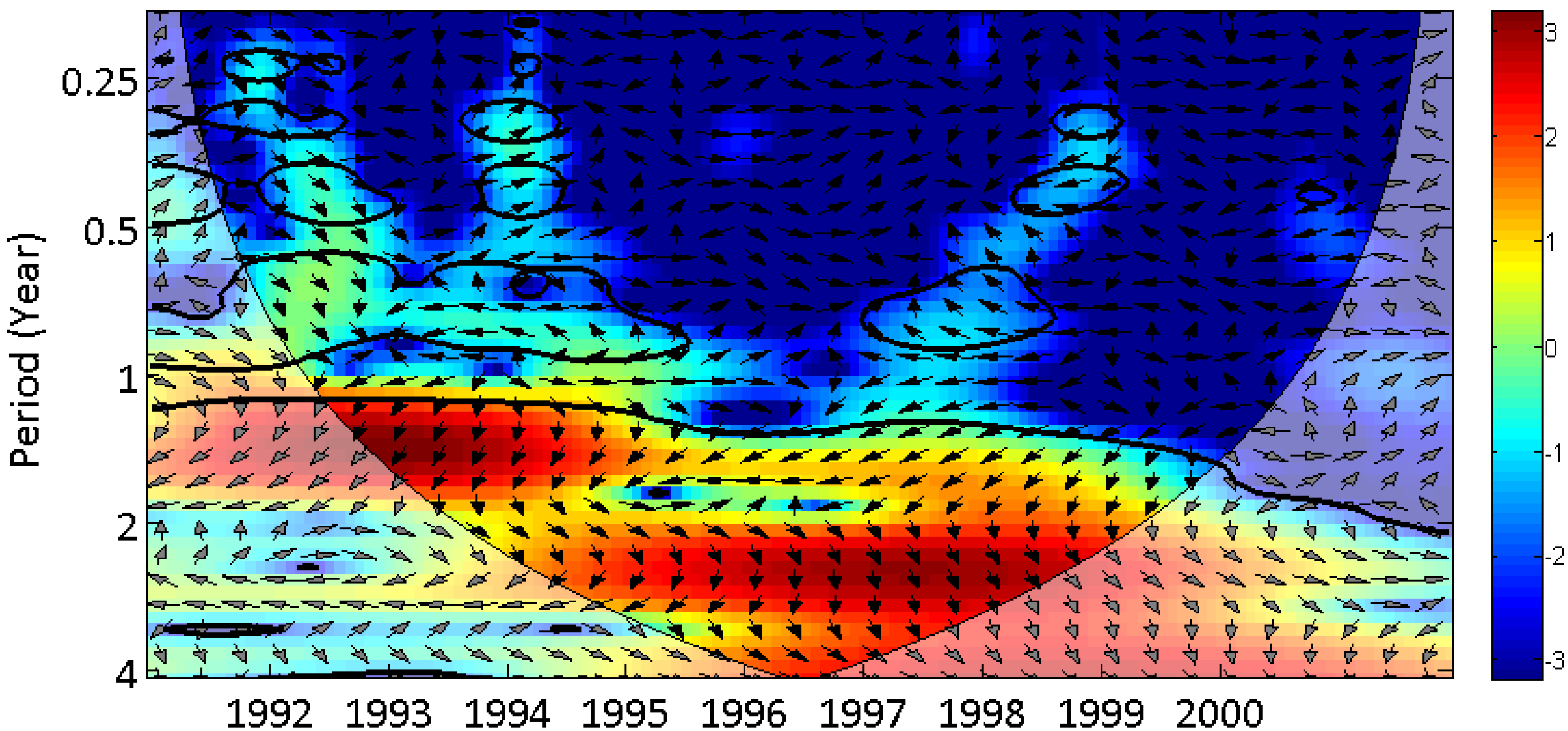


Figure 5.31 Cross-Wavelet of Temperature Minimum Anomaly (TMINA) and Cholera Cases in Piura.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

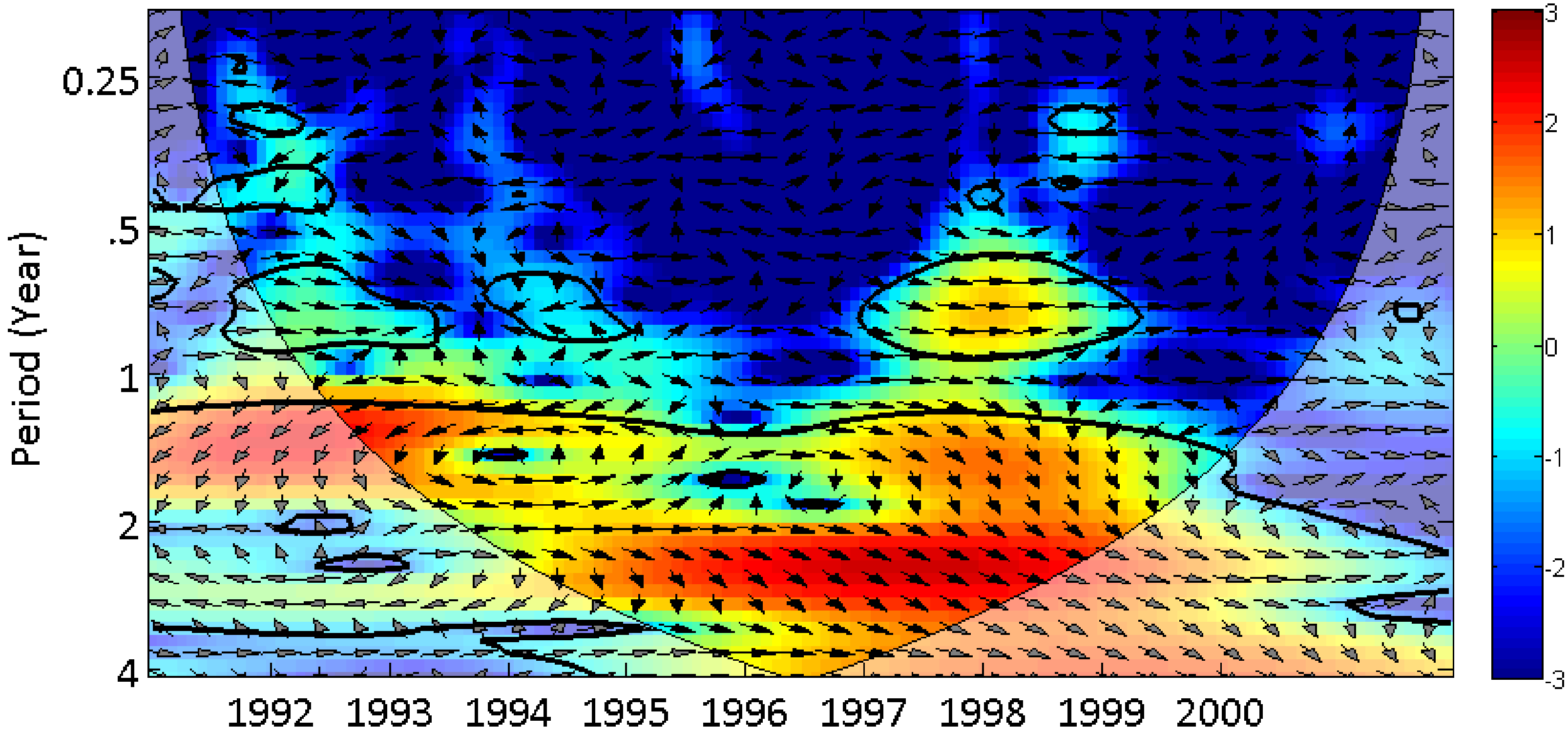


Figure 5.32 Cross-Wavelet of Rainfall Anomaly and Cholera Cases in Piura from 1991 to 2001.

The cross-wavelet transform indicates where the two time series share common power by period (scale by year). Common power increases from blue to red. The direction (phase) and temporal lead/lag (i.e., the phase angle or difference) are indicated by arrows, as such: north (climate lags); south (climate leads); east (climate and cholera in phase); and west (climate and cholera out of phase). Statistical significance (95.0% confidence level) is indicated by areas with black outlines outside the cone of influence (COI), where edge effects are not influential.

5.4.3 Cross-Correlation Analysis: Climate-Cholera

The results from cross-correlation analyses between the cholera and global and local climate time series are displayed in **Table 5.7.** Cholera had a strong association with SSTA parameters at 6 and 7 month lags. There were also strong associations at 5 month lag (Niño 1+2 SSTA) and 8 month lag (Paita). With rainfall, cholera was correlated at 1-2 month lags and 6-7 month lags. It was also found that the direction of associations between cholera and global and local climate parameters was positive and that climate led cholera. The temporal lags associated with SSTA and local temperature anomaly parameters were typically longer compared to rainfall anomaly. In sum, the cross-correlation analyses supported the wavelet coherence results (See **Table 5.8** for a summary of wavelet coherence by lag, direction and phase). In addition, it was shown that the strongest associations were with Niño 3.4 SSTA.

Table 5.7 Cross-Correlations between Cholera Case Anomaly and Global and Local Climate Time Series

Lag by month	NIÑO 3.4 SSTA	NIÑO 1+2 SSTA	PAITA SSTA	Rainfall Anomaly	Std. Error
-12	0.23	0.04	0.01	-0.09	0.091
-11	0.25	0.02	0.01	-0.10	0.091
-10	0.25	0.03	0.01	-0.08	0.091
-9	0.22	0.01	-0.01	-0.05	0.090
-8	0.20	-0.02	-0.04	-0.06	0.090
-7	0.17	-0.04	-0.09	-0.10	0.089
-6	0.14	-0.03	-0.11	-0.12	0.089
-5	0.13	-0.02	-0.13	-0.13	0.089
-4	0.13	0.01	-0.13	-0.13	0.088
-3	0.14	0.04	-0.09	-0.11	0.088
-2	0.15	0.09	-0.05	-0.01	0.088
-1	0.19	0.15	0.00	0.02	0.087
0	0.25	0.20	0.06	0.06	0.087
1	0.32	0.25	0.12	0.14	0.087
2	0.37	0.28	0.18	0.16	0.088
3	0.42	0.30	0.22	0.12	0.088
4	0.47	0.33	0.26	0.09	0.088
5	0.50	0.35	0.31	0.12	0.089
6	0.53	0.37	0.34	0.14	0.089
7	0.52	0.37	0.35	0.14	0.089
8	0.50	0.34	0.33	0.09	0.090
9	0.45	0.29	0.29	0.07	0.090
10	0.39	0.23	0.23	0.03	0.091
11	0.33	0.17	0.15	-0.05	0.091
12	0.26	0.12	0.08	-0.09	0.091

Gray areas indicate the strongest associations for each climate parameter.

Table 5.8 Summary of Wavelet Coherence Analyses by Lag, Direction, and Phase

	Cholera Cases Anomaly		
Climate Variable	Lag	Direction of Relationship	Phase
NIÑO 3.4 SSTA	>6months	Positive	Lead
NIÑO 1+2 SSTA	6 months*	Positive	Lead
PAITA SSTA	>6 months	Positive	Lead
Rainfall A	Zero	Positive	In

* led by 6 months at 1.5 yr scale and 2-3 months at 2 yr scale.

5.5 The Social Vulnerability Index (Objective 3)

The aim of this section is to examine the spatial associations between cholera incidence and social vulnerability by district in Piura in 1997-98. In 1997 and 1998 health authorities in the subregion of Piura reported a total of 4,172 confirmed and suspected cholera cases across 33 districts. The spatial distribution of district-level cholera by total number of cases and incidence rate (per 1000 persons at risk) from 1997-98 is displayed in **Figure 5.33** and **5.34**. Please refer back to Figure 4.6 reference map for a complete description of the names of each district in the subregion of Piura. The greatest number of cases were reported in the northern part of the subregion (e.g., Piura [n = 1160], Castilla [n = 749] and Chulucanas [n = 525]); while the highest incidence rates were found in the southern and central parts of the subregion (e.g., Sechura [11.1/1000] and Rinconada [16.0/1000], and San Juan de Bigote [13.8/1000]).

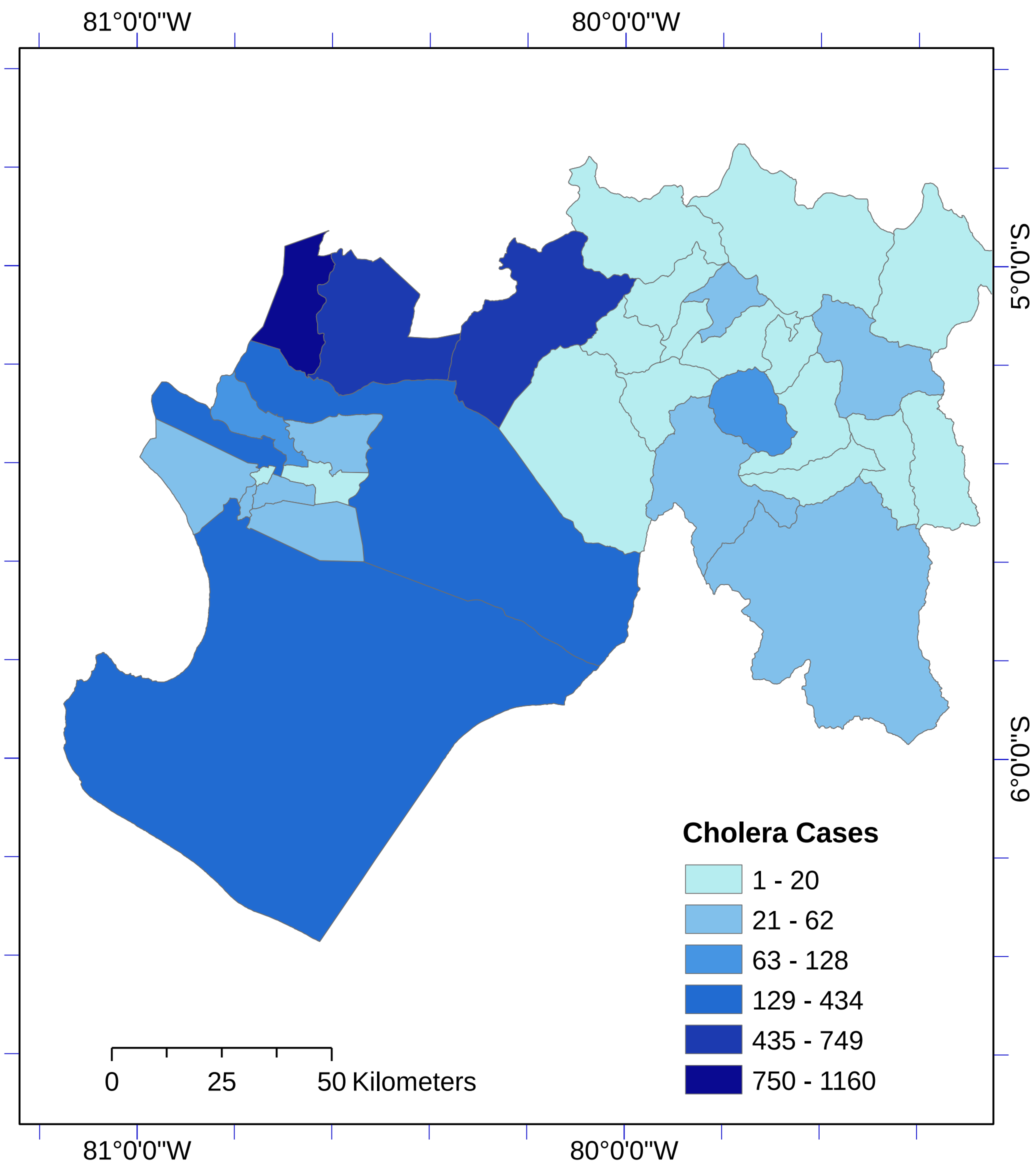


Figure 5.33 Total cholera cases in Piura for 1997-98, based on natural breaks classification.

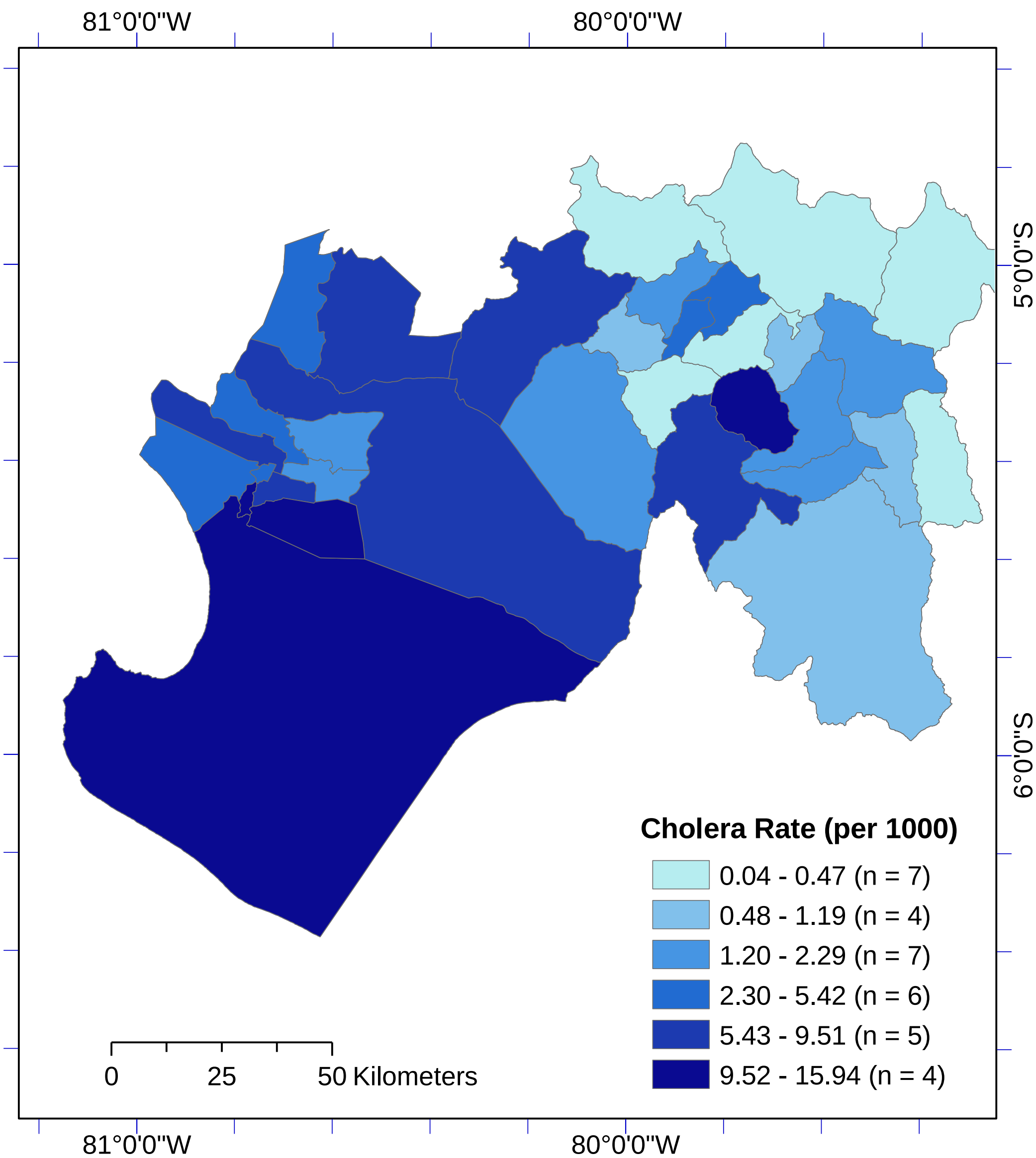


Figure 5.34 Cholera incidence rate (per 1000) for 1997-98 in Piura, based on natural breaks classification.

In order to better understand the spatial distribution of cholera incidence in Piura, I examined the effect of social vulnerability on cholera. Using PCA analysis, I constructed a Social Vulnerability Index (SVI). The SVI estimated social vulnerability to cholera transmission based on factors mainly related to water and sanitation accessibility. **Tables 5.9** and **5.10** show the results from the PCA analysis including the total variance explained and the dominant loadings (>0.50) for each dimension (factor). Four factors were extracted that explained 78.0 % of the variance in the data. A description of each factor, their dominant variables and how each variable contributes to the SVI (e.g.., positive/negative) will follow.

Table 5.9 SVI - Total Variance Explained in the Principal Components Analysis (PCA)

	Initial Eigenvalues			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	4.867	37.441	37.441	3.744	28.802	28.802
2	2.286	17.582	55.023	2.596	19.968	48.770
3	1.529	11.760	66.784	2.208	16.982	65.751
4	1.403	10.793	77.576	1.537	11.825	77.576
5	.937	7.204	84.780			
6	.717	5.514	90.294			
7	.488	3.751	94.046			
8	.304	2.340	96.386			
9	.239	1.838	98.224			
10	.111	.857	99.081			
11	.085	.654	99.734			
12	.034	.259	99.993			
13	.001	.007	100.0			

Table 5.10 Rotated Component Matrix in the Principal Components Analysis (PCA)

	1	2	3	4
ELEM_EDUC	**0.945**	0.034	0.021	-0.088
BATHRM_NO	**0.774**	0.226	-0.205	0.256
IMPROV_HSING	**-0.739**	0.297	0.067	-0.119
ILLITERATE	**0.730**	-0.193	0.038	-0.493
URBAN	**-0.638**	0.382	0.495	0.320
KITCHEN_NO	0.034	**0.947**	-0.007	-0.085
KITCHEN_YES	0.105	**-0.938**	-0.200	-0.014
WATER_TRUCKS	-0.086	**0.622**	0.053	0.119
WATER_WELL	0.314	0.085	**0.818**	-0.118
KITCHEN_SHARE	-0.408	-0.007	**0.711**	0.300
WATER_RIVER	**0.569**	-0.288	**-0.676**	-0.244
WATER_PUMP	-0.396	0.121	0.473	-0.453
WATER_OTHER	-0.021	0.044	0.130	**0.845**

Rotation Method: Kaiser Normalization; bold indicates dominant loadings.

SVI Factor 1 (SVIF1) – Rural (River Water)

The first factor included 6 variables which explained 28.8 % of the variance. Elementary education (ELEM_EDUC), illiteracy among adults (ILLITERATE), without bathroom in household (BATHRM_NO), and river water (WATER_RIVER) were positive variables; and urban (URBAN) and living in improvised housing (IMPROV_HSING) were negative variables. These loadings may represent districts where rural people may have limited education and bathroom infrastructure to wash and dispose of waste and thus, use river water to meet their basic needs. Living without bathroom facilities and using river water for basic needs may be an important transmission cycle in rural areas.

SVI Factor 2 (SVIF2) – Urban (Water Truck)

The second factor included 4 variables which explained 20.0 % of the variance. Persons without a kitchen (KITCHEN_NO) and water trucks (WATER_TRUCKS) were positive; and exclusive kitchen (KITCHEN_YES) was negative. Although urban (URBAN) was not a dominant loading, I included it because it was positive (0.38) and may suggest that this factor characterizes non-rural areas. Overall these loadings are indicative of people living in an urban area, without a kitchen, and in need of water trucks to meet their basic needs. Furthermore, these characteristics are suggestive of people living in urban shantytowns, without access to proper cooking facilities or access to potable water, who rely on water trucks. Cholera transmission may have occurred through contaminated water via water trucks.

SVI Factor 3 (SVIF3) – Urban (Public Well Water)

The third factor included 3 variables which explained 17.0 % of the variance. Shared kitchen (KITCHEN_SHARE) and public well water (WATER_WELL) were positive; and river water (WATER_RIVER) was negative. This factor is suggestive of people living in urban areas in houses with a shared a kitchen, using public well water. Cholera may have been transmitted in these communities through the common sharing of a kitchen (i.e., exposure through an infected person in the household) and contaminated well water.

SVI Factor 4 (SVIF4) – Other Water Sources

The fourth factor included two variables which explained 11.8 % of the variance. 'Other water sources' (WATER_OTHER) and urban (URBAN) were positive. This factor is suggestive of people living in urban areas with access to other water source(s), which may refer to street vendors. Reportedly, consuming water (as well as food) from street vendors was an important risk factor for cholera transmission in Piura and Peru (Ries et al 1992). Therefore, particular attention will be given to this factor in the interpretation of my findings.

In sum, the SVI and its four factors (SVI 1-4) describe the different vulnerability pathways by which cholera may have been transmitted in the population of Piura. The next section presents the spatial distribution of the SVI and the four factors (hereafter referred to as sub-indices) in Piura.

5.5.1 Mapping the SVI by District

Figures 5.35 to **5.39** are maps of the SVI and the sub-indices. The overall SVI ranged from 1.30 to -1.26. Both the highest and lowest vulnerability was concentrated on the west coast of Piura (**Figure 5.35)**. The most vulnerable district was Rinconada Llicuar, which also had the highest estimated cholera incidence in 1997-98 (16.0/1000 persons at risk). Refer to **Appendix 4** for Table of the SVI and sub-indices from high to low social vulnerability compared with cholera incidence rates. The least vulnerable district was Piura, where cholera incidence was 5.4/1000 persons. The low SVI score and cholera incidence in Piura might be expected because it is the capital of the Department of Peru, where a concentration of public resources may have been available.

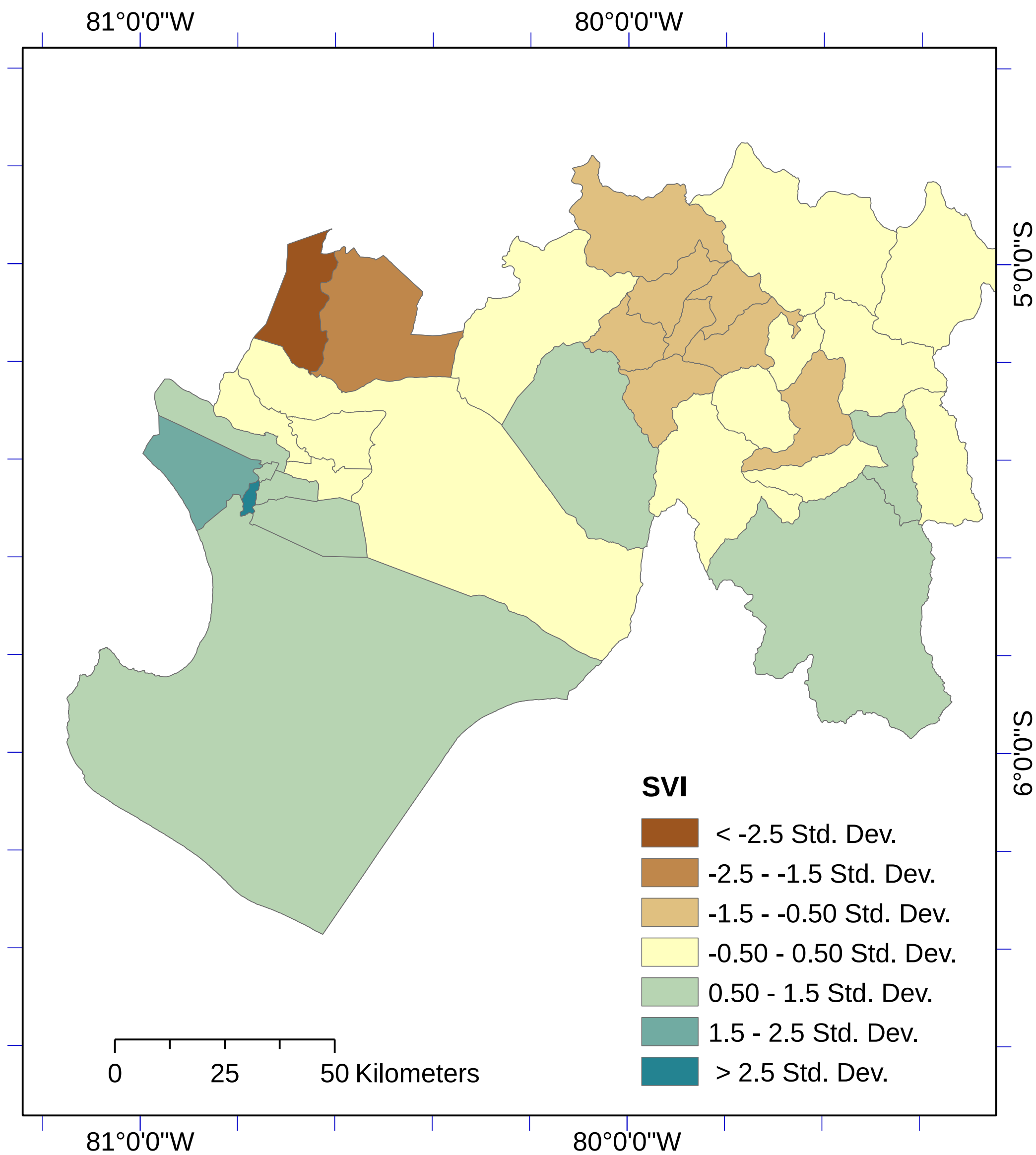


Figure 5.35 Social Vulnerability Index (SVI), based on standard deviation classification.

Figure 5.36 shows the distribution of rural and river water vulnerability (SVIF1). The SVIF1 ranged from 1.54 to -3.39. The highest to lowest vulnerability appears to be contrasted between districts in the eastern part (further inland) of Piura and those in the west coast of Piura. The most vulnerable districts are: Pacaipampa (SVIF1 = 1.54), Sondorillo (SVIF1 = 1.44), and Huarmaca (SVIF1 = 1.43). Interestingly, all of these districts reported low cholera incidence (< 2.0/1000 persons) in 1997-98. Some possible reasons for these observations are discussed further in section 6.3. The least vulnerable districts were Piura (SVIF1 = -3.39) and its neighbor Castilla (SVIF1 = -2.55), which had an estimated cholera incidence of 7.4/1000 persons.

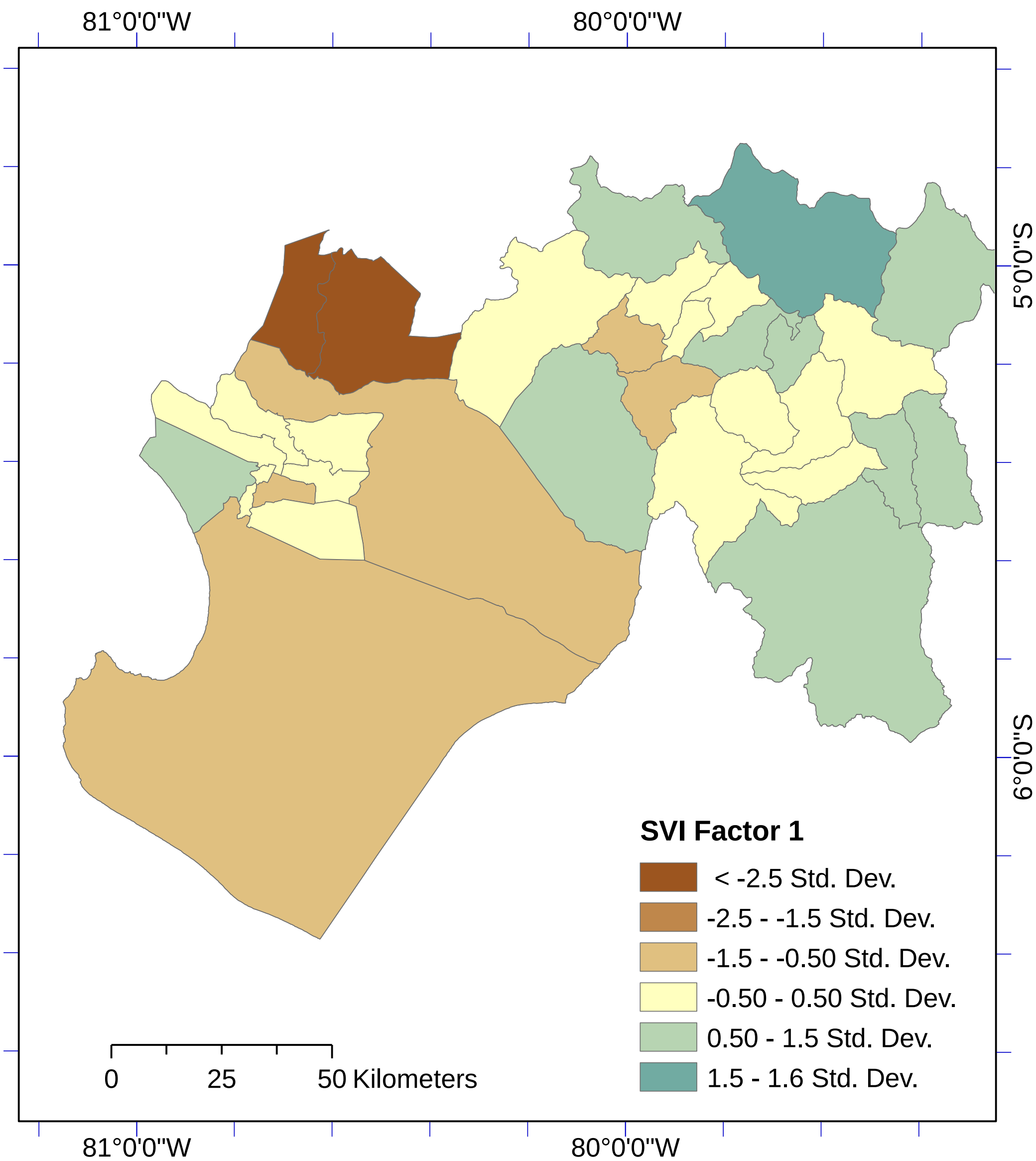


Figure 5.36 Rural and River Water (SVIF1), based on standard deviation classification.

Figure 5.37 shows the distribution of urban and water truck vulnerability (SVIF2). The SVIF2 ranged from 2.59 to – 1.69. The highest vulnerability was concentrated on the west coast, while the lowest vulnerability was in the west coast to central part of Piura. The most vulnerable districts were: Vice (SVIF2 = 2.59) and Sechura (SVIF2 = 2.12). Cholera incidence in Sechura (11.1/1000 persons) was notable compared to Vice (3.7/1000 persons). The least vulnerable districts were: El Tallan (SVIF2 = -1.69) in the west and Santo Domingo (SVIF2 = - 1.47) in the central.

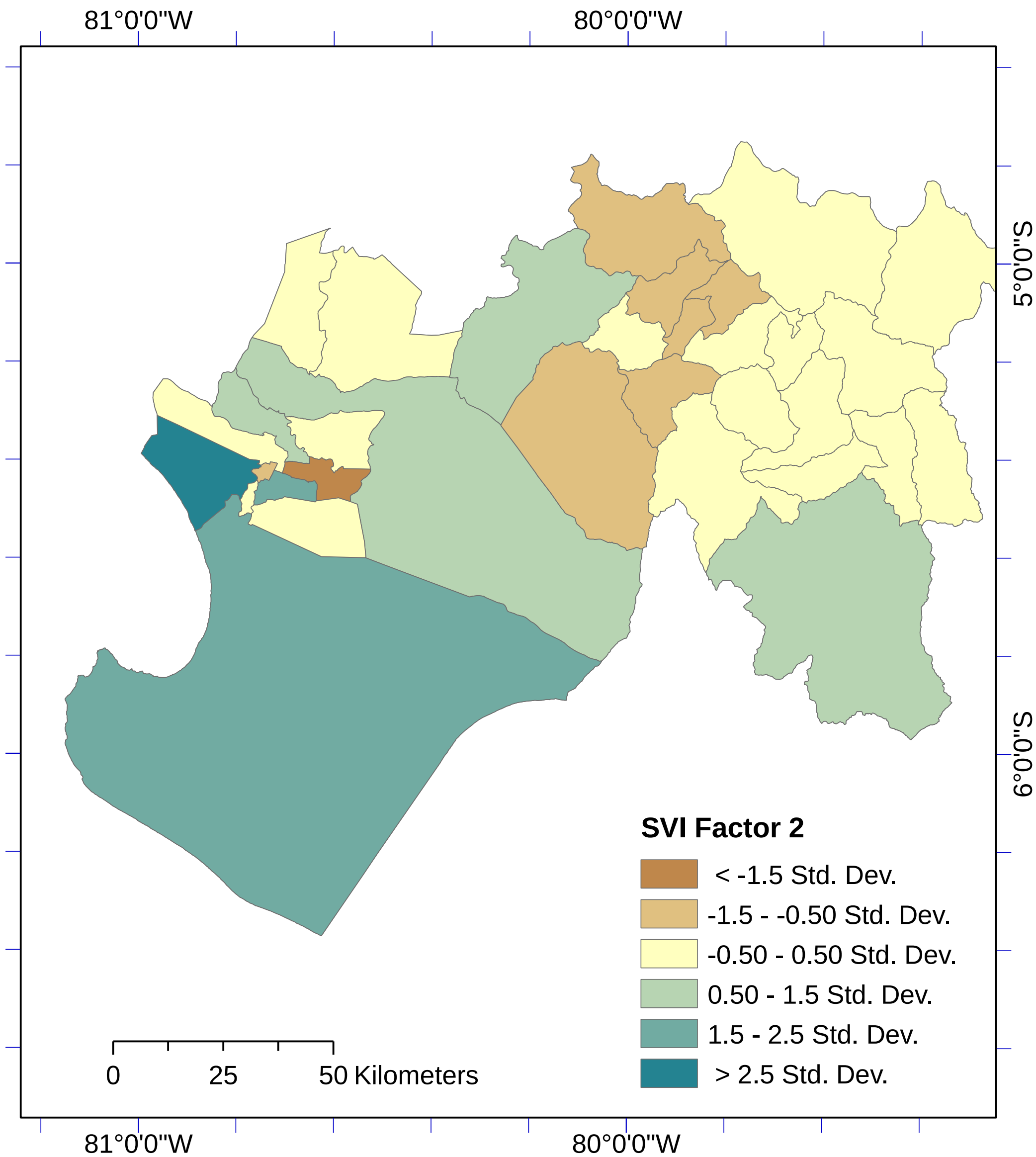


Figure 5.37 Urban and Water Truck (SVIF2), based on standard deviation classification.

Figure 5.38 shows the distribution of urban and well water vulnerability (SVIF3). The SVIF3 ranged from 2.66 to -1.56. The highest vulnerability was found in the west coast, while the lowest vulnerability was in the coast and central Piura. The most vulnerable districts were La Matanza (SVIF3 = 2.66) and El Tallan (SVIF3 = 2.45). Cholera incidence in these two districts was <2.5/1000 persons. The least vulnerable districts were La Laquiz (SVIF3 = -1.56) and El Carmen de la Frontera (SVIF3 = -1.41).

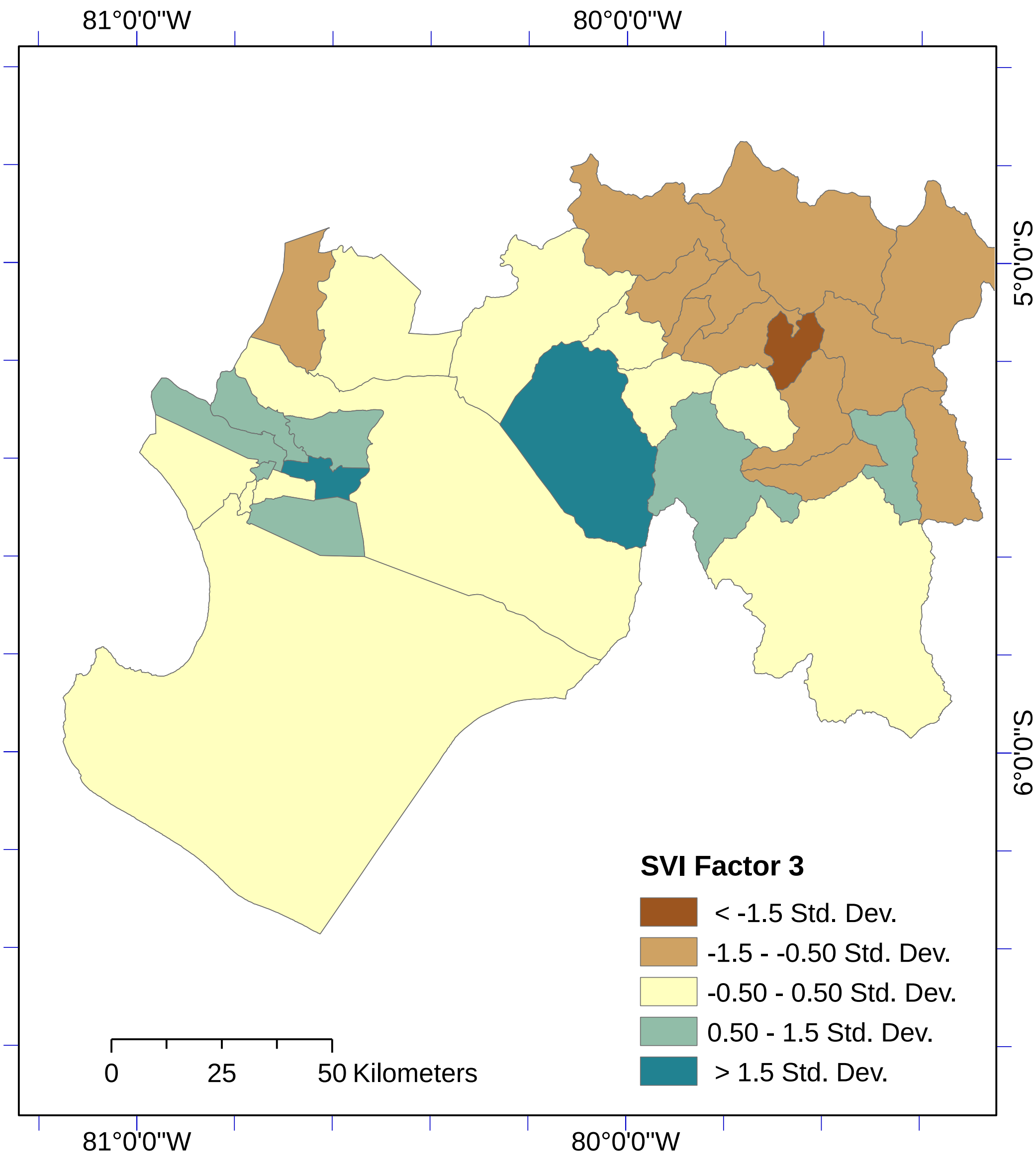


Figure 5.38 Urban and Well Water (SVIF3), based on standard deviation classification.

Figure 5.39 shows the distribution of 'other water sources' vulnerability. The SVIF4 ranged from 4.60 to -1.34. The highest vulnerability was found on the west coast. The lowest vulnerability was distributed throughout the west coast, central and eastern parts of Piura. The most vulnerable district was Rinconada Llicuar, which was also the most vulnerable according to the overall SVI. The least vulnerable district was La Arena (SVIF4 = -1.34). La Arena had an estimated cholera incidence of 3.9/1000 persons.

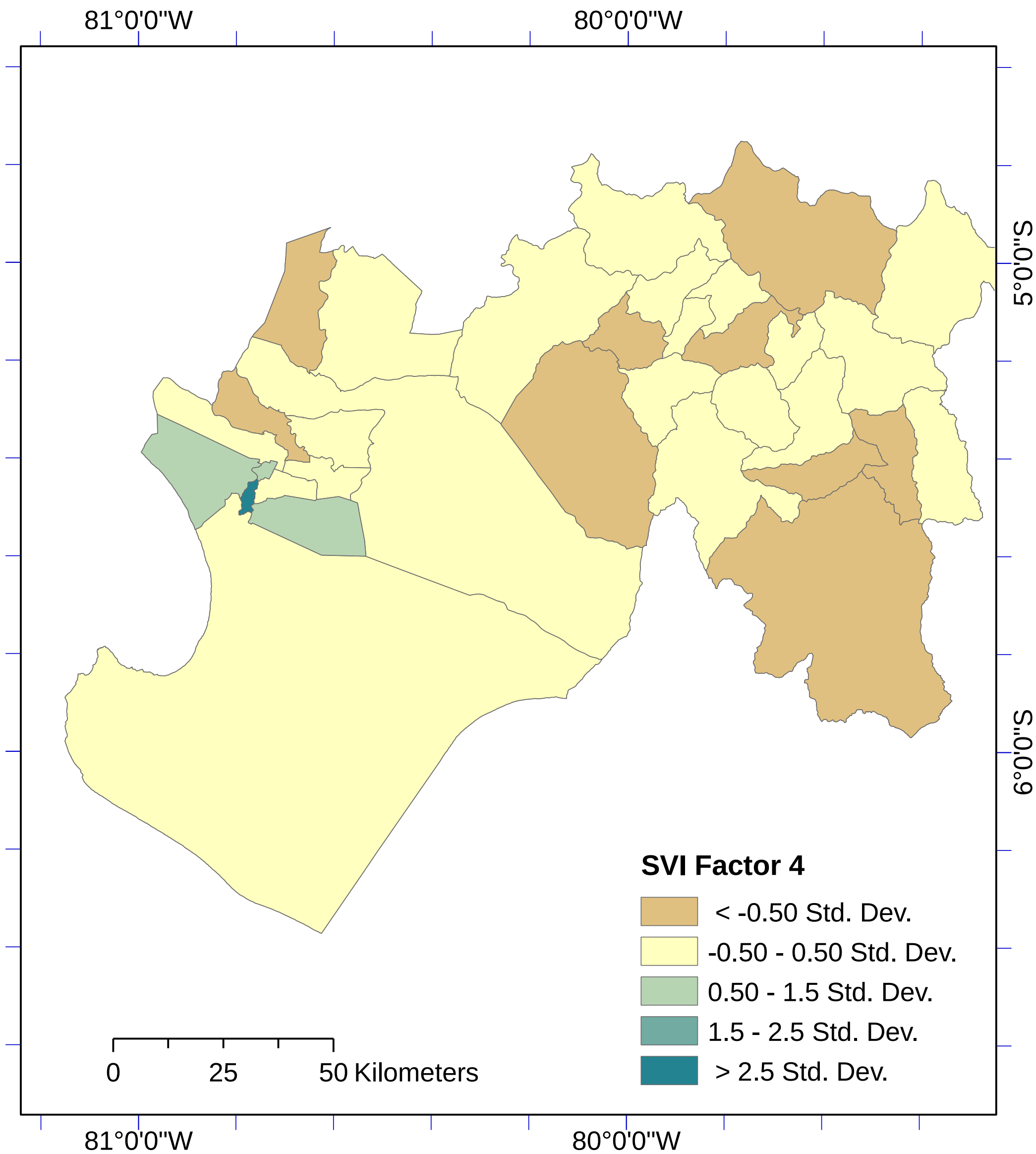


Figure 5.39 Other Water Sources (SVIF4), based on standard deviation classification.

5.6 Measuring Associations between the SVI and Cholera Incidence (Objective 4)

The results of the global regression (OLS) analyses estimating the effect of SVI and SVIF1-4 on cholera incidence are presented in **Table 5.11**. These analyses show that the SVI is significantly associated with cholera incidence (B= 0.65, *p*-value = 0.07) at the 0.01 level. Of the SVI sub-indices, using 'water from other sources' (SVIF4) had a significant and positive association with cholera incidence (B = -0.46, *p*-value = 0.008). In contrast, living in rural areas and using water from the river (SVIF1) had a significant and negative association with cholera incidence (B= -0.46, *p*-value = 0.008).

Table 5.11 Summary Statistics for Ordinary Least Squares Regression (OLS)

	Coefficient	Standardized Error	*t* value	*p* value
Intercept SVI	1.7712 0.6500	0.1735 0.3524	10.2073 1.8443	0.0000 0.0747
Intercept SVIF1	1.7712 **-0.4636**	0.1634 0.1659	10.8417 -2.7947	0.0000 **0.0088**
Intercept SVIF2	1.7712 0.2856	0.1757 0.1784	10.0821 1.6009	0.0000 0.1195
Intercept SVIF3	1.7712 0.3087	0.1745 0.1772	10.1529 1.7423	0.0000 0.0914
Intercept SVIF4	1.7712 **0.5194**	0.1580 0.1605	11.2074 3.2362	0.0000 **0.0029**

Bold indicates variables that are significant at 95.0% confidence level.

Table 5.12 compares the global model and local model estimates (GWR] by r^2 and residuals. Generally the GWR results supported the OLS findings except for the association with overall SVI (i.e., was not significant). SVIF1 and SVIF4 had significant associations with cholera incidence. Compared to the other indices the variance explained by SVIF1 (R2 = 0.45) and SVIF4 (R2 = 0.46) was substantially greater. Furthermore, their residuals were also relatively smaller, suggesting a closer fit between the predicted values and the observed data.

Table 5.12 Comparison Statistics for Geographically Weighted Regression (GWR) and Ordinary Least Squares Regression (OLS)

	AICc		R-Squared		Adj. R-Squared		Residuals
Variable	GWR	OLS	GWR	OLS	GWR	OLS	GWR
SVI	89.68	95.38	0.4089	0.0989	0.3230	0.0698	20.20
SVIF1	**86.62**	91.40	**0.4515**	0.2012	0.3789	0.1755	**18.75**
SVIF2	89.93	96.19	0.4271	0.0764	0.3299	0.0466	19.58
SVIF3	92.20	95.73	0.3548	0.0892	0.2634	0.0598	22.06
SVIF4	**85.08**	89.21	**0.4617**	0.2525	0.3995	0.2284	**18.40**

Bold indicates variables that are significant at the 95.0% confidence level

5.6.1 Mapping Associations between SVI and Cholera Incidence

Figures 5.40 to **5.45** are maps of the predicted values and standardized residuals for SVI[20], SVIF1 and SVIF4 from the GWR analyses. The predicted values represent the local effect of social vulnerability (specified by the defined mechanisms) on cholera incidence by districts. The standardized residuals represent risks factors other than social vulnerability –i.e., unexplained risk factors for cholera incidence across districts. For SVI and the sub-indices, there was a consistent spatial pattern in predicted values; such that, estimations are distinctly higher to lower from the west coast to the eastern part of Piura. This pattern was also observed in the standardized residuals maps;

[20] I included the SVI for comparative purposes since it represents overall social vulnerability.

however, values from west to east were generally moderate (Std. Dev. < 1.5). This finding suggests that there may be an association between areas where local cholera rate estimations were high to moderate and areas where much remains unexplained by the GWR models. Thus, these districts could be important places of inquiry to investigate climate associations with cholera in 1997-98.

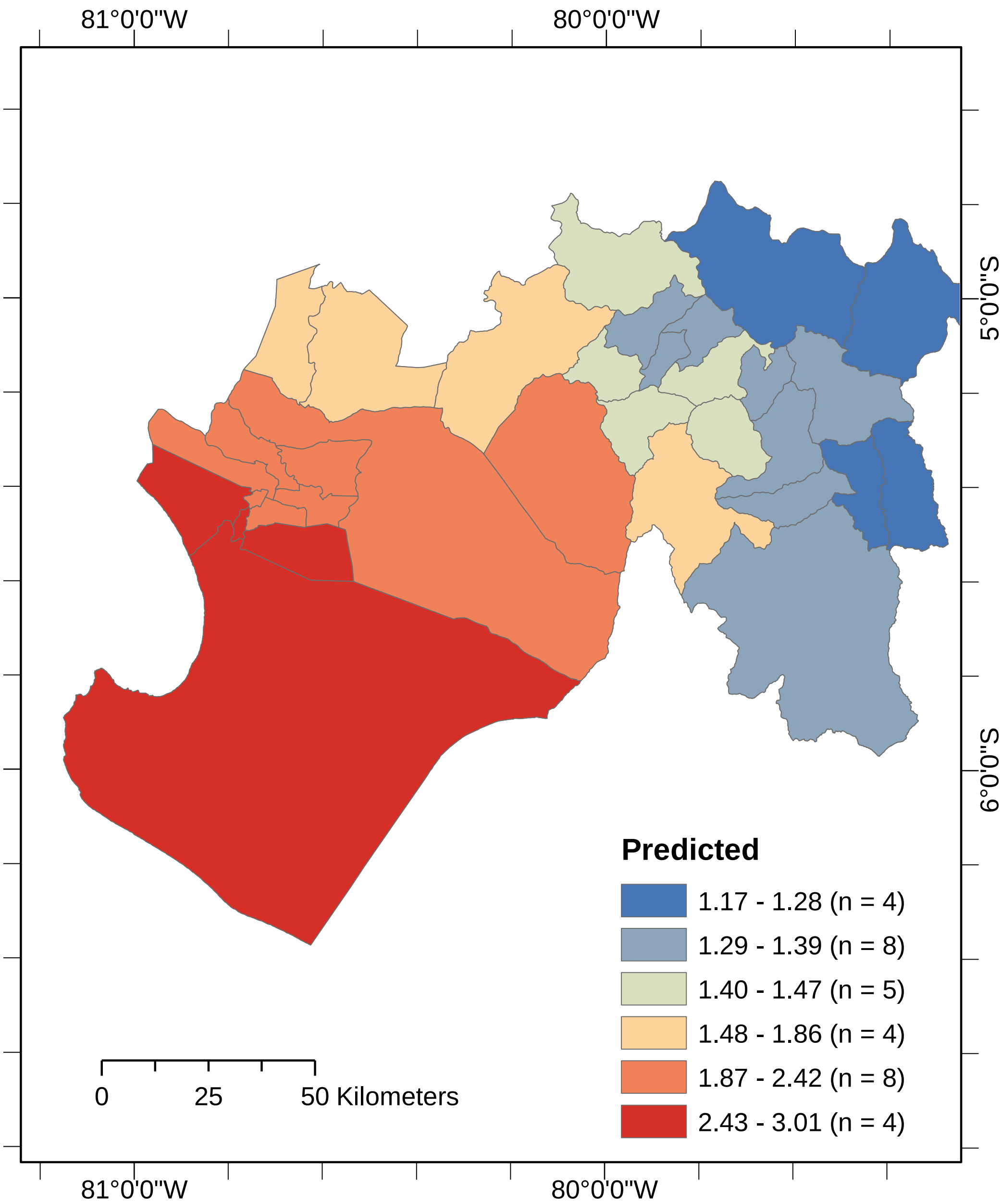


Figure 5.40 Cholera Incidence Predictions by Social Vulnerability Index (SVI). Predicted values, based on natural breaks classification, from geographically weighted regression (GWR).

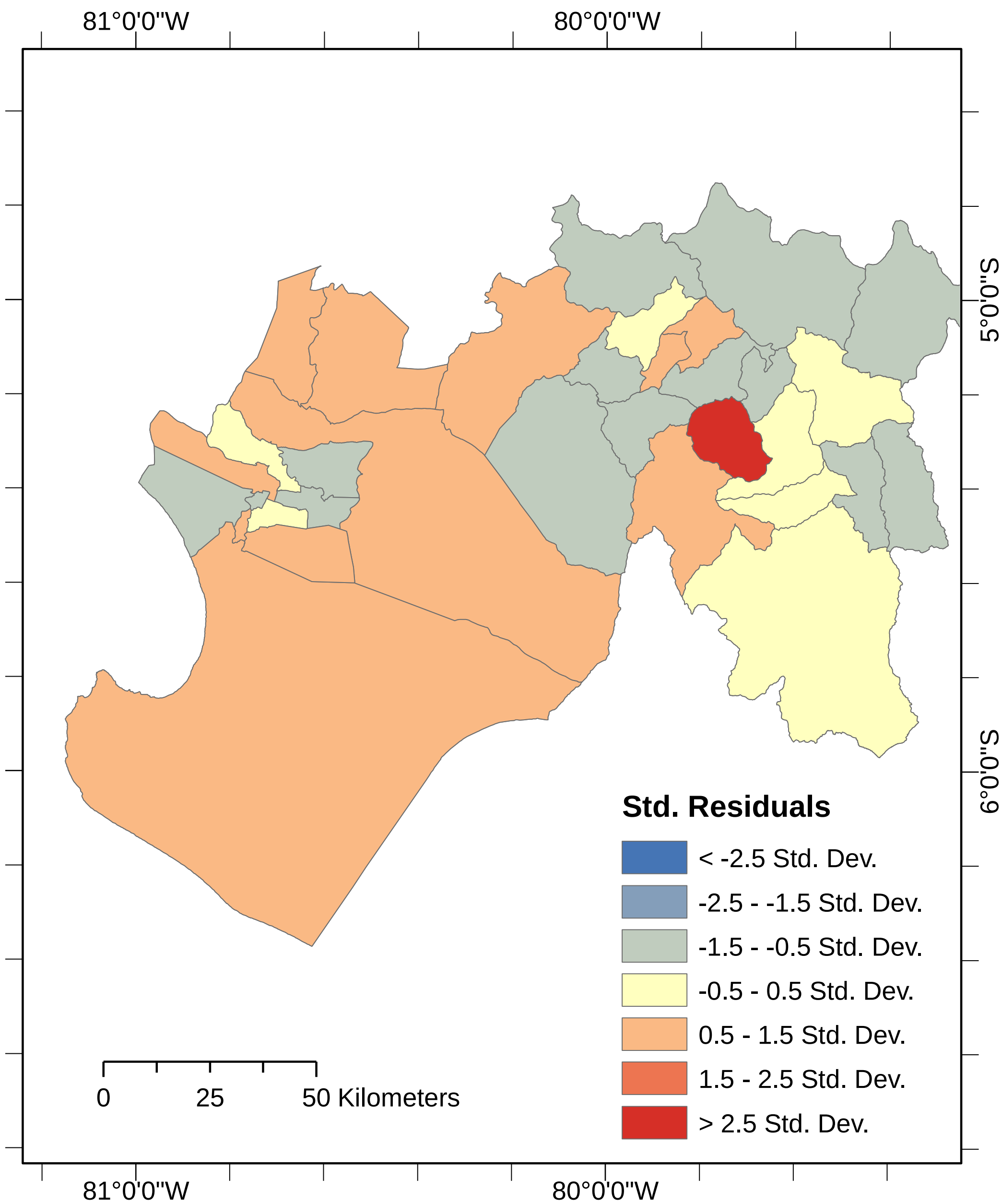


Figure 5.41 Cholera Incidence Predictions by Social Vulnerability Index (SVI). Standardized residuals, based on the standard deviation classification, from geographically weighted regression (GWR).

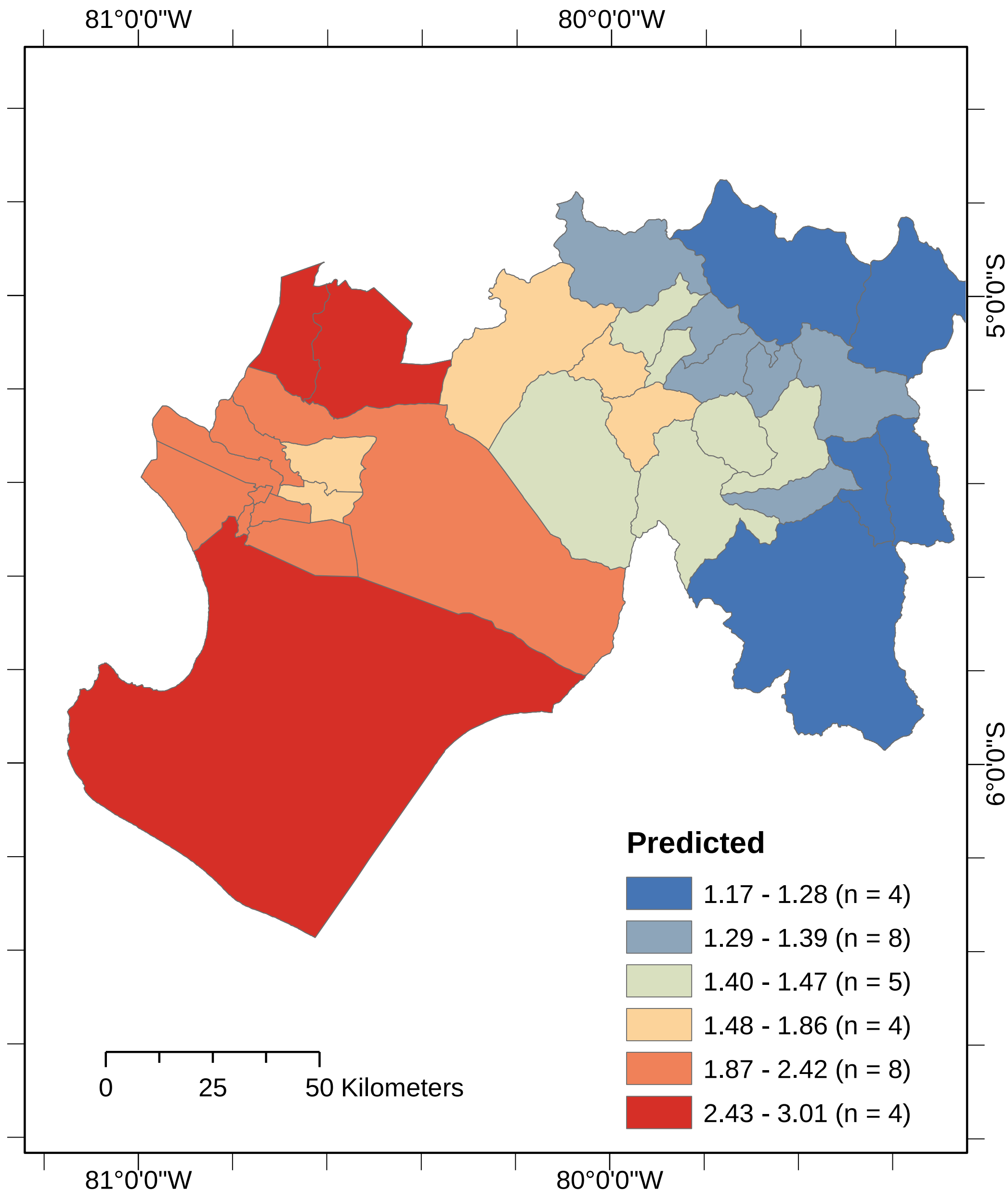


Figure 5.42 Cholera Incidence Predictions by Social Vulnerability Index Factor 1 (SVIF1). Predicted values, based on natural breaks classification, from geographically weighted regression (GWR).

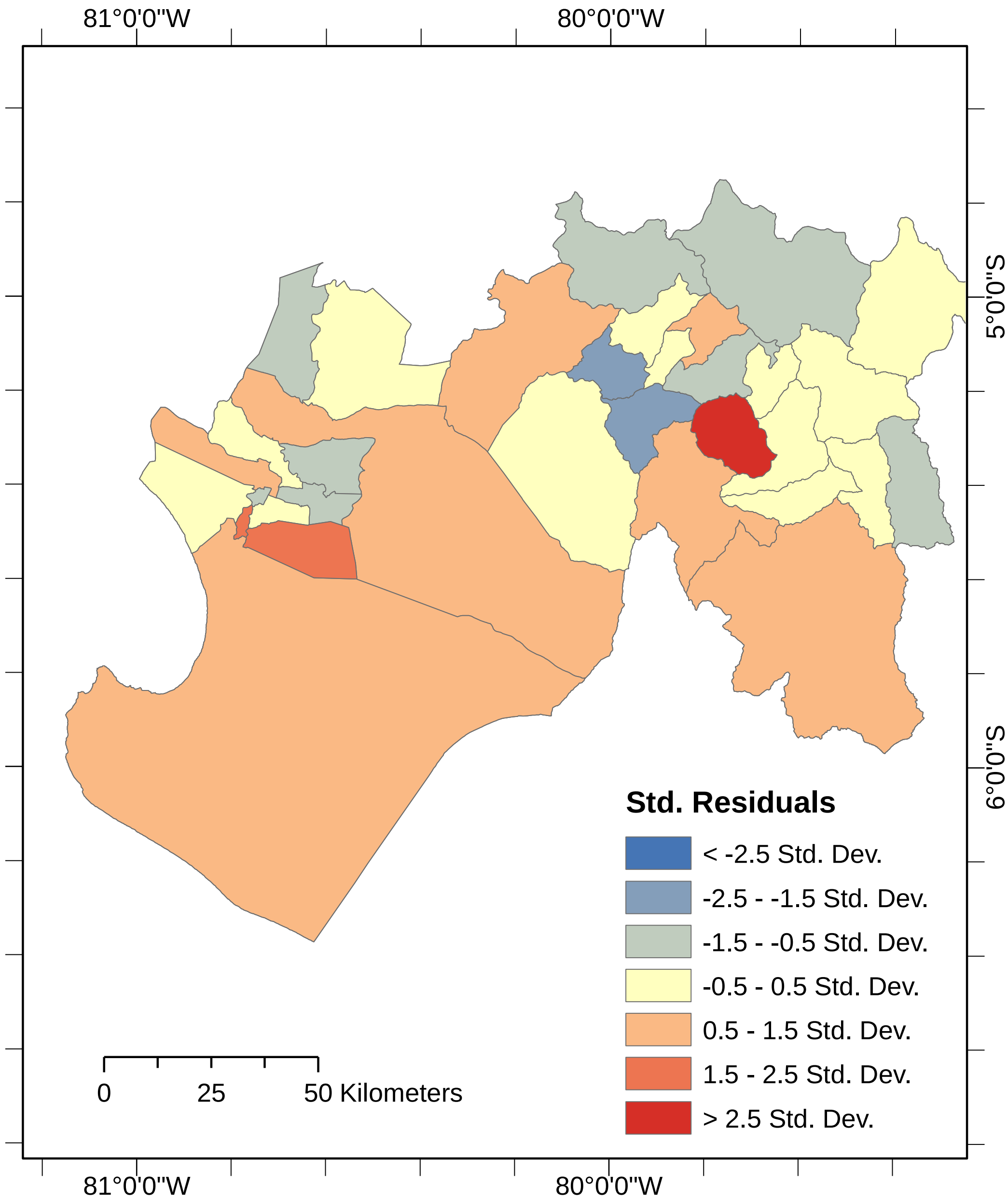


Figure 5.43 Cholera Incidence Predictions by Social Vulnerability Index Factor 1 (SVIF1). Standardized residuals, based on the standard deviation classification, from geographically weighted regression (GWR).

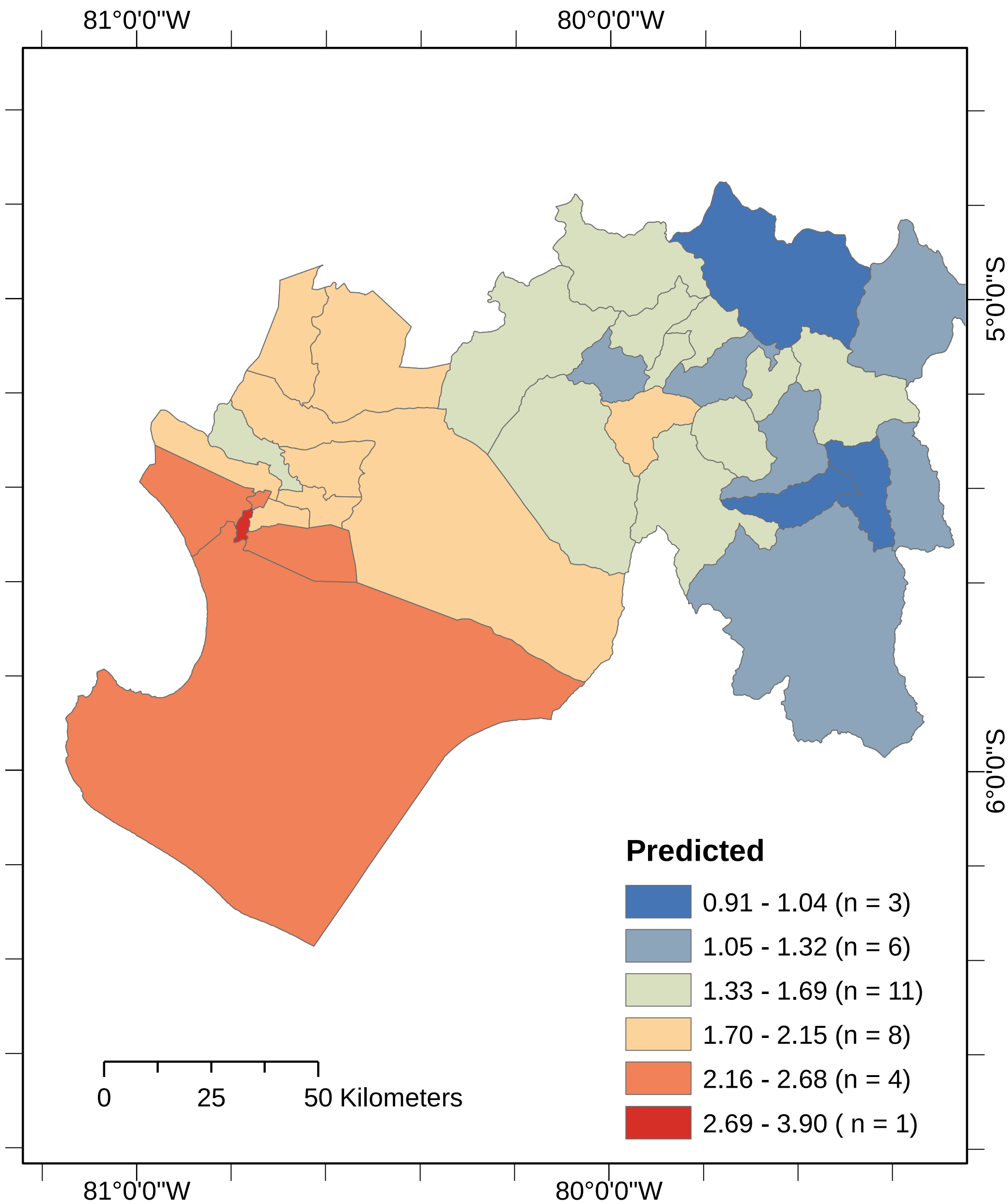


Figure 5.44 Cholera Incidence Predictions by Social Vulnerability Index Factor 4 (SVIF4). Predicted values, based on natural breaks classification, from geographically weighted regression (GWR).

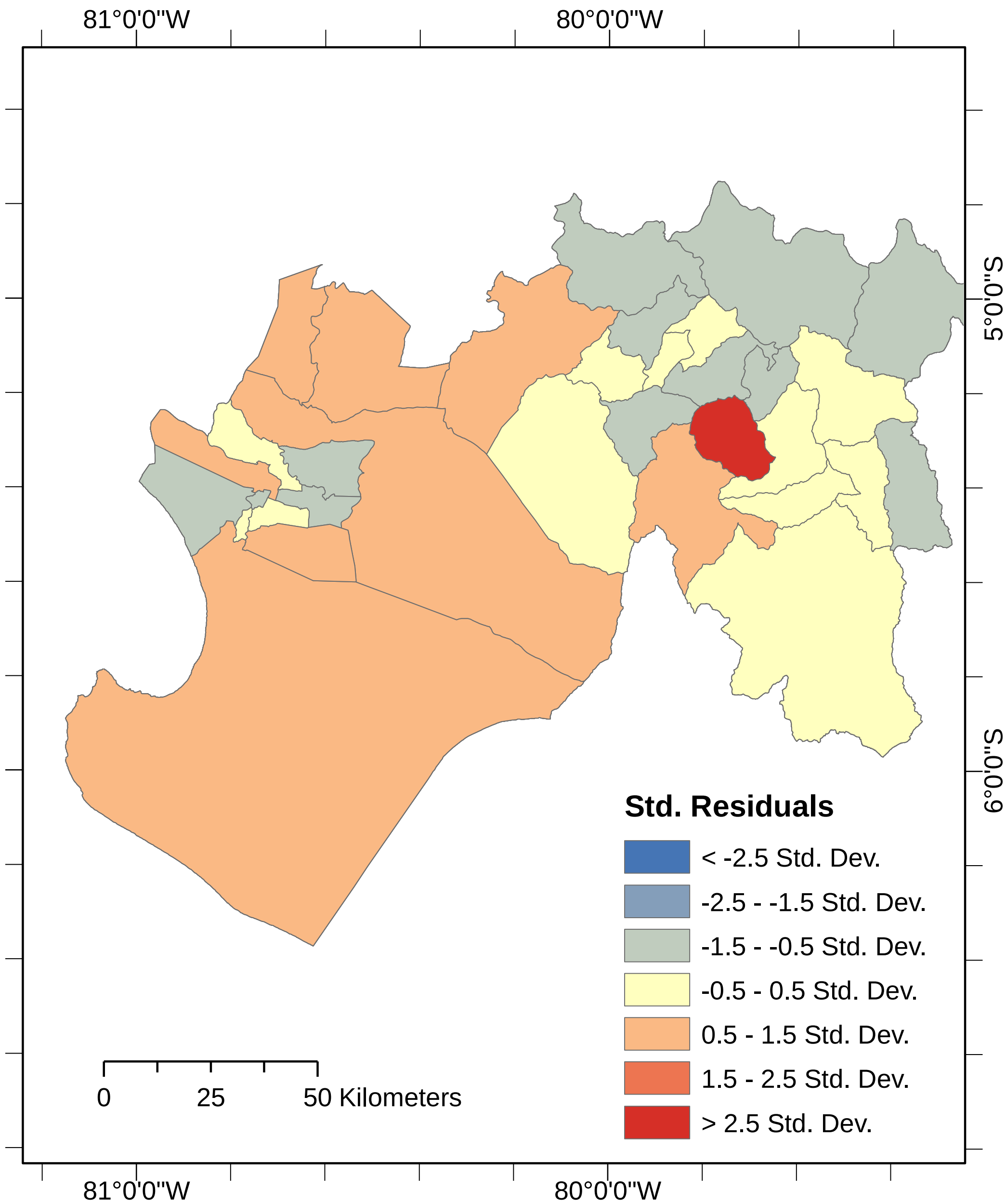


Figure 5.45 Cholera Incidence Predictions by Social Vulnerability Index Factor 4 (SVIF4). Standardized residuals, based on the standard deviation classification, from geographically weighted regression (GWR).

Districts where high (red) to moderate (orange –light orange) predicted values and high standardized residuals overlapped are highlighted in **Table 5.13**. These districts included (by order of ID): 1) Piura (0); Castilla (1); Catacaos (2); La Arena (5); La

Union (6); Huarmaca (12); Chulucanas (17); Chalaco (19); Salitral1 (22); San Juan de Bigote (23); Sechura (27); Bernal (29); Cristo Nos Valga (30); Vice (31); and Rinconada Llicuar (32). Twelve of these areas were identified in 3 of 4 indices. Although predicted values for cholera in San Juan de Bigote were moderate, it was included because residuals for this district were consistently high (Std. Dev. > 2.5) across indices. It also reported the second highest cholera rate (13.8 per 1000) in 1997-98. In the next section, cholera incidence in these selected districts will be examined for associations with global and local climate parameters.

Table 5.13 Selected Districts from Geographically Weighted Regression (GWR) based on Predicted Values and Standardized Residuals

ID	SVI	SVIF1	SVIF2	SVIF3	SVIF4
0	PIURA			PIURA	PIURA
1	CASTILLA	CASTILLA		CASTILLA	CASTILLA
2	CATACAOS	CATACAOS	CATACAOS	CATACAOS	CATACAOS
5	LA ARENA	LA ARENA		LA ARENA	
6	LA UNION	LA UNION	LA UNION	LA UNION	LA UNION
12		HUARMACA			
17	CHULUCANAS		CHULUCANAS	CHULUCANAS	CHULUCANAS
19		CHALACO			
22	SALITRAL	SALITRAL1	SALITRAL1	SALITRAL1	SALITRAL1
23	SAN JUAN DE BIGOTE	SAN JUAN DE BIGOTE	SAN JUAN DE BIGOTE	SAN JUAN DE BIGOTE	SAN JUAN DE BIGOTE
27	SECHURA	SECHURA	SECHURA	SECHURA	SECHURA
29	BERNAL	BERNAL	BERNAL	BERNAL	
30	CRISTO NOS VALGA	CRISTO NOS VALGA	CRISTO NOS VALGA	CRISTO NOS VALGA	CRISTO NOS VALGA
31		VICE			
32	RINCONADA LLICUAR	RINCONADA LLICUAR	RINCONADA LLICUAR	RINCONADA LLICUAR	RINCONADA LLICUAR

5.7 Measuring Climate Associations with Cholera by District (Objective 4)

In this section I examine the associations between cholera incidence and global and climate parameters by districts in 1998. **Figure 5.46** is monthly cholera incidence (per 100,000 persons) for Piura in 1997-98. The graph illustrates that cholera incidence increased sharply in December of 1997 after a decline that year in the number of reported cases (<40). Cholera incidence peaked in February and March of 1998 and then gradually declined throughout the remainder of the year. In 1998, most districts in the study area observed this pattern of cholera incidence, i.e., sharp rise in SH summer, fall in SH winter (See **Figures 5.47** to **5.52** for monthly cholera incidence per 1000 persons by districts).

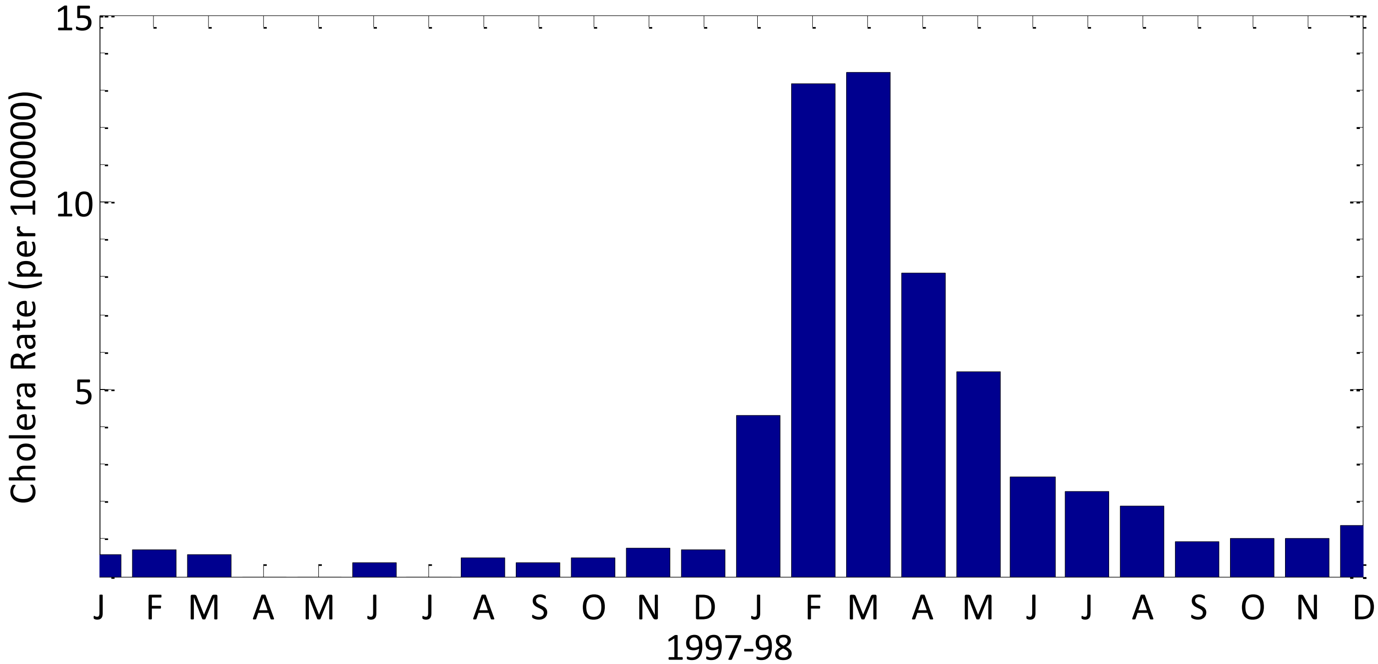


Figure 5.46 Cholera Incidence Rate per 100,000 (square-root transformed) for Piura in 1997-98 by month.

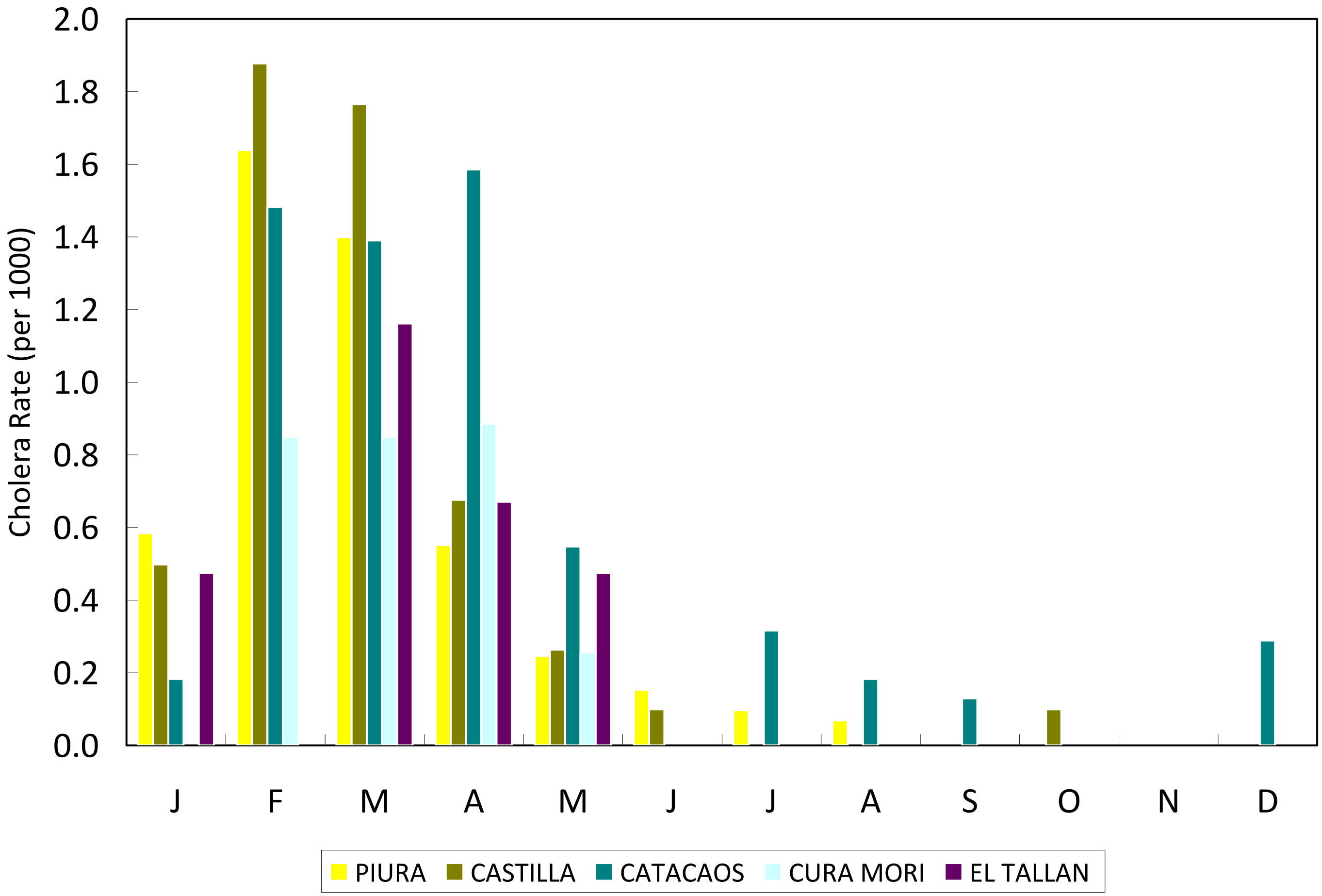


Figure 5.47 Cholera Incidence Rate per 1000 (square-root transformed) by district and month in 1998.

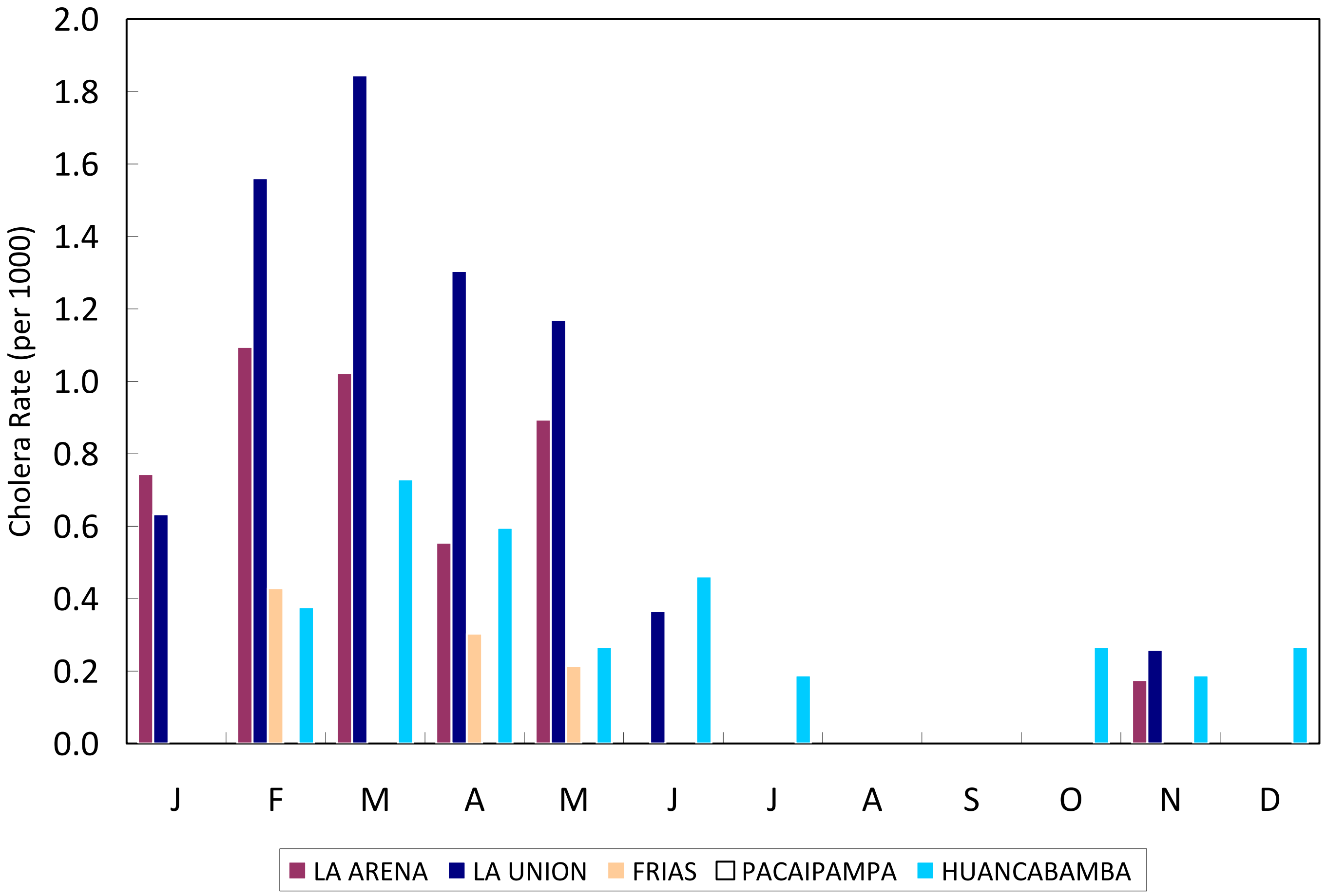


Figure 5.48 Cholera Incidence Rate per 1000 (square-root transformed) by district and month in 1998.

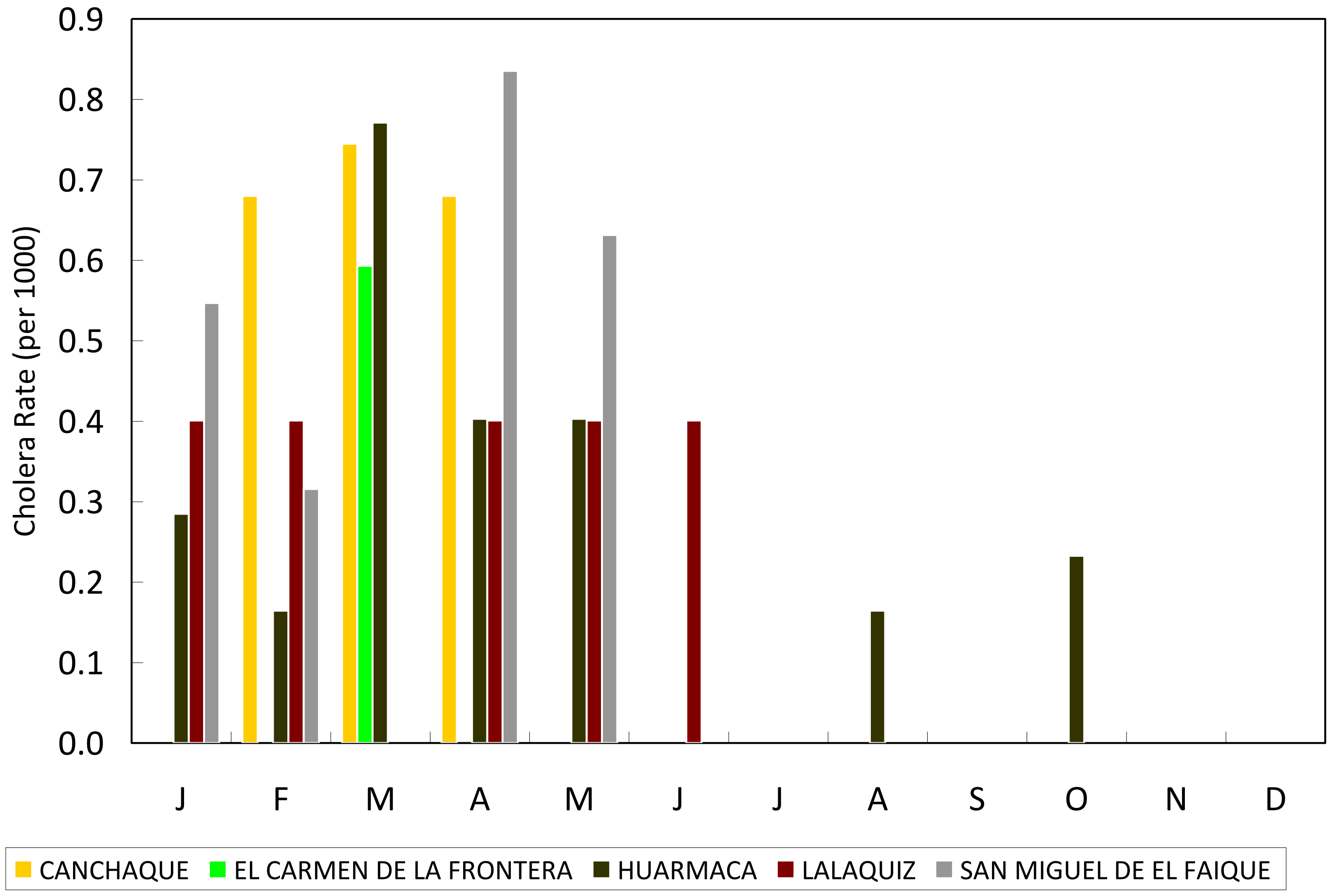


Figure 5.49 Cholera Incidence Rate per 1000 (square-root transformed) by district and month in 1998.

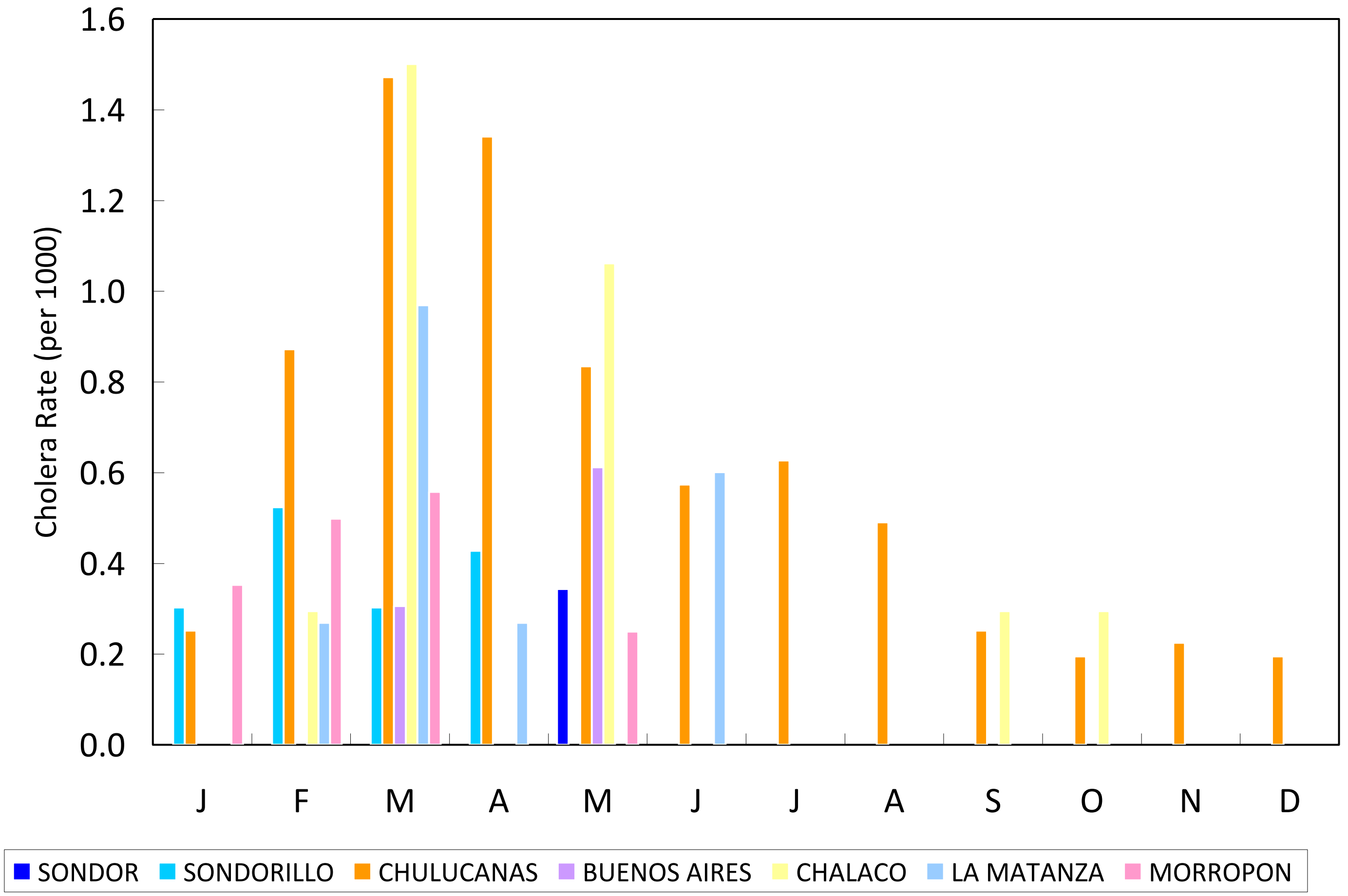


Figure 5.50 Cholera Incidence Rate per 1000 (square-root transformed) by district and month in 1998.

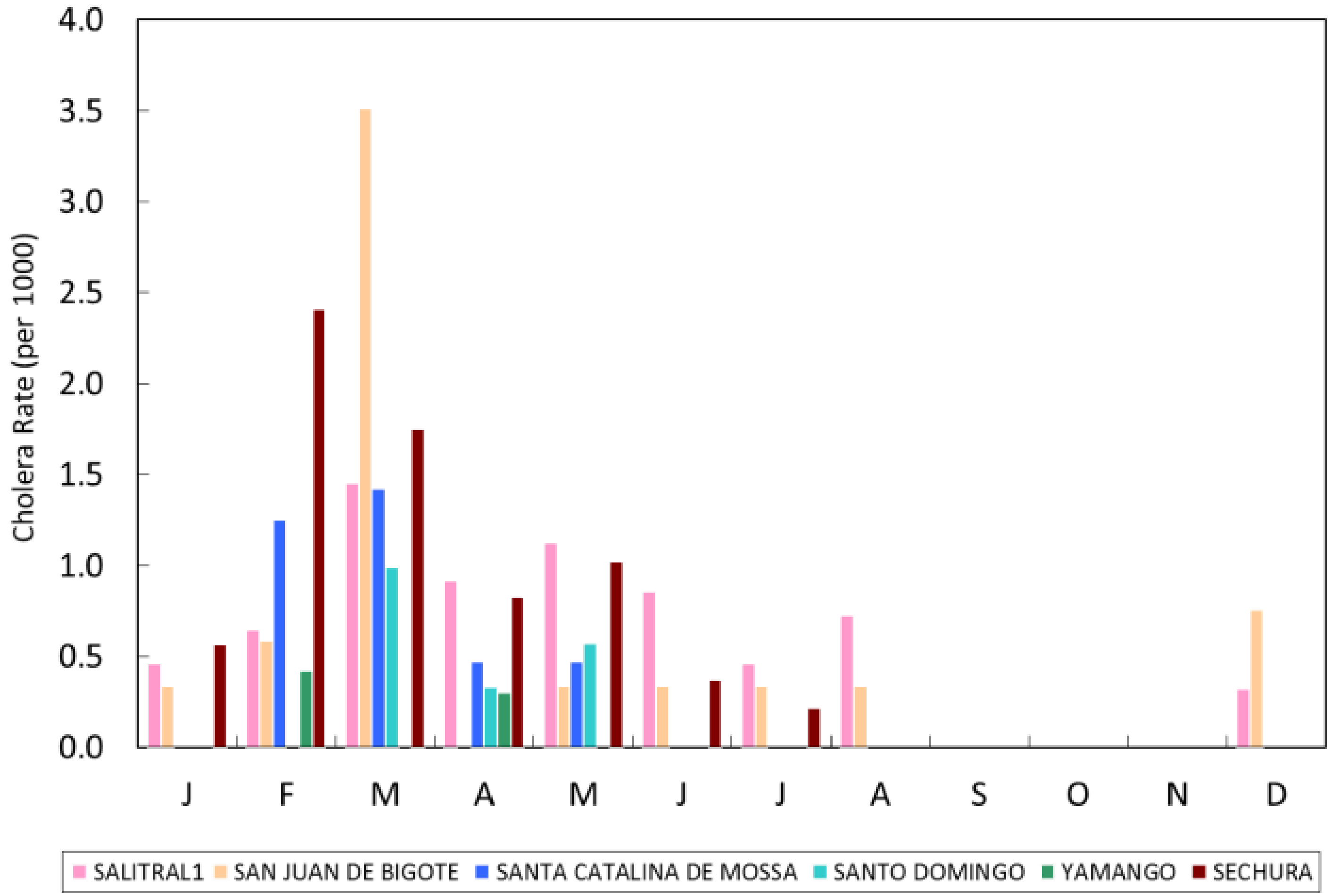


Figure 5.51 Cholera Incidence Rate per 1000 (square-root transformed) by district and month in 1998.

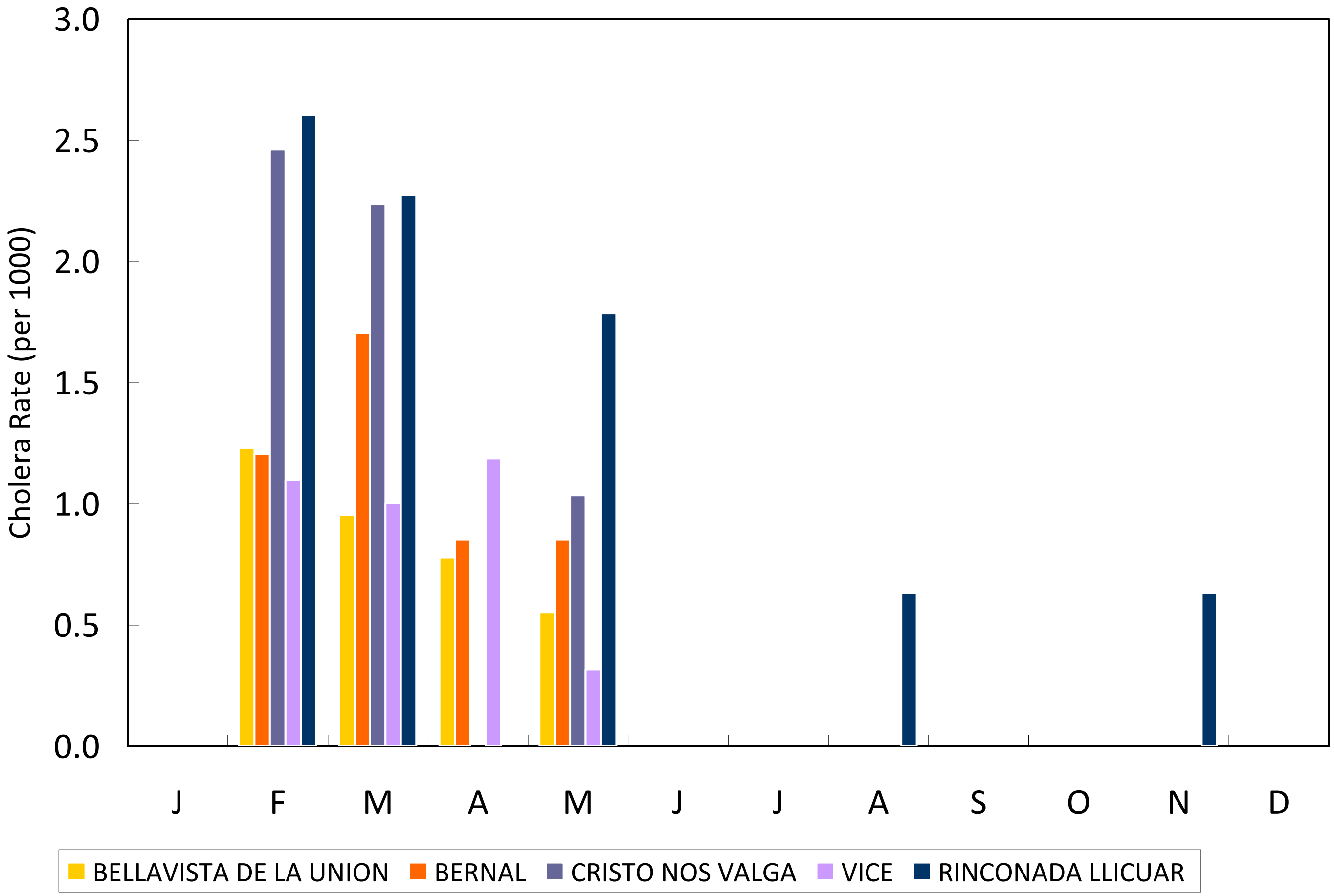


Figure 5.52 Cholera Incidence Rate per 1000 (square-root transformed) by district and month in 1998.

In 1997-98, the rise in cholera incidence coincided with the strongest El Niño of the century, which had a strong influence on regional and local climate in Piura. In **Figure 5.53**, a rise in SSTA (Niño 1+2, Niño 3.4 and Paita) was observed in the SH summer of 1997. SSTA anomalies remained above 1°C until the next summer in 1998. Local mean and minimum temperature anomalies in Piura also show a pattern similar to SSTA in 1997-98 (**Figure 5.54)**. Although a rise in anomalies was observed for local maximum temperature in Piura too, it was followed by a decline from September 1997 to January 1998 (**Figure 5.54)**. **Figure 5.55** is a graph of monthly rainfall anomaly (mm) in Piura in 1997-98. Rainfall's pattern during this time appeared similar to cholera incidence; rainfall total rose sharply in the SH summerand subsequently declined as the SH winter approached.

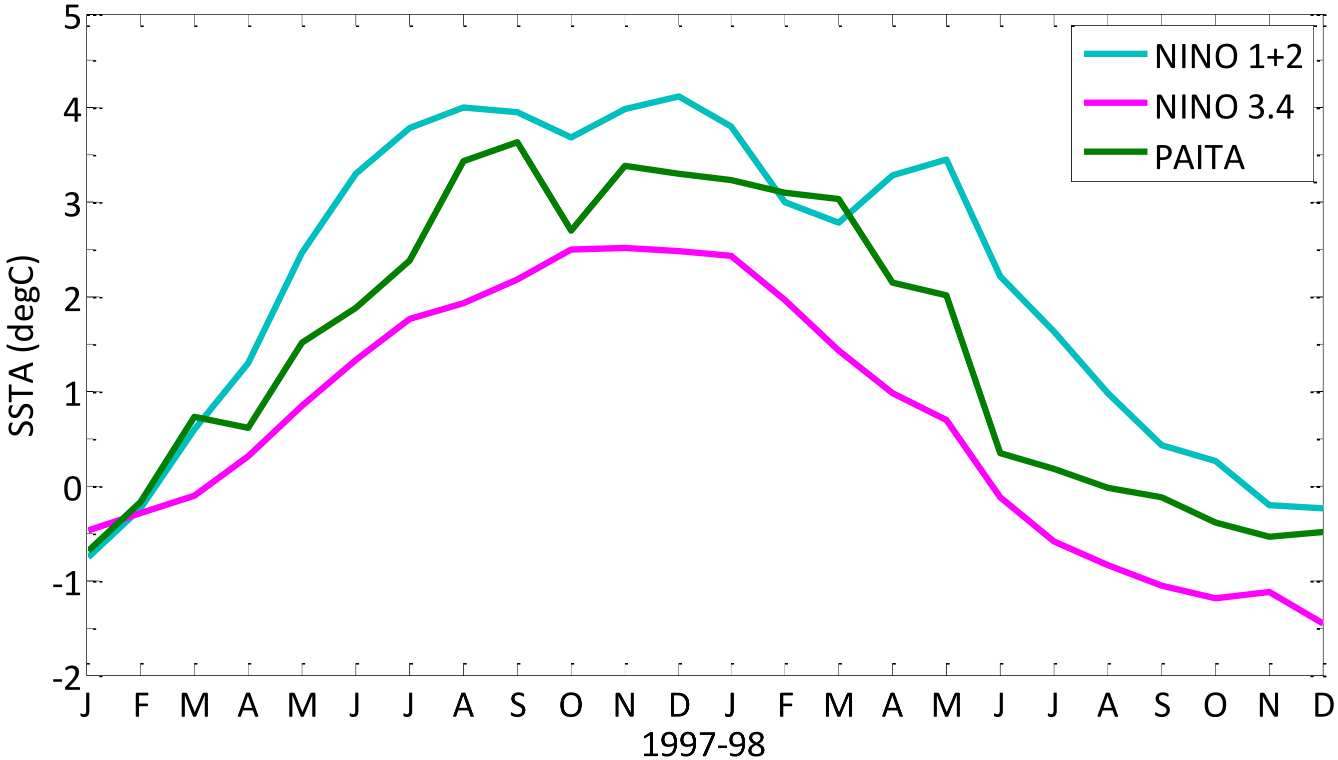


Figure 5.53 Sea Surface Temperature Anomaly (SSTA) by month for Niño 3.4, Niño 1+2, and Paita in 1997-98.

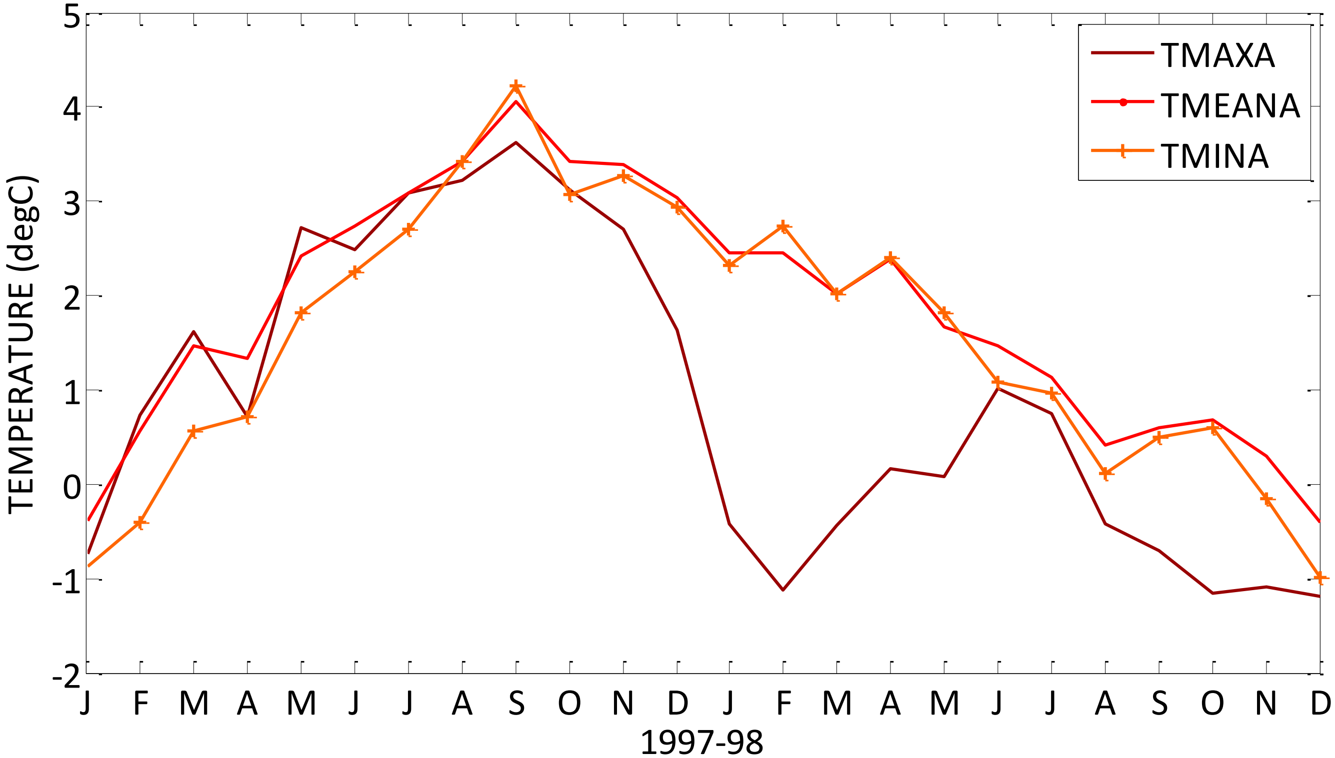


Figure 5.54 Temperature Maximum (TMAXA), Mean (TMEANA), and Minimum (TMINA) Anomalies by month in 1997-98.

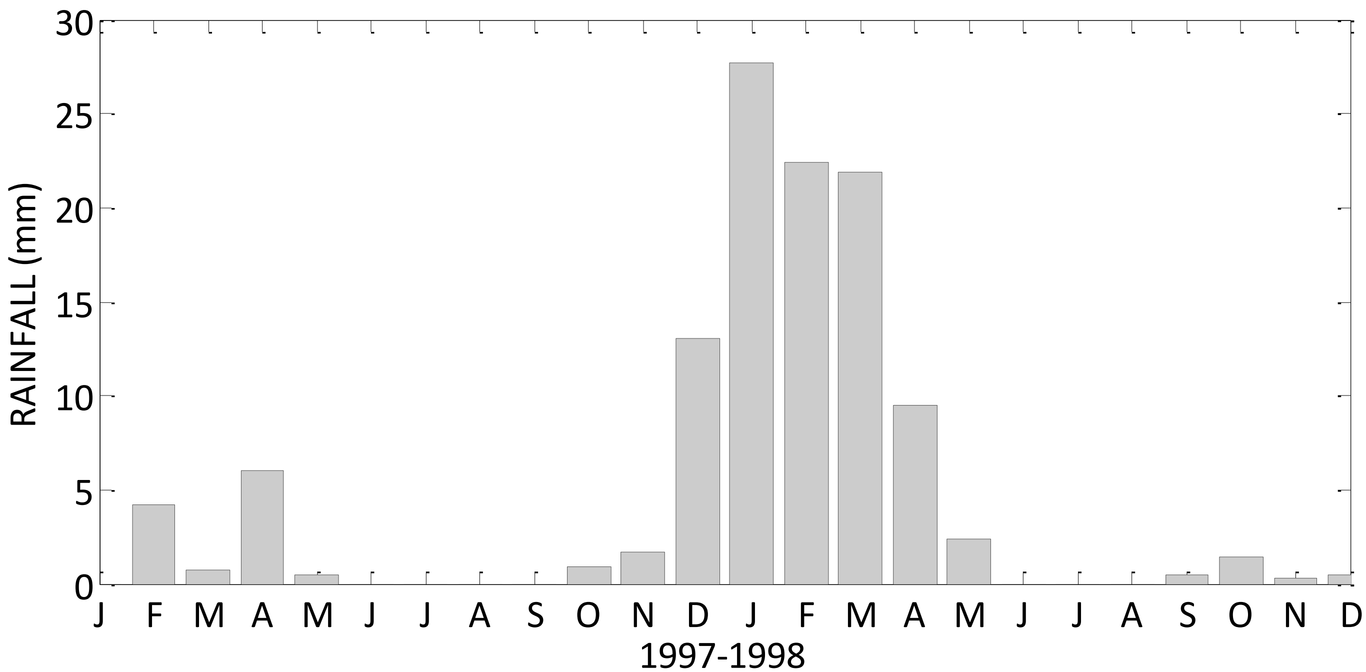
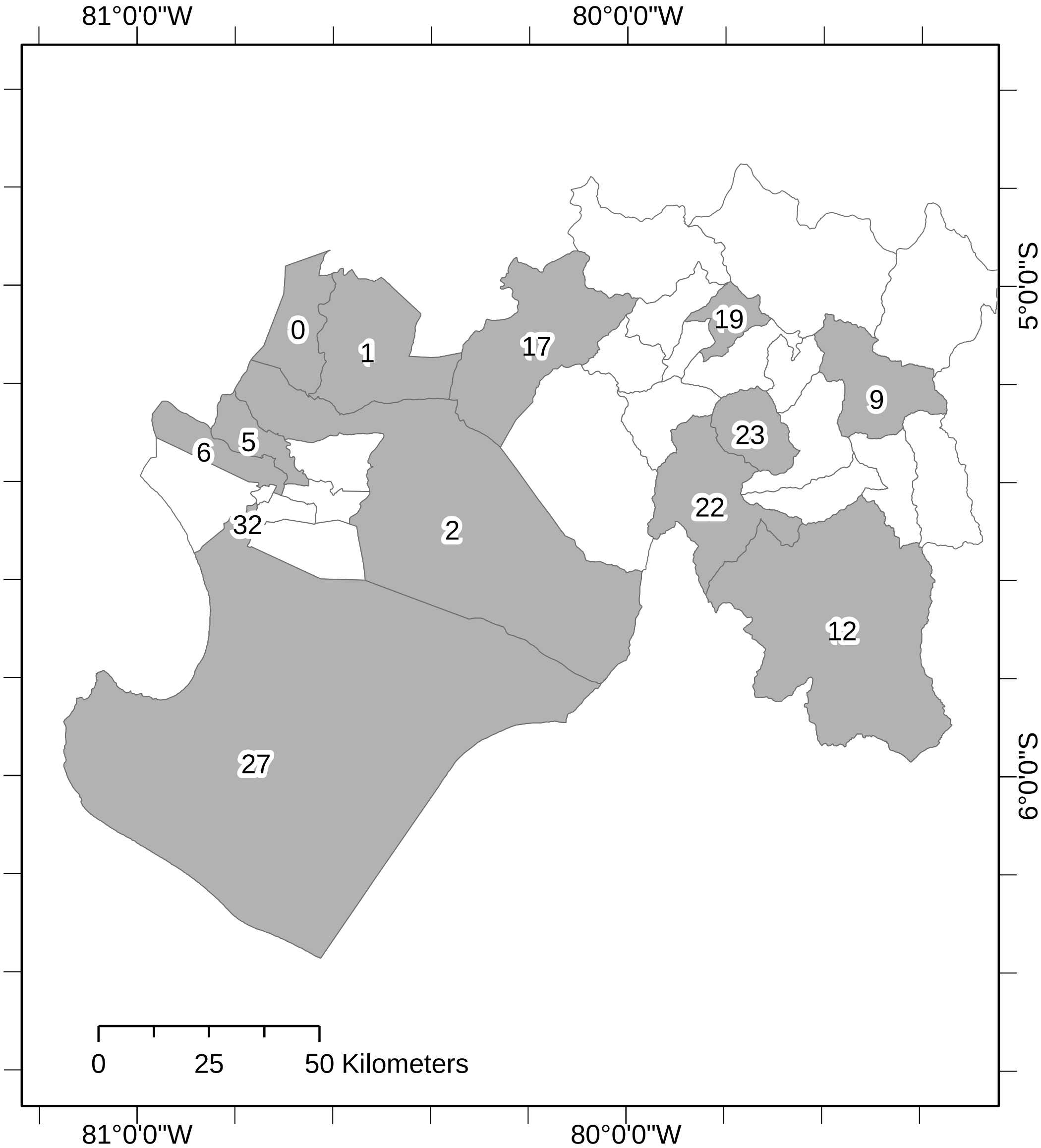


Figure 5.55 Rainfall (square-root transformed) by month in 1997-98.

The spatial associations between climate parameters and monthly cholera incidence by districts (n = 13) were examined using OLS regression. Thirteen districts were selected for a monthly analysis of 1998 based on (a) the GWR analysis; (b) the number of reported cases (>40); and (c) the number of months of reported cholera (=>5).[21] **Figure 5.56** is a map of the selected districts for the climate-cholera analysis. A total of 689 regressions were performed. Approximately 47.0% (324) of associations were statistically significant at the 0.05 level. All the associations were positive and the strength of these associations (measured by r^2) varied by climate variable, temporal lag and district. See **Appendix 5** for a table that shows the r^2 and *p* values (<0.05) by district. The climate parameters with the greatest number of associations were TMEANA (n = 63) and TMINA (n = 61). The climate parameters with the lowest number of associations were rainfall (n = 33) and TMAXA (n = 34). The districts with the most associations were La Union (n = 41), La Arena (n = 38), Sechura (n = 38), and Salitral1 (n = 37). The least number of associations were found in Huancabamba (n = 9), Rinconada Llicuar (n = 6), and Chalaco (n = 3). In San Juan de Bigote no statistically significant associations were observed. The most common time lags were 0-2 months; the least common was 7 months.

[21] I initially began with 15 districts from the GWR analysis and then eliminated 3 districts based on the criteria discussed above. I included the district of Huancabamba even though it was not selected in the GWR analysis because this district reported cholera cases 9 out of 12 months.



District	ID	District	ID
PIURA	0	CHULUCANAS	17
CASTILLA	1	CHALACO	19
CATACAOS	2	SALITRAL1	22
LA ARENA	5	SAN JUAN DE BIGOTE	23
LA UNION	6	SECHURA	27
HUANCABAMBA	9	RINCONADA LLICUAR	32
HUARMACA	12		

Figure 5.56 Map of Selected Districts for Climate-Cholera Analysis.

5.7.1 Mapping Climate Associations with Cholera by District

The climate parameters and temporal lags (>0) which exhibited the strongest associations ($r^2 > 0.70$) were Niño 3.4 SSTA (1 month lag), Paita SSTA (1 month lag), Rainfall (1 month lag), Rainfall (2 month lag), TMAXA (6 month lag), and TMEANA (6 month lag). The climate parameter with the weakest associations was Niño 1+2 SSTA. Associations with lags greater than zero were highlighted because of their potential usefulness to policymakers for early warning systems. **Figures 5.57** to **5.60** are maps of cholera incidence associations with Niño 3.4 SSTA (1 month lag) and Paita SSTA (1 month lag). The strongest associations for these climate parameters were in west coast districts, such as Piura, La Arena, La Union and Sechura. These same districts are also places where cholera was strongly associated with rainfall (1 month lag) (**Figures 5.61** and **5.62**). A cholera-rainfall (1 month lag) link is also strong in two additional west coast districts, Castilla and Catacaos. At a 2 month lag (**Figures 5.63** and **5.64**), cholera's association with rainfall has greater spatial variability; and strong associations shift eastward. Here, Chulucanas and Salitral1 demonstrate strong associations, whereas La Union remains the only strong association on the west coast. The strongest associations between cholera and TMAXA and TMEANA were found at a 6 month lag (**Figures 5.65** to **5.68**). Both parameters had the best associations with cholera incidence on the west coast in the districts of La Union, La Arena, and Sechura[22]. There were also strong

[22] Sechura ($r^2 = 0.63$).

associations between cholera incidence and TMEANA in Huarmaca (eastern Piura) and Chulucanas (central Piura).

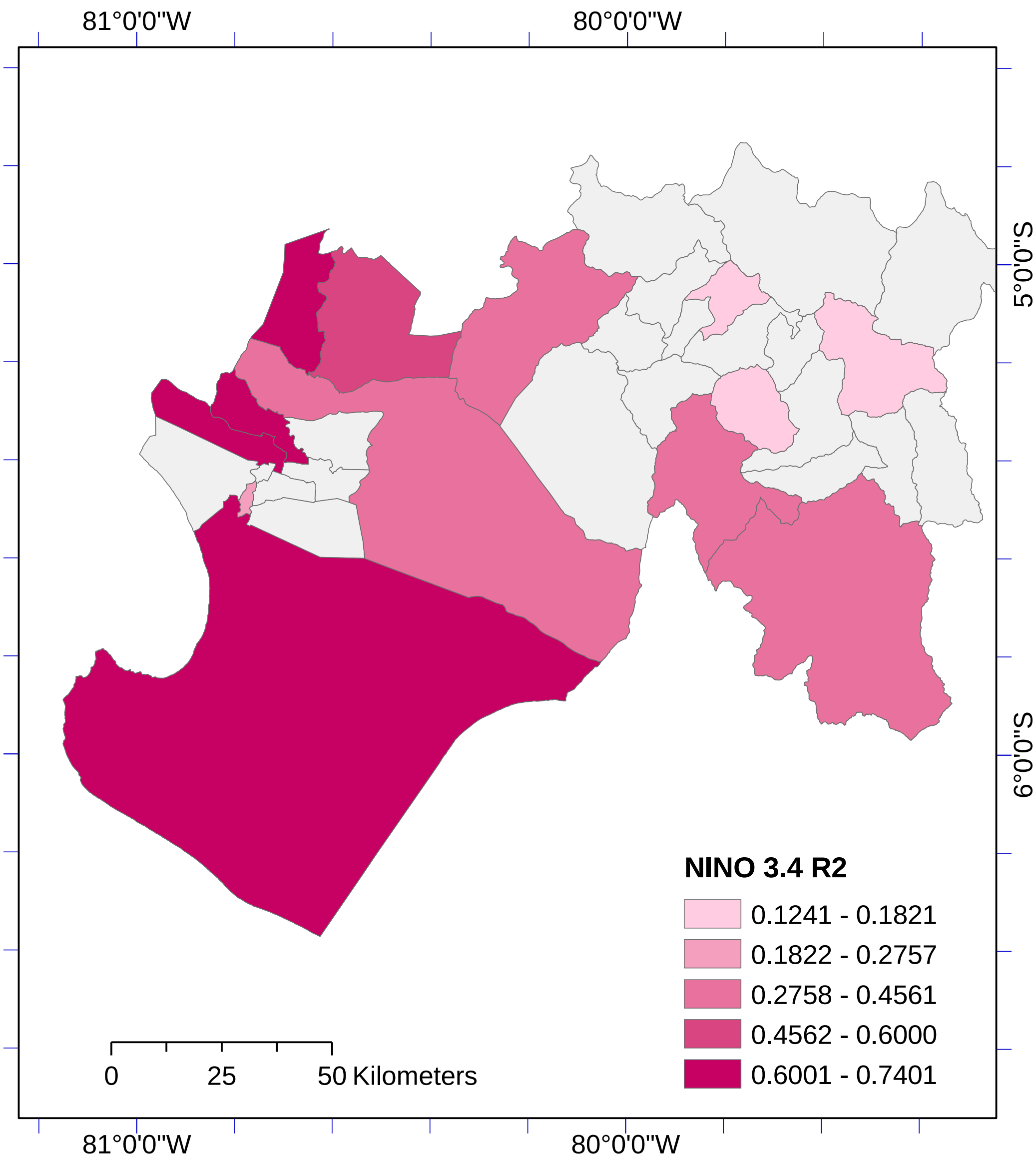


Figure 5.57 Niño 3.4 Sea Surface Temperature Anomaly (SSTA) (1 month lag) Associations with Cholera Incidence Rates (per 1000), R-squared values based on natural breaks classification.

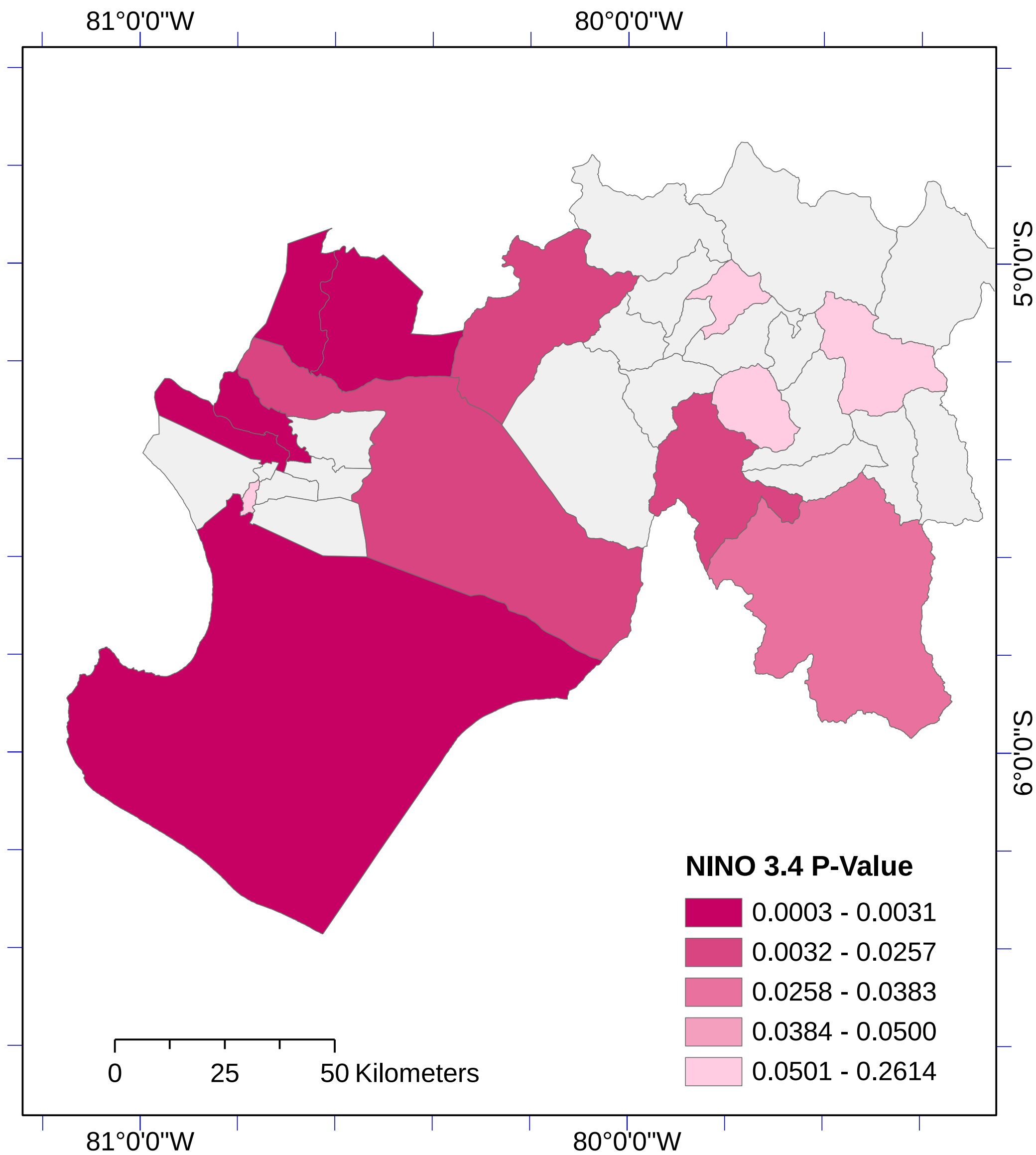


Figure 5.58 Niño 3.4 Sea Surface Temperature Anomaly (SSTA) (1 month lag) Associations with Cholera Incidence Rates (per 1000), *P* values based on natural breaks classification.

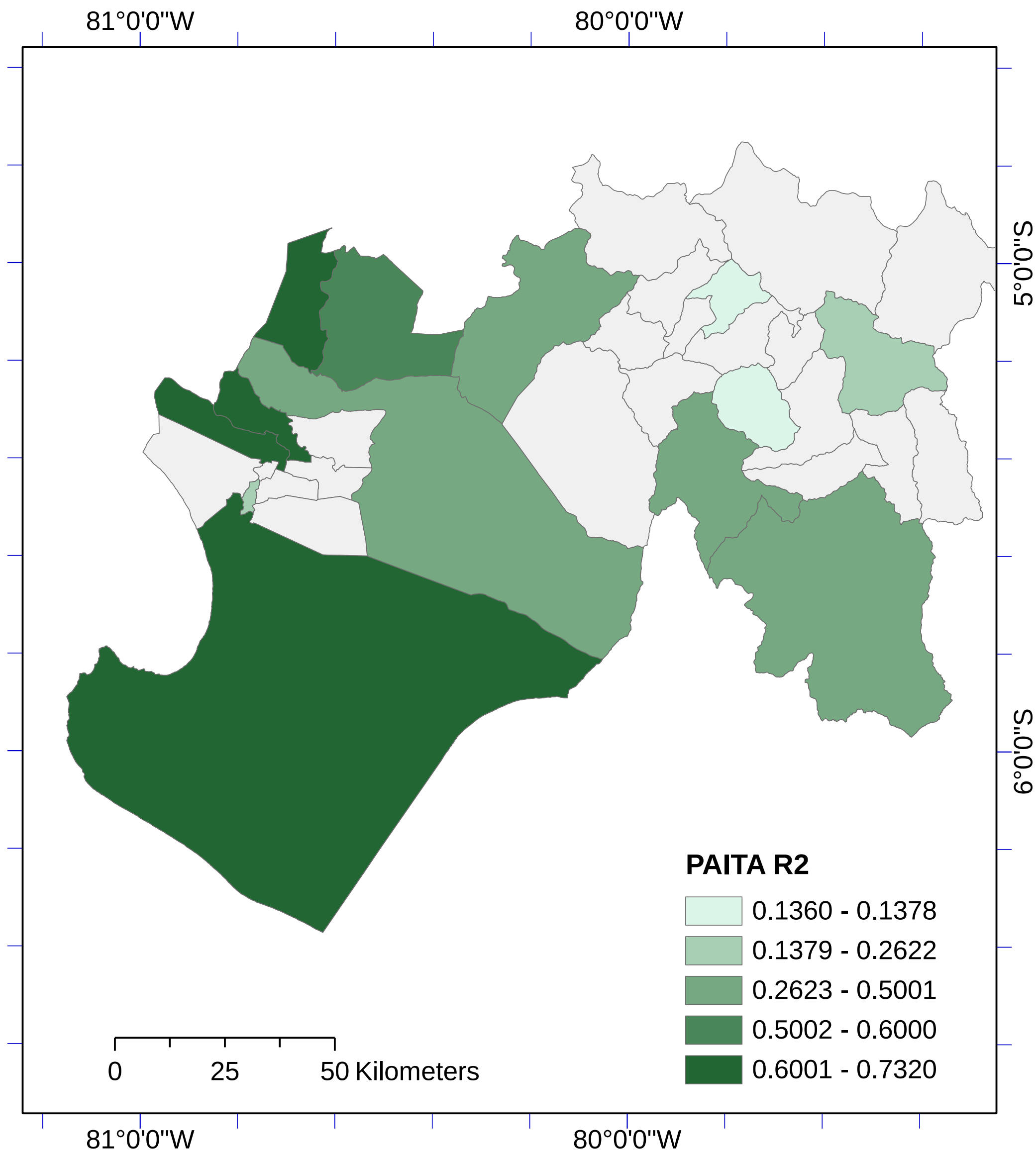


Figure 5.59 Paita Sea Surface Temperature Anomaly (SSTA) (1 month lag) Associations with Cholera Incidence Rates (per 1000), R-squared values based on natural breaks classification.

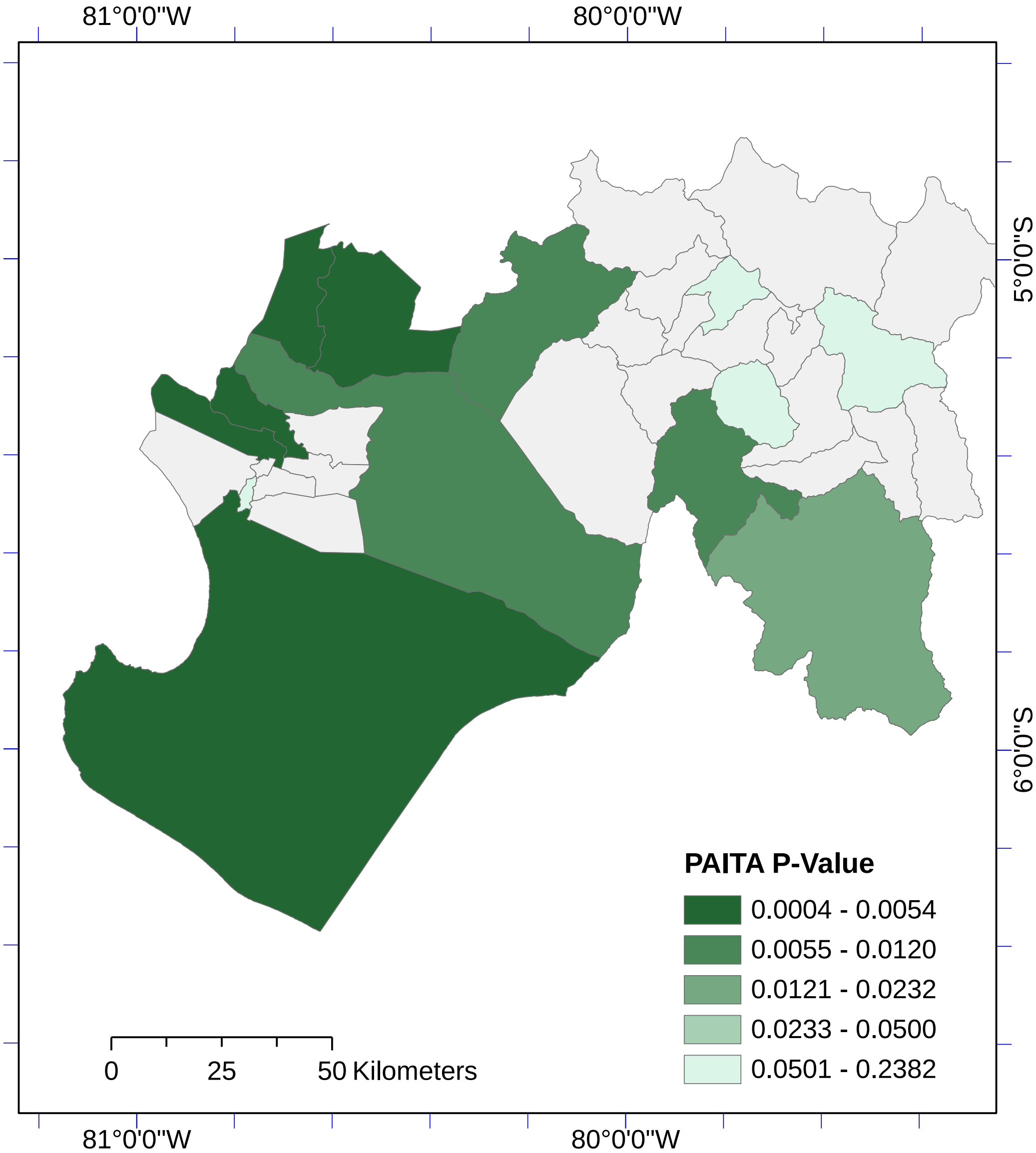


Figure 5.60 Paita Sea Surface Temperature Anomaly (SSTA) (1 month lag) Associations with Cholera Incidence Rates (per 1000), *P* values based on natural breaks classification.

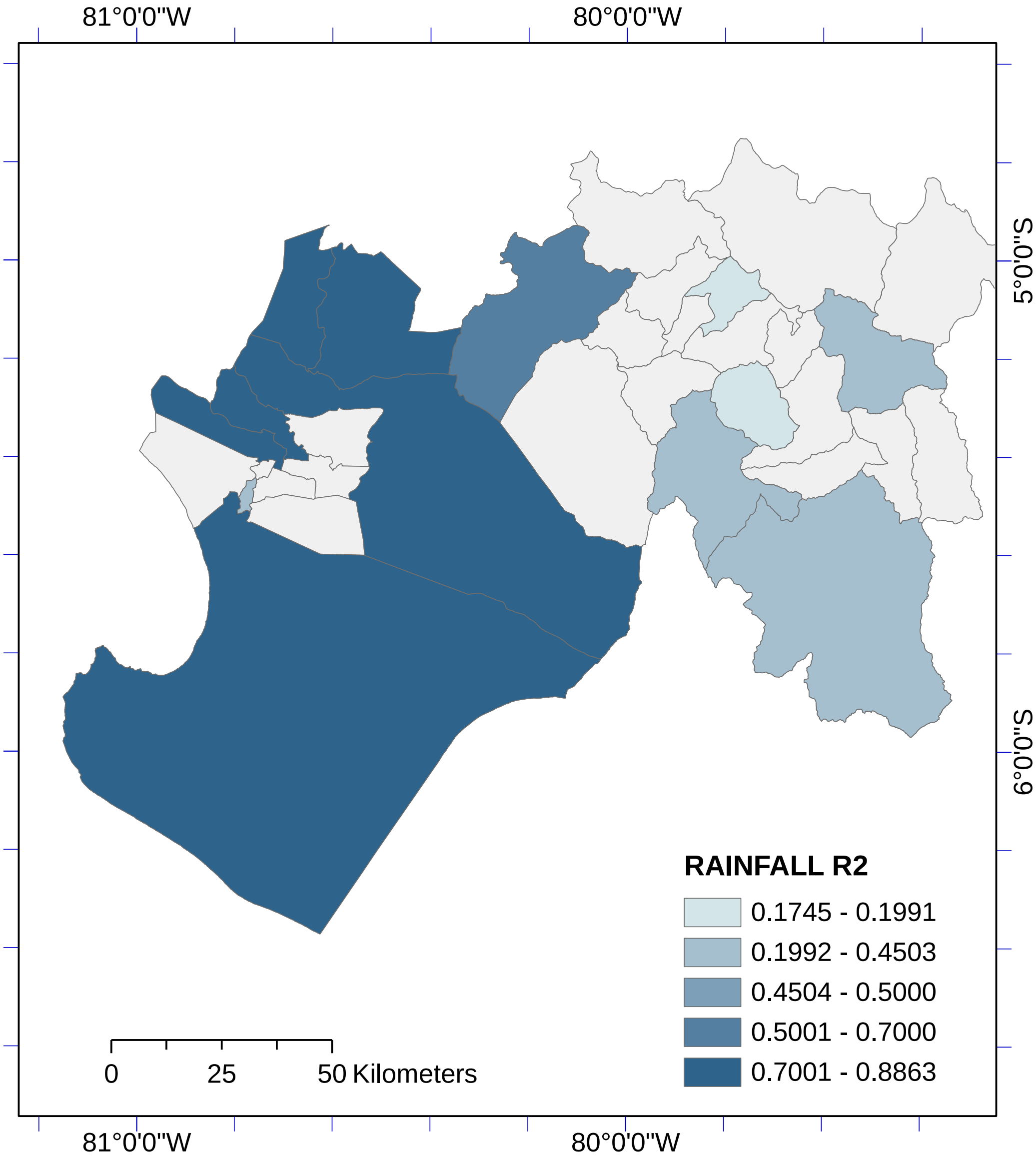


Figure 5.61 Rainfall Total (1 month lag) Associations with Cholera Incidence Rates (per 1000), R-squared values based on natural breaks classification.

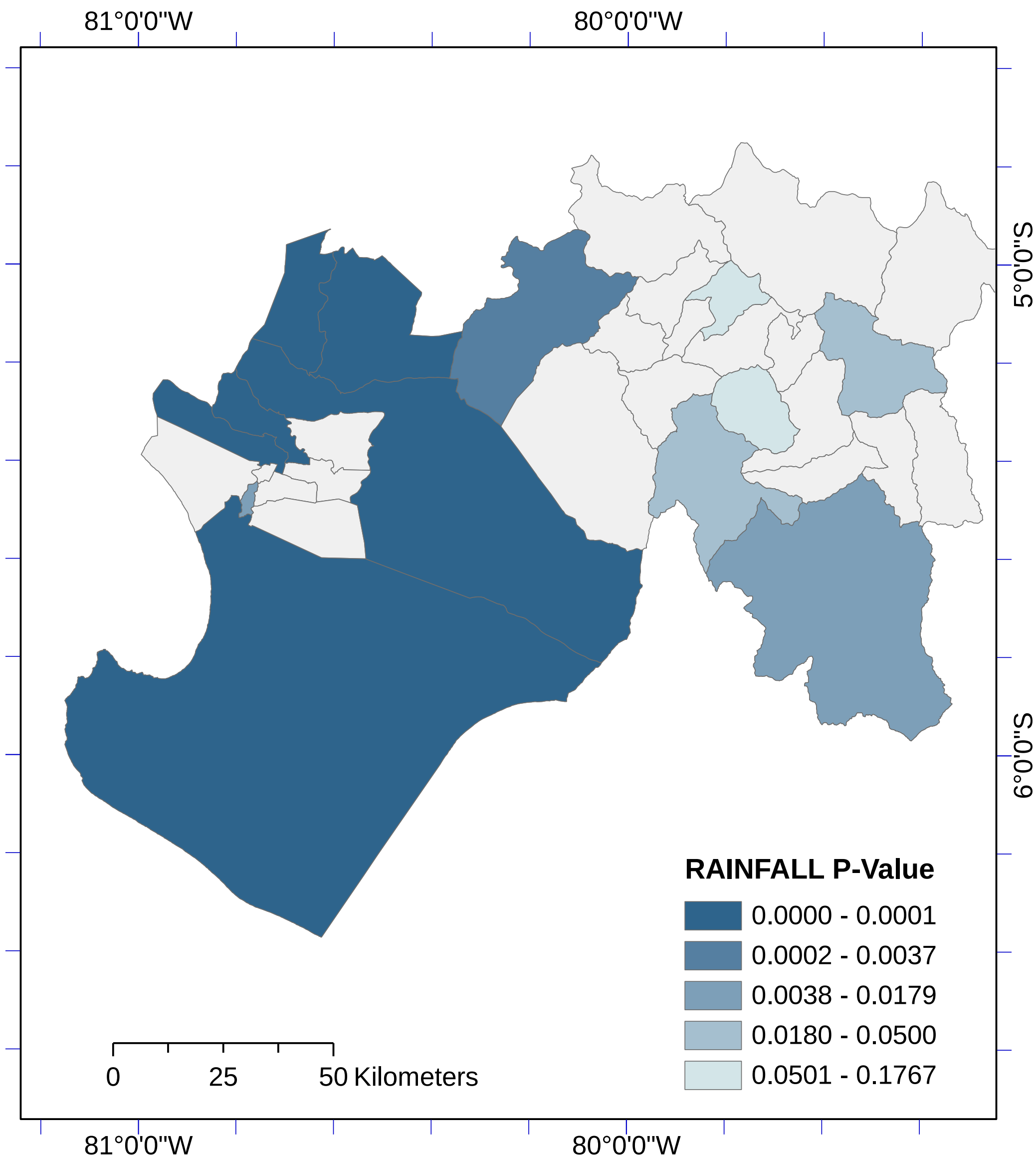


Figure 5.62 Rainfall Total (1 month lag) Associations with Cholera Incidence Rates (per 1000), *P* values based on natural breaks classification.

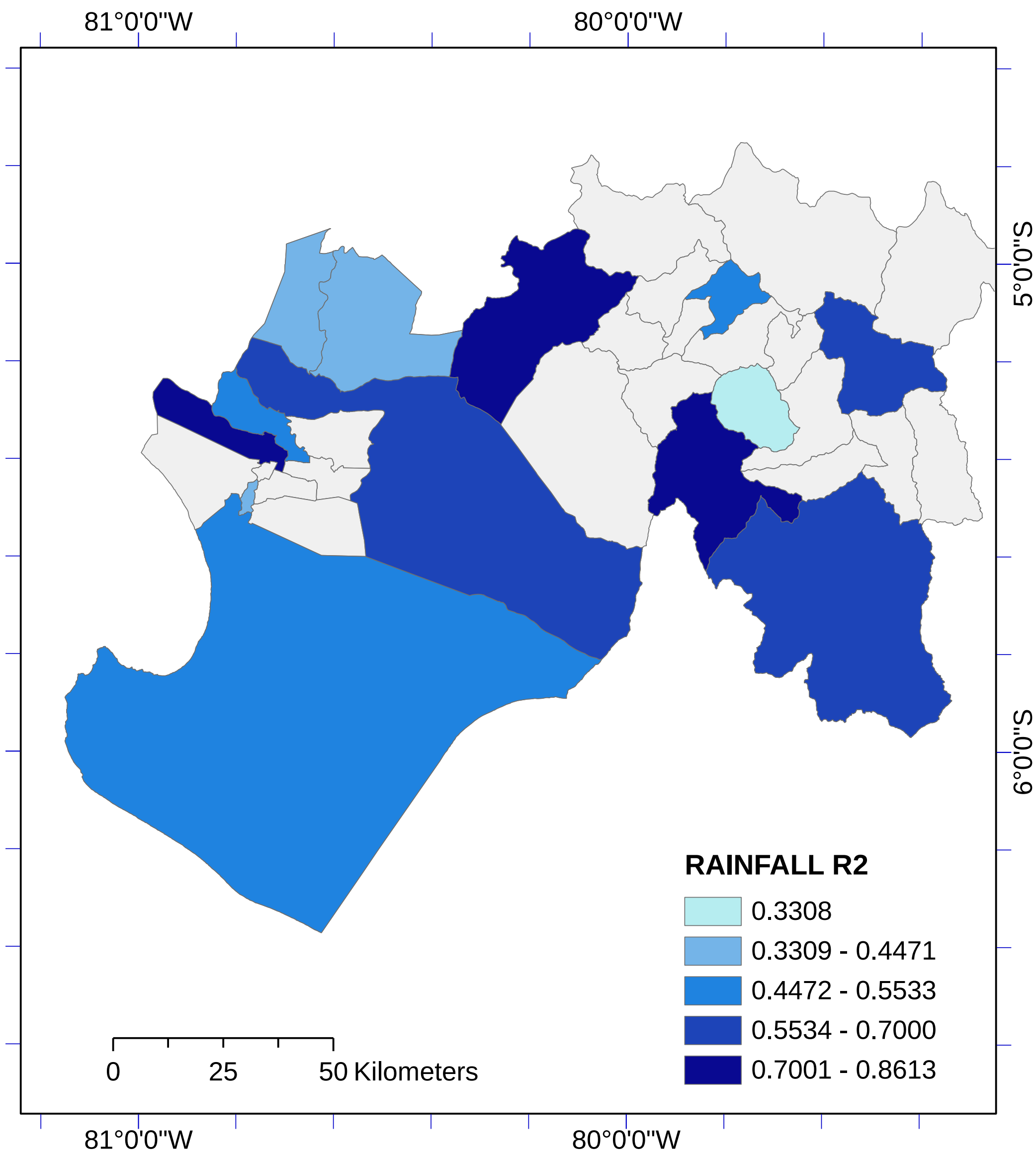


Figure 5.63 Rainfall Total (2 month lag) Associations with Cholera Incidence Rates (per 1000), R-squared values based on natural breaks classification.

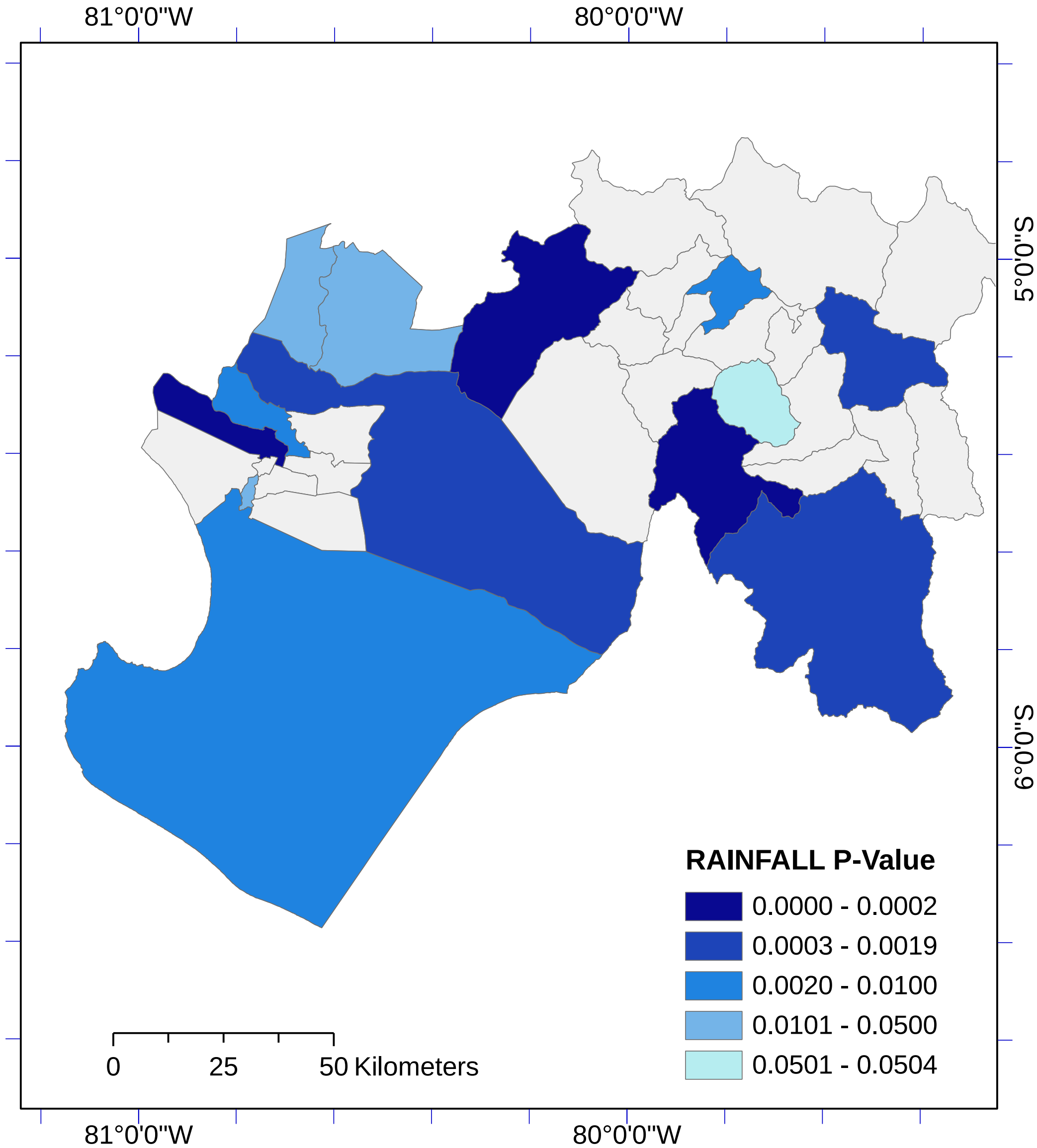


Figure 5.64 Rainfall Total (2 month lag) Associations with Cholera Incidence Rates (per 1000), *P* values based on natural breaks classification.

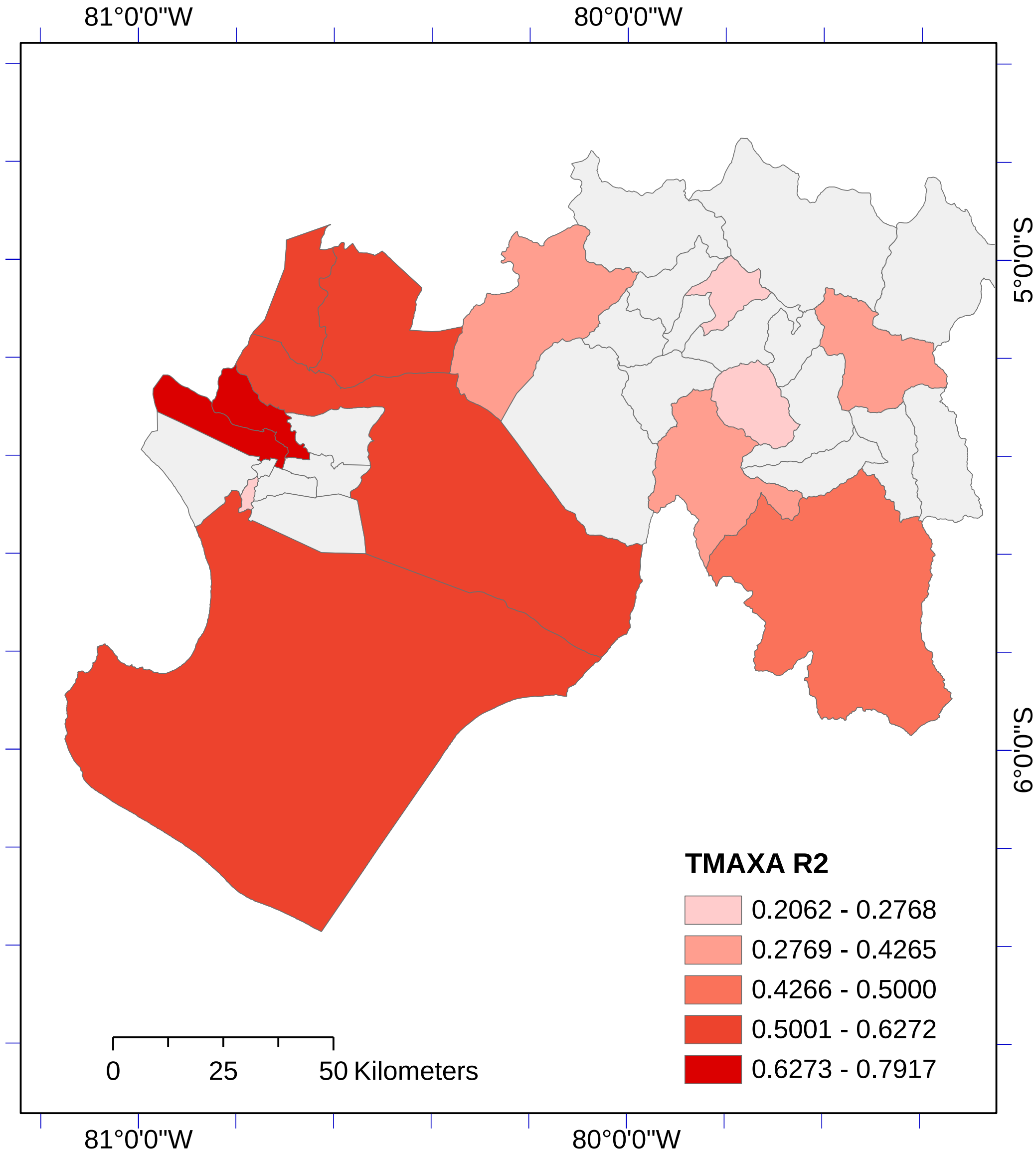


Figure 5.65 Temperature Maximum Anomaly (TMAXA) (6 month lag) Associations with Cholera Incidence Rates (per 1000), R-squared values based on natural breaks classification.

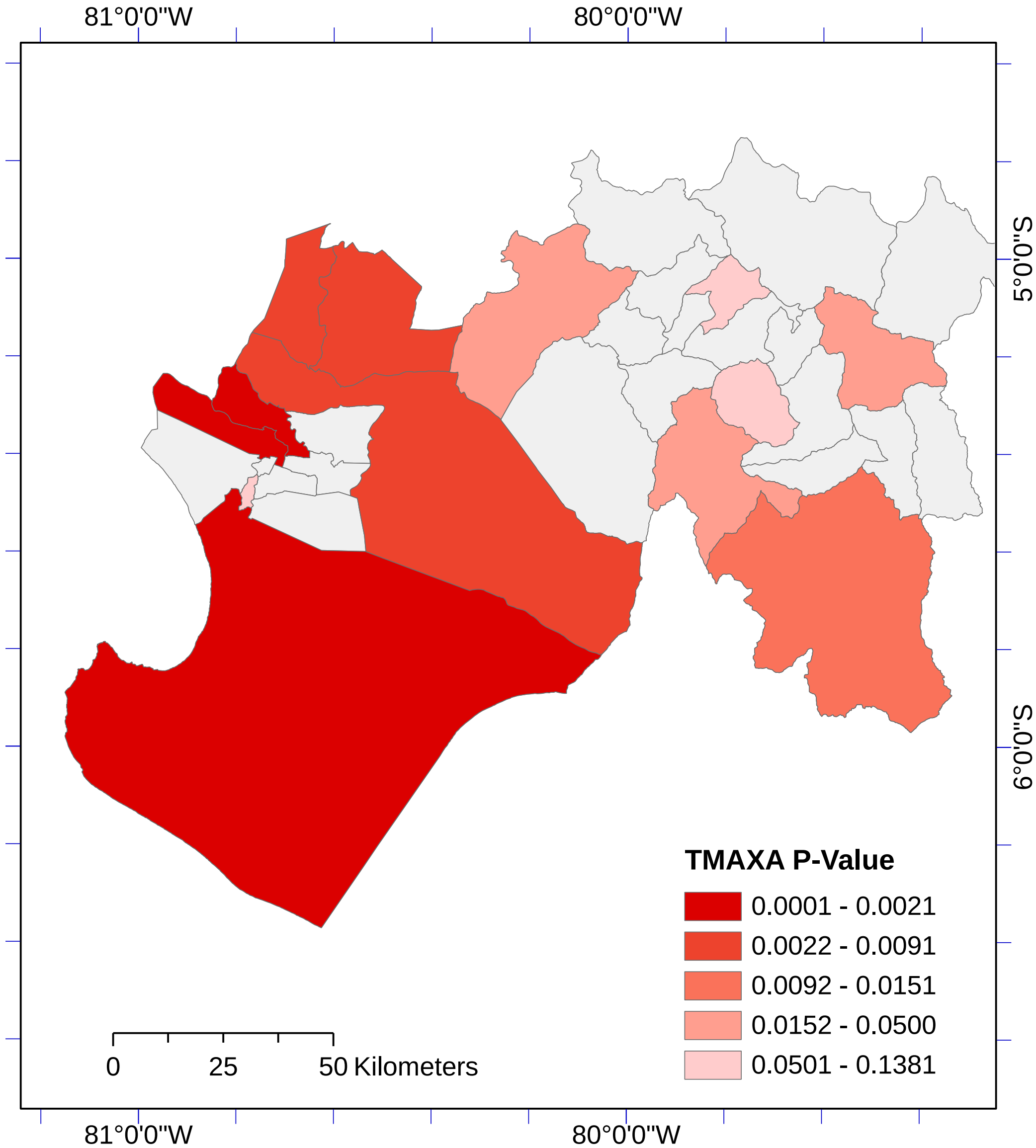


Figure 5.66 Temperature Maximum Anomaly (TMAXA) (6 month lag) Associations with Cholera Incidence Rates (per 1000), *P* values based on natural breaks classification.

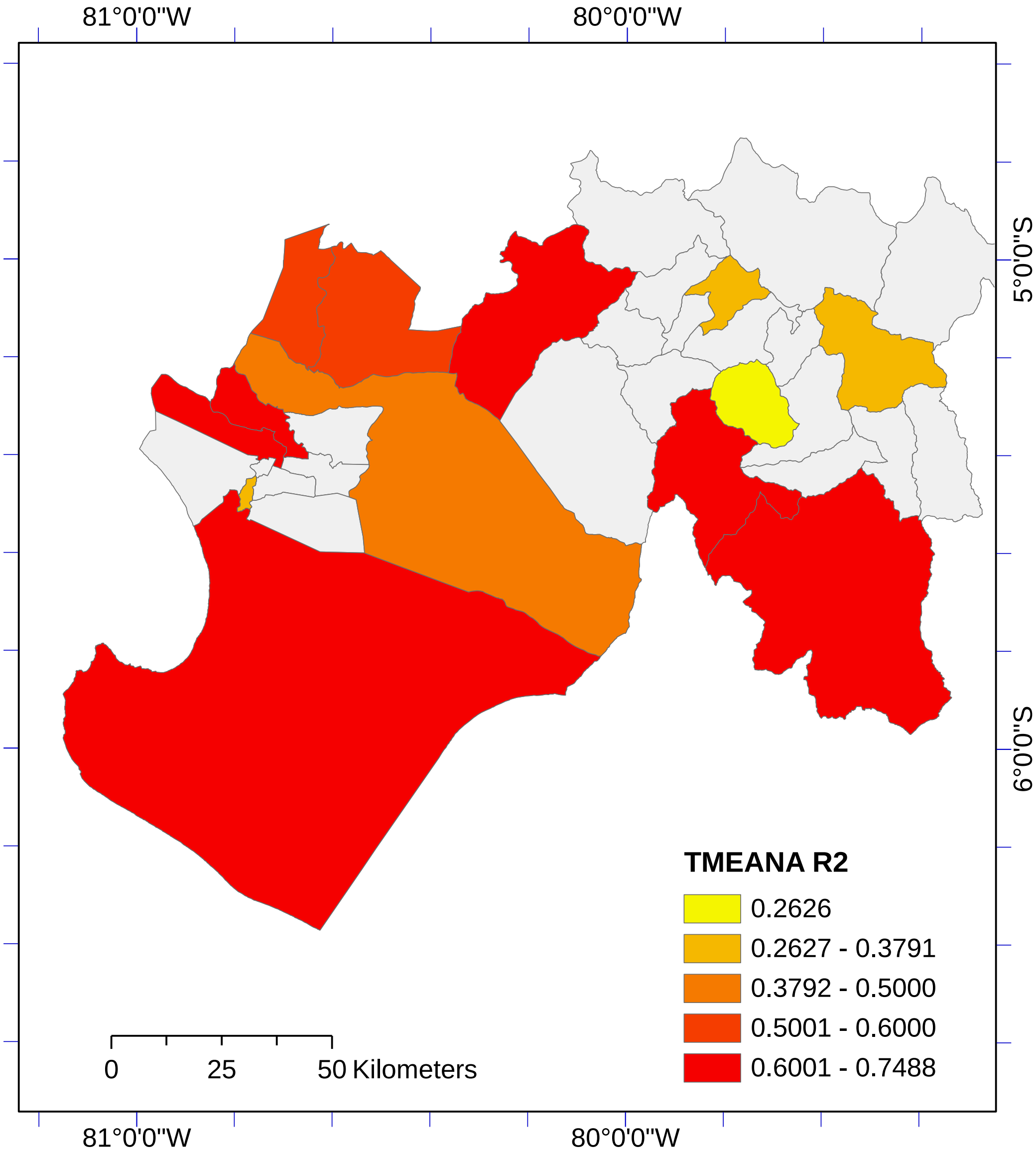


Figure 5.67 Temperature Mean Anomaly (TMEANA) (6 month lag) Associations with Cholera Incidence Rates (per 1000), R-squared values based on natural breaks classification.

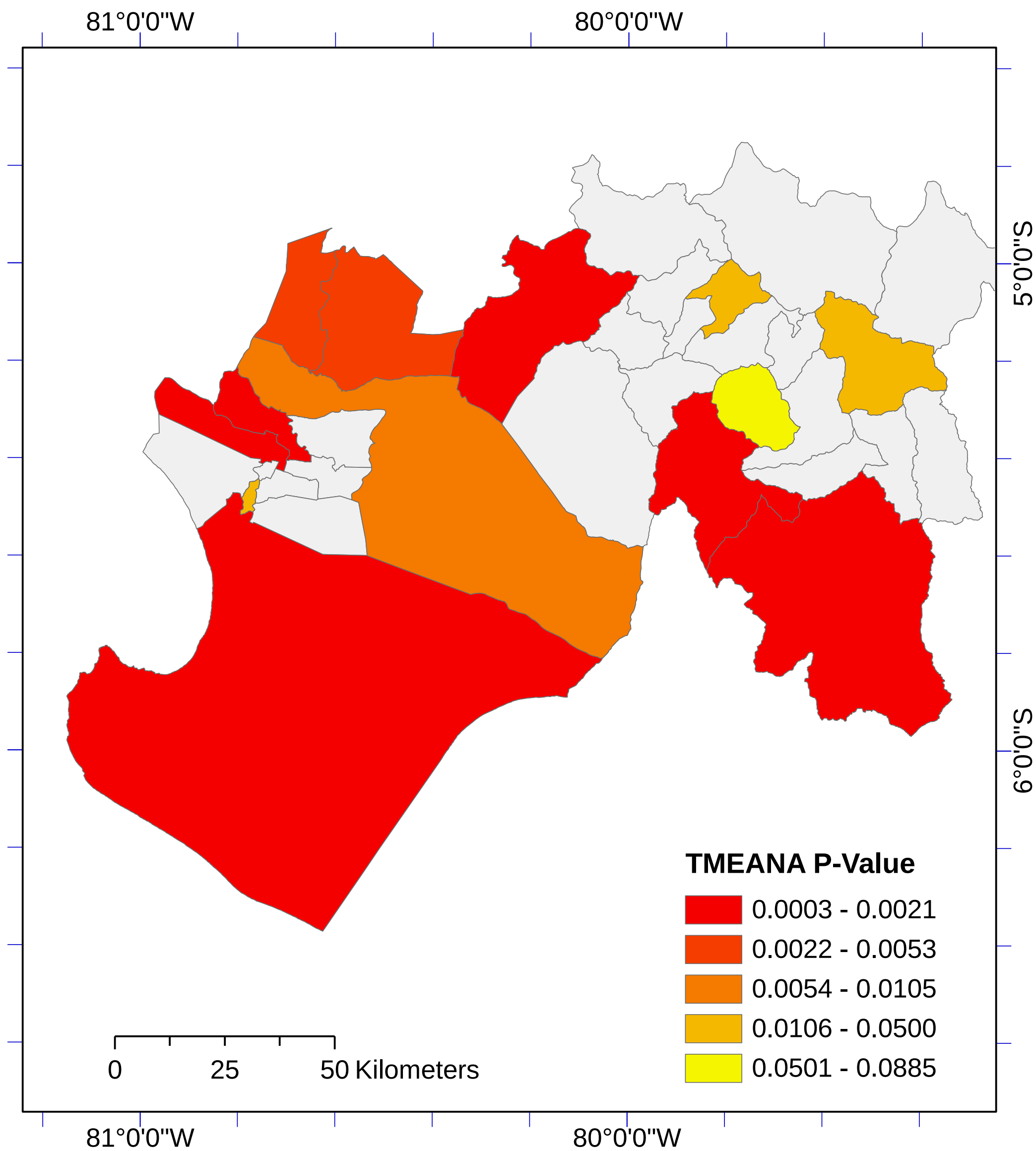


Figure 5.68 Temperature Mean Anomaly (TMEANA) (6 month lag) Associations with Cholera Incidence Rates (per 1000), *P* values based on natural breaks classification.

In sum, associations between cholera and climate parameters were strongest on the west coast. The time lag associated with local temperature anomaly link to cholera was greater (6 months) than those associated with SSTA and rainfall (1 month). In terms of parameters, rainfall had the strongest association (p > 0.85) with cholera incidence among all climate parameters for several districts.

CHAPTER 6: DISCUSSION

In my dissertation research I investigated the temporal and spatial associations between ENSO and cholera incidence in Piura, Peru from 1991 to 2001. I also examined whether the temporal associations were stronger after 1992 and whether social vulnerability could explain the spatial variability of the ENSO-cholera associations during the 1997-98 El Niño. In this chapter, I first discuss the key findings of this dissertation in order to answer my research questions and hypotheses. I then present a reflective statement about the ethical geographies of my dissertation results and the overall research project.

6.1 The ENSO Context

The comparative examination of ENSO events by Niño region revealed that there were important differences and similarities between the Niño 3.4 and Niño 1+2 indices throughout the 1990s. From 1990 to 1995, El Niño conditions were more prevalent in the Niño 3.4 region compared to the Niño 1+2 region, where La Niña conditions were the dominant mode. There were also differences in the timing of the onset of El Niño conditions in each of the regions. For instance, during the first year of the cholera epidemic the Niño 3.4 index indicated that an El Niño began in May of 1991 and lasted until July of 1992. However, according to the Niño 1+2 index, it was shown that an El Niño began in November of 1991 and lasted until June of 1992. Of import here is that each region's ENSO characteristics, while different, commonly suggested that El Niño developed well after the onset of the cholera epidemic in October of 1990 (based on

Seas et al. [2001]). Similarly, in 1997, the two Niño regions have different onset dates (i.e., March versus May of 1997), but also show and support the notion that El Niño conditions were present during the onset of the cholera resurgence. In the subsequent sections, I interpret my results given this ENSO context.

6.2 Temporal Associations between Cholera and ENSO in Piura, Peru: 1991-2001

In Objective 2, I demonstrated the existence of temporal associations between cholera cases in Piura and global and local sea surface temperature anomalies (i.e., Niño 3.4 SSTA, Niño 1+2 SSTA and Paita SSTA) and local rainfall anomaly. These associations measured as the wavelet coherence between cholera and climate can be summarized as non-stationary positive relationships, where cholera and climate parameters were correlated and co-varied in localized time frequency space. Significant coherence between cholera and sea surface temperature anomalies were detected at two time intervals at a scale band of 1.5-2 yr as follows: (a) cholera and Niño 3.4 SSTA – 1993 and 1997 to 1999; (b) cholera and Niño 1+2 SSTA – 1993-94 and 1997 to 1999; and (c) cholera and Paita SSTA – 1993-94 and 1998-99. Significant coherence between cholera and local rainfall anomaly was detected from 1997 to 1999 at several scales ranging from 7 months to 2.25 yr. Although an association between cholera and local temperature anomalies (i.e., maximum, mean and minimum) was found, their phase relationships (i.e., direction of association) were inconsistent across scales, suggesting that these associations were dubious and therefore, unreliable (Grinsted et al. 2004). It was also shown that the temporal associations between cholera and global and local

SSTA, and local rainfall anomalies, were positive and lagged in time such that cholera followed each climate series as follows by time interval: (i) in 1993-94 – Niño 3.4 SSTA and Paita SSTA by more than 6 months; and Niño 1+2 SSTA by 6 months; (ii) in 1997-99 - Niño 3.4 SSTA and Paita SSTA by more than 6 months; Niño 1+2 by 2-3 months; and local rainfall anomaly by zero to one month.

6.2.1 Cholera and Global Climate

On a global scale, the exposure pathways associated with the Niño 3.4 region suggested that sea surface temperature anomalies contributed to cholera incidence in Piura through a six-month process (i.e., the time lag) via ecological impacts on: (a) distant marine conditions which in turn affected vibrios or aquatic reservoirs off the coast, supporting previous studies in Dhaka, Bangladesh, which found that cholera fluctuated with Niño 3.4 SST (Pascual et al. 2000; Rodo et al. 2002; Koelle et al. 2005); and/or (b) local climate inland (i.e., via teleconnections) which in turn may have influenced vibrio reproduction (e.g., temperature – Pascual et al. 2000), distribution (e.g., rainfall – Ruiz-Moreno et al. 2007), or transport (e.g., rainfall – Ruiz-Moreno et al. 2007).

Two key factors associated with the pathways described above are the time lag and the distance from the ocean-climate source of impact to the vibrio source of infection. In a study by Pascual et al. (2000), it was suggested that cholera incidence followed Niño 3.4 SST by 8 to11 months because of the distance (of the teleconnection) between Dhaka, Bangladesh and the central equatorial Pacific Ocean. Therefore, the time relationship found between cholera incidence and Niño 3.4 SSTA in this dissertation research may be explained by Piura's geographic proximity to air-sea interactions in the central equatorial Pacific Ocean. Thus, the shorter time delay (i.e., 6 months +, but less than a year) observed in Piura may be explained by the shorter distance to the Niño 3.4 region.

While distance may explain part of the temporal link between cholera and Niño 3.4, it cannot fully explain cholera's link with the Niño 1+2 region. Niño 1+2 represents sea surface temperature conditions off the coast of northern Peru and southern coast of Ecuador. Given the proximity of this Niño region, one could assume based on the Niño 3.4 finding that the shorter distance to the climate source of impact would also suggest a shorter time delay. Although this study did find a shorter time lag (i.e., 2-3 months) between cholera and Niño 1+2 SSTA from 1997 to 1999, it also found that Niño 1+2 lead cholera by 6 months in 1993-94, just as the Niño 3.4 estimates indicated. This finding may suggest that understanding the temporal link requires a closer look at the geography of the region.

First, the characteristics of each region in terms of sea surface temperature conditions at each time interval could reveal additional information to help understand the temporal pathway associated with Niño 1+2 SSTA (see Table 5.1). For example, interestingly, in 1993 it was estimated that both regions were in neutral conditions. During that year cholera cases followed the seasonal pattern observed nationally by public health authorities in Peru (i.e., up in summer, down in winter, up as summer approaches – see Table 5.3). It was not until the spring of 1994 that the SST conditions in the two regions began to diverge; an El Niño developed in the Niño 3.4 region, while a La Niña developed in the Niño 1+2 region. Actually, it appeared that cholera cases declined with the onset of ENSO events. In contrast, in 1997 to 1999, most monthly sea surface temperature conditions were either El Niño or La Niña in each region. Furthermore, these conditions were associated with strong El Niño and La Niña events and the cholera resurgence. This observation may suggest that the difference in the magnitude of anomalies from 1997 to 1999 may have had a stronger influence on the ecology of cholera in Piura, and therefore, should also be studied in order to understand temporal associations between cholera and SST.

Second, in addition to sea surface temperature conditions in the region, it may also be important to consider the region's proximity to the South American continent and Piuran population. This is not to suggest that distance is a factor again; rather it is to propose that coastal land features coupled with population factors (e.g., sociodemographic) on the immediate coast may explain the differences between the Niño 3.4 and Niño 1+2 regions and their associations with cholera. Unlike the Niño 3.4 region, the Niño 1+2 region is adjacent to the South American continent. Importantly it borders a low lying desert environment inhabited by coastal communities of Piura where livelihoods consist of fishing and farming. This may support Epstein's initial theory about climate and cholera which suggests that run-off from agricultural activities, as one example, may have contributed to the plankton blooms on the coast of Peru, which subsequently lead to transmission inland (1993). It highlights that the complexity of local topography, climate and human-environment interactions on Piura's coast contributed to different temporal associations between cholera and the eastern end and central equatorial Pacific Ocean.

6.2.2 Cholera and Local Climate

On a local scale, it was shown that cholera was temporally associated with sea surface temperature anomalies at Paita in 1993-94 and 1997 to 1999. As discussed earlier, Paita is a port in Piura. Although it is located on the immediate coast, the SST impact on cholera was delayed by more than 6 months. This observation reiterates the importance of locality in the temporal process of cholera transmission as stated above because it provides evidence that local SST associations previously found in Lima (e.g., time lags were 0-1 month – Gil et al. [2004]) are different by location. The association at Paita may in part be explained by the influence of the Niño 3.4 region on Paita SSTA. Paita is highly sensitive to changes in ocean-atmosphere interactions in the equatorial Pacific Ocean, namely El Niño (Rodriguez 2005). A wavelet coherence analysis (data not shown) of Paita and Niño 3.4 indicated that there existed strong teleconnections between this global and local climate parameter throughout most of the 1990s at a range of time lags of zero to 1 month. This association was most evident in 1997-98.

In addition to SST impacts, this study also found a temporal association between cholera and rainfall anomaly in Piura during the resurgence of cholera in 1997-98. Rainfall was approximately in phase with cholera at multiple scales suggesting that rainfall may have affected cholera transmission at several time periods through 1997-98. This is an important finding because it provides quantitative evidence that substantiates reports by PAHO during that time period of collapsed infrastructure from flooding and subsequent contamination of the water supply in Piura (see Chapter 3). Although it can be assumed that heavy rainfall was the exposure pathway, it should also be noted that rainfall can play a dual role in cholera transmission (Kovats et al. 2003; Ruiz-Moreno et al. 2007). Therefore, rainfall deficit may also have impacted cholera transmission through its potential effects on water supply (Akanda et al. 2008). Lastly, it should be noted that there was a strong interannual relationship (e.g., 3 to 8 years) between rainfall in Piura and Niño 3.4 SSTA, Niño 1+2 SSTA, and Paita SSTA throughout the 1990s (based on wavelet coherence and cross-wavelet data not shown). I draw attention to this association because it may potentially explain the interrelated links among global climate, local climate, and local cholera incidence in Piura, Peru. Studies by Pascual et al. (2000) and Bouma and Pascual (2001) suggest that this is a potential mechanism that mediates the climate and cholera relationships in Bangladesh and India. Therefore, it warrants further investigation.

6.2.3 Was there a temporal association between cholera incidence in Piura and ENSO in the 1990s? Was this association stronger after 1992?

In this dissertation research, I demonstrated that global and local sea surface temperature anomalies and local rainfall anomaly positively influenced cholera incidence in Piura in the 1990s. The scales of these relationships suggested that there was an interannual component to cholera's temporal variability following the second wave of the cholera epidemic in 1992 (i.e., 1993-94) and during the resurgence of cholera in 1997-98. Furthermore, there was an intrannual component of cholera associated with local rainfall anomaly from 1997 to 1999. The wavelet results along with the comparison of ENSO events by Niño 3.4 and Niño 1+2 regions strongly suggest that the 1997-98 El Niño and a subsequent La Niña (i.e., estimated in both regions) were temporally associated with cholera incidence from 1997 to 1999. These findings support a previous study in Peru that found an association between coastal seawater and cholera (Gil et al. 2004); however, it also highlights a geographic difference (i.e., in terms of time lag) between those results in Lima and Piura. Although the wavelet analysis also showed a temporal association at the time period of 1993-94, the results from the comparison could not support an association with ENSO because neutral sea surface temperature conditions estimated in 1993 were followed by diverging sea surface temperature conditions (i.e., El Niño in Niño 3.4 and La Niña in Niño 1+2) in each region. Therefore, it could be argued that the association between cholera and ENSO was stronger after 1992. Lastly, it was discerned that the temporal associations between cholera and sea surface temperatures in the Niño regions were potentially mediated through local sea surface temperatures at Paita and local rainfall in Piura.

6.3 ENSO and the Social Vulnerability of Cholera Incidence in Piura, Peru: 1997-98

In Objectives 3 and 4, I examined the spatial distribution of social vulnerability and its association with cholera incidence by district (n = 33) in the subregion of Piura in 1997-98. In a subsequent analysis based on the findings of social vulnerability, I also examined the association between global and local climate and cholera incidence by district in 1998. In the social vulnerability analysis I constructed an overall social vulnerability index and four sub-indices of vulnerability: (SVIF1) rural and river water; (SVIF2) urban and water truck; (SVIF3) urban and public water well; and (SVIF4) 'other' water sources. All of these indices were based on potential risk factors associated with cholera transmission, such as factors related to contaminated water exposure from poor sanitation accessibility.

Mapping the overall social vulnerability and sub-indices revealed that the highest overall social vulnerability, urban and water truck vulnerability, urban and water well vulnerability, and 'other water sources' vulnerability was generally found on the west coast of Piura. Furthermore, it suggested that those living on the coast were at highest risk. This could be explained by populous urban areas found on the immediate coast of Piura. River and rural water vulnerability (SVIF1) was found in the eastern part of Piura, which reflects a population that may be living in rural areas where infrastructure and public services are poor and people use river water. By comparing cholera incidence of the most vulnerable districts, I demonstrated that the district with the highest vulnerability also had the highest cholera incidence in Piura (i.e., Rinconada Llicuar located on the west coast based on overall SVI and SVIF4). I also demonstrated that the highest vulnerability by district did not always reflect the highest cholera incidence. For example, several districts that were estimated as having the highest vulnerability based on SVIF1 were places where cholera incidence was lowest (<2.0/1000 persons) in 1997-98. Another example is the district of Piura, which was found to be the least vulnerable according to overall social vulnerability. These findings suggested that although some places exhibited characteristics of cholera risk, there were other factors in these districts (not captured by the SVI) that may have protected the population from cholera transmission, such as population density, geographic isolation or perhaps the environments in these districts were not suitable for bacteria proliferation. In the case of the district of Piura, it may have been the availability of public resources and services, which enhanced the resilience of the population since it is where the capital of the Department is located.

6.3.1 Cholera and Social Vulnerability by District: 1997-98

Using global and local regression, I demonstrated that rural and river water vulnerability and 'other water sources' vulnerability were significant factors that explained the spatial distribution of cholera incidence in Piura. However, I also found that each vulnerability index had a different impact. The effect of rural and river water vulnerability on cholera transmission was negative; while the effect of 'other water sources' vulnerability on cholera transmission was positive. While the former finding may appear counterintuitive at first, it may also suggest that other factors not captured by the sub-index prevented cholera transmission, such as population size or geographic isolation. For example, cholera incidence in areas with rural and river water vulnerability may also have been places with seasonal migrants or persons traveling between urban and rural areas. Cholera cases in rural areas may have been isolated and did not pose a threat to cholera transmission in those areas. Another possible explanation is that the optimal conditions for *V. cholerae* reproduction may not have been present in these districts. Therefore, low population along with poor ecology may have prevented cholera transmission among these communities.

As suggested previously (Chapter 5), 'other water sources' vulnerability was an interesting finding because it may refer to street vendors or a source not accounted for in the vulnerability analysis. According to Ries et al (1992), ice from street vendors was one of the primary vehicles of cholera transmission in the city of Piura in the first few months of the cholera epidemic in 1991. Although I was unable to obtain documentation for 1997-98 to support this exposure pathway, it is well known that street vendors are a popular source of cheap food and drink throughout many Latin American countries particularly during the summer months when temperatures increase. Therefore, it may have been an important risk factor for cholera during the 1997-98 El Niño.

Furthermore, my results from the social vulnerability analysis revealed that there was a pattern of vulnerability and unexplained risk of high to low values from west to east associated with rural and river water vulnerability and 'other water sources' vulnerability. Of notable interest were those districts that exhibited high to moderate vulnerability and high to moderate unexplained risk. I proposed that climate in part might account for the unexplained risk and therefore, I explored these districts further to understand the spatial variation of cholera vulnerability in Piura.

6.3.2 Cholera and Global and Local Climate by District: 1998

Following the spatial analysis of cholera and social vulnerability, I investigated the associations between cholera incidence and global and local sea surface temperatures and local temperatures and rainfall by district (n = 13) and month (n = 12) in Piura in 1998. Using global regression, I demonstrated that climate had a positive effect on cholera incidence but that the strength of these associations (i.e., determined by the r^2) varied by parameter, temporal lag and place (district and location). The strongest associations were found in districts located on the west coast of Piura. One possible reason is that the climate data employed in this study were measurements from the district of Piura on the west coast. Therefore, it is likely the data is representative of conditions in this part of Piura. Alternatively, the stronger climate-cholera connection on the coast could be related to the influence of El Niño's teleconnections, which are stronger in Peru's north coast. It supports Glantz's 'geographic' notion that teleconnections are strongest the closer a place is to the central equatorial Pacific Ocean; equally, the farther a teleconnection is, the weaker that association will be (2001).

The strongest associations with cholera incidence were: Niño 3.4 SSTA (1 month lag), Paita SSTA (1 month lag), rainfall (1 month lag), and rainfall (2 month lag). One interesting observation is that the time lag for Niño 3.4 was notably different from the wavelet results (e.g., 6 months); the time lag for Paita SSTA appears to agree with the wavelet which found a shorter time delay in 1997-98 (e.g., 2-3 months). The sea surface temperature associations support previous studies in Peru (Gil et al. 2004) and South

Africa (Mendelsohn and Dawson 2008), which documented short time delays between SST and cholera. Niño 1+2 SSTA was weakly associated with cholera.

In contrast to the wavelet results, local temperature maximum (TMAXA) and temperature mean (TMEANA) were strongly associated with cholera incidence. The time lags associated with TMAXA and TMEANA were 6 months, similar to results in Bangladesh (Pascual et al. 2000) and Ghana (de Magny et al. 2008). These findings also support evidence in Peru that temperature increases may have impacted the reproduction of *V. cholerae* in local water sources inland (Franco et al. 1994; Speelmon et al. 2000). In addition, these findings may suggest that exposure through a temperature pathway may have been important for cholera transmission in central and eastern Piura (e.g., districts of Huarmaca and Chulucanas).

One of the most important findings was the association between cholera and rainfall (1 month lag). It was the strongest climate association ($r^2 = 0.85$) in this segment of the analysis. It reinforced empirical evidence found in the wavelet analysis that rainfall was an important transmission factor for cholera transmission during the 1997-98. It was particularly stronger in the districts of the west coast; however, as the time lag increased to 2 months, the strongest associations moved eastward, which indicates that during the 1997-98, rainfall impacts may have shifted to the highlands. It may also reflect a time lag between El Niño and climate conditions in the highlands since they are further away from the ocean.

6.3.3 How did social vulnerability influence the climate-cholera relationships in Piura? Does the spatial distribution of social vulnerability within districts in Piura explain the spatial variability of the ENSO-cholera associations in Piura in 1997-98?

In this dissertation project, I also demonstrated that rural and river water vulnerability and 'other water sources' vulnerability were significant factors that explained the spatial distribution of cholera incidence across districts in Piura during the 1997-98 El Niño. Moreover, I showed that global and local climate parameters were significantly associated with cholera incidence in 1998. In order to assess whether social vulnerability could explain the climate-cholera associations in Piura, I selected the 10 districts with the strongest associations in the climate-cholera analysis for a discussion.[23] **Figure 6.1** is a map showing these districts. They mainly represent districts on the west coast since the strongest associations were located there; however there are a few in the central and eastern part of Piura too. I also focused on the climate variables, which had the strongest associations with cholera incidence.

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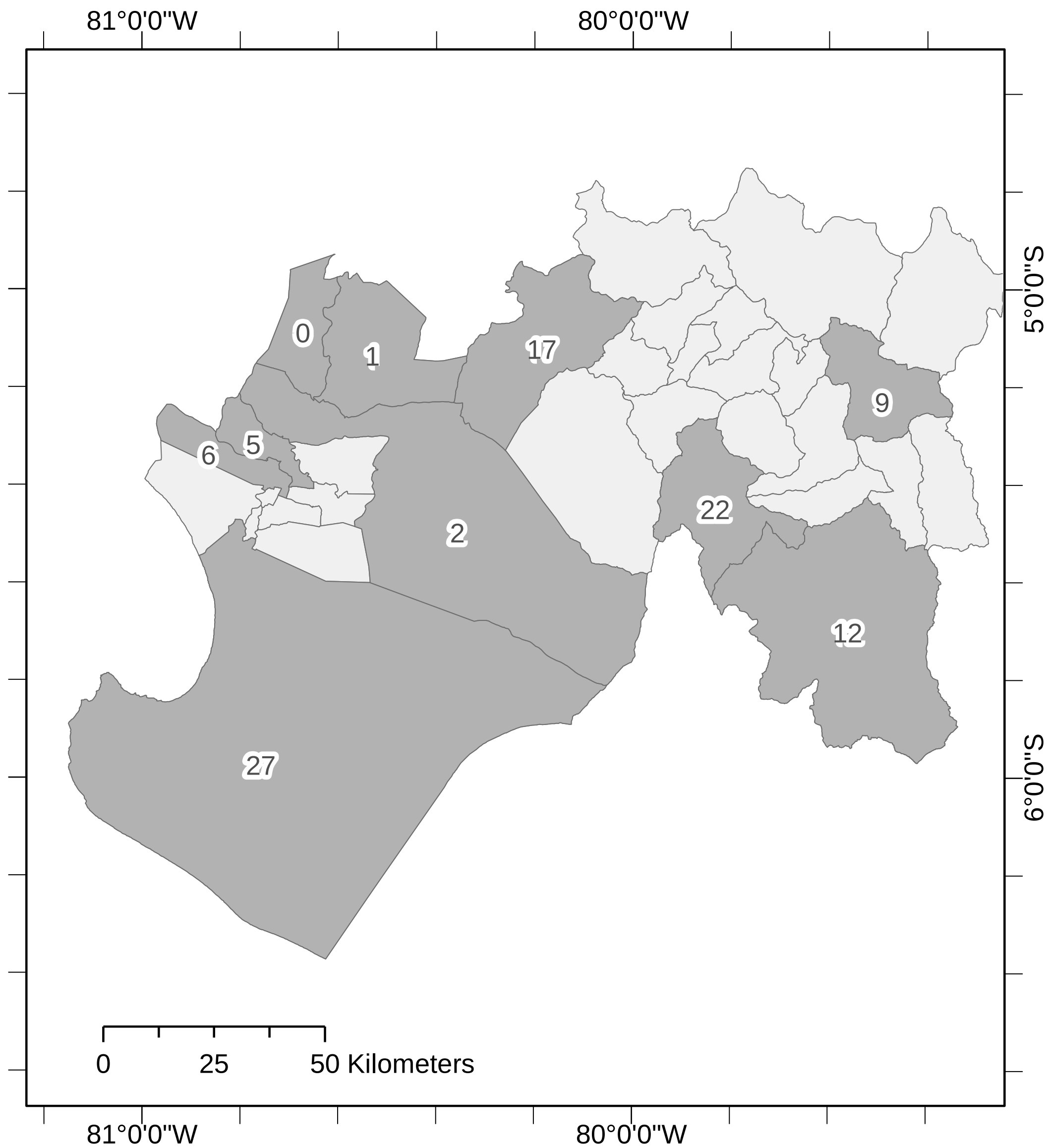
[23] Chalaco, Rinconada Llicuar, and San Juan de Bigote were not included in this assessment because teleconnections in these districts were weakly associated with cholera (r^2 = < 0.60) or not statistically significant.



District	ID	District	ID
PIURA	0	HUANCABAMBA	9
CASTILLA	1	HUARMACA	12
CATACAOS	2	CHULUCANAS	17
LA ARENA	5	SALITRAL1	22
LA UNION	6	SECHURA	27

Figure 6.1 Map of Selected Districts for Comparative Analysis.

Table 6.1 compares social vulnerability and climate associations (based on r^2 values) with cholera by district. The distribution of values by district suggests that 'other water sources' vulnerability partly explained the distribution of TMEANA (6 months lag) which was concentrated on the west coast. It may also explain how cholera transmission was enhanced in most districts where rainfall was strongly associated with incidence. Rainfall's impact was found in 8 out of 10 districts. At a 1 month lag, rainfall's impacts are distinctly associated with coastal districts (e.g., Piura, Castilla, Catacaos, La Arena, La Union and Sechura). The combination of flooding and overwhelmed water and sanitation infrastructure (due to flooding sewers) may have contaminated the munipal water supply; subsequently, exposure to *V. cholerae* may have occurred through drinks from street vendors or other water sources (not identified in the census data).

Table 6.1 Comparison of Social Vulnerability and Climate Associations (r^2) with Cholera

ID	District	SVIF1	SVIF4	NIÑO 3.4 SSTA1	PAITA SSTA1	Rainfall1	Rainfall2	TMAXA6	TMEANA6
0	PIURA	0.05	0.26	0.68	0.61	0.85	0.40	0.57	0.57
1	CASTILLA	0.08	0.24	0.60	0.55	0.85	0.45	0.56	0.56
2	CATACAOS	0.10	0.27	0.46	0.48	0.84	0.64	0.51	0.50
5	LA ARENA	0.03	0.30	0.74	0.71	0.81	0.55	0.76	0.63
6	LA UNION	0.02	0.32	0.69	0.73	0.89	0.82	0.79	0.75
9	HUANCABAMBA	0.26	0.13	0.18	0.26	0.37	0.67	0.41	0.38
12	HUARMACA	0.25	0.17	0.36	0.42	0.45	0.64	0.46	0.63
17	CHULUCANAS	0.16	0.20	0.41	0.49	0.59	0.86	0.42	0.68
22	SALITRAL1	0.22	0.18	0.44	0.50	0.36	0.75	0.43	0.70
27	SECHURA	0.04	0.34	0.67	0.63	0.84	0.54	0.63	0.63

The colors indicate in which districts the SVI indices may influence climate associations

At a 2 month lag, rainfall impacts 1 coastal district (La Union), 1 central district (Chulucanas) and 1 eastern district (Salitral1). The latter two places are interesting. For example, both districts share similar time lag associations with rainfall (possibly influenced by the distance from the equatorial Pacific Ocean); however, they are influenced by vulnerability in different ways. For example, while cholera risk was enhanced by 'other water sources' vulnerability in Chulucanas; rural and river water vulnerability reduced risk for cholera transmission in Salitral1, where it appears that mean temperature also influenced incidence. This suggests that while climate processes have the potential to impact cholera, there are other factors that prevent human transmission. As discussed previously (in section 6.3.1), factors such as the population size or geographic isolation (from infected migrants from the coast) may have prevented cholera transmission. Furthermore, although river water was the main source of water, it may not have been contaminated. These factors should be explored further in future studies.

The comparative analysis also suggests that in the coastal districts of La Arena and La Union, the impact of several climate variables on cholera incidence was enhanced by 'other water sources' vulnerability. Of import here is that several transmission pathways may have been present independently or interactively in these districts. In contrast, in Huancabamba and Huarmaca located in the east, like the district of Salitral1, rural and river water vulnerability may have lessened or prevented the impacts of climate on cholera transmission; climate impacts in these districts were less influential (associations were weak).

6.4 Study Limitations

This study has several caveats and provides lessons for future cholera research. One limitation is the possibility that cholera cases were under-reported and that cases were clinically confirmed and not laboratory confirmed. Relatedly, cholera case data were unclear after 1998; several datasets I obtained had varying counts from 1999 to 2001. I also observed this discrepancy in the department and national datasets; the number of cholera cases reported by MINSA conflicted with PAHO. There was also a lack of population data over time; therefore I was unable to calculate incidence rates in the temporal analysis. Another limitation is that I was also unable to fully examine the initial cholera outbreak in 1991-92 during the wavelet analysis in Objective 2. Much of my data fell within the cone of influence. I suspect that the short length of the cholera time series (11 yrs) limited the number of scales that I could analyze (Compo, personal communication January 2011). There was also the lack of spatial cholera data before 1997 and after 1998 in the subregion of Piura. Therefore, my results from the temporal-spatial analysis in Objective 4 may not be applied to the entire decade. Yet, another limitation is related to the vulnerability index, which was static rather than dynamic. I utilized census data in 1993 to represent social conditions in 1998. Furthermore, the SVI indices cannot capture the full complexity of human vulnerability to cholera; this is a typical critique of vulnerability indicators and indices (Hahn et al. 2009). One way I attempted to circumvent these limitations was to utilize literature and anecdotal evidence that I collected in Piura and Lima during my fieldwork. I also consulted with my collaborators in Piura and Lima. In the future, I will also consider using interviews (public health authorities) to fill in gaps of knowledge.

In addition, my climate data was not representative of the entire subregion. I used one station which was biased towards the west coast of Piura. However, it could be argued that I measured cholera associations with this station using a 'teleconnected approach' to impacts; to some degree neighboring stations in the subregion of Piura are likely correlated with one another, and therefore, the information obtained in this project was still useful to gain some understanding of the association between climate and cholera in Piura. Furthermore, my assessment of the influence of social vulnerability on the ENSO-cholera association during the 1997-98 El Niño was limited by scalar differences. It highlights the challenges that face researchers in the quest to understand climate and social impacts on disease and health, particularly in developing countries. Lastly, from this research I did not learn about individual exposures to cholera or how cholera was transmitted among individuals in a population. I also recognize that there may be gender and age differences in how people are exposed to cholera and these differences may vary by socioeconomic status, occupation and migration.

6.5 Ethical Geographies of the Cholera Epidemic in Piura

In conclusion of this chapter, I present a coda that reflects my ethical perspective on the findings in this dissertation as well as the research process as it relates to my fieldwork in Peru. My aim is to highlight several ethical challenges/issues raised by the study of the cholera epidemic in Piura. I will focus on two ethical lines of inquiry. The first ethical consideration addresses the empirical findings in this dissertation. The second ethical consideration addresses issues that arose while conducting this research, e.g., context of the fieldwork and the research setting.

I begin this statement by defining my ethical lens which considers both an ethics of climate and an ethics of development. These perspectives are needed to evaluate the ethical considerations described above because cholera transmission is indirectly influenced by climate variability and by the human development conditions in which people live. Furthermore, during my fieldwork I encountered several issues associated with inequity in scholarship and epistemological concerns in regards to local understandings of the cholera epidemic and El Niño. I go on to present several ethical challenges/issues which I herein refer to as 'ethical geographies' that emerged from this dissertation.

6.5.1 Ethics of Climate and Development

Climate ethics is a growing field that has emerged in philosophy to address the moral implications of anthropogenic climate change for society (Gardiner 2010: 3). In this reflective statement, I employ the lens of an ethics of climate based on the climate affairs approach used in this study. Climate ethics from this perspective is defined as moral issues or questions associated with harms or challenges to society that arise from climate-society interactions; it also considers the principles that ought to guide a society in its decisions about climate and climate-related impacts (Glantz 2003: 165). According to its mantra, a climate affairs ethics views climate phenomena and climate-related issues more broadly then the current climate ethics literature.[24] Therefore, I suggest that a climate affairs-based ethics is more suitable to address moral questions about the cholera epidemic in Piura and its relationship with ENSO, which is natural climate variability.[25] This approach to climate ethics considers topics, such as inter- vs. intragenerational equity conflict, precautionary principle, North-South divide (e.g., the socioeconomic development gap between developed and developing countries), and environmental justice (Glantz 2003: 65-74). It is also concerned with questions about the ethics of impacts and vulnerability, a topic which has received less attention. From this conception, a climate affairs-based ethics shares concerns with an ethics of global development (Gasper 2005; Crocker 2008).

Development ethics is a subfield in philosophy which is concerned with ethical issues and questions that arise from global development policies and practice (Crocker 2008: 1), as well as the interpretation of the concept (Gasper 2005: 1). Namely, development ethics addresses the social and economic inequities that are experienced by societies by uneven global development (de Blij 2009); furthermore, it emphasizes the greatest concern for the poorest and socially disadvantaged subpopulations. One particular conception of development ethics that is useful to examine ENSO and the

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[24] Generally, the climate ethics literature has been concerned with arguments that support the reduction of greenhouse gas emissions to address human-induced climate change. See Gardiner et al. (2010) for a collection of essays on the subject.

[25] I make this distinction here because studies suggest that ENSO's behavior has not been impacted thus far by anthropogenic climate change.

cholera epidemic in Piura is the capability approach to human development (Sen 1999; 2010; Nussbaum 2003; 2011). The notion of human capability suggests that human development be viewed through a broader context than just incomes, resources, or goods. It provides the conceptual space to evaluate human well-being through 'capabilities', which are elements that enable humans to function and flourish in society (Sen 1999). Important to this concept is 'freedoms' which represent people's 'real' opportunities that are instrumental and intrinsically valuable to their flourishing (Aristotle's notion as cited in Nussbaum 2000). Well-being is judged by the extent to which freedoms can be achieved and the actual achievements, which freedoms and capabilities facilitate for people. The Human Development Index (HDI) by the United Nations is based on human capabilities (UNDP 2009). Combining climate ethics with a capability approach provides this reflective statement a great insight to evaluate ethical issues that arise in health, medical and human-environment geographic research, and in this case, ENSO and the cholera epidemic in Piura.

6.5.2 Ethical Geographies

In this section I discuss several ethical geographies that emerged from this research including my experience during fieldwork in Peru in 2008 and 2009 and subsequent collaborations with my institutional partners in Piura and Lima, Peru.

6.5.2.1 Ethical Geography 1

ENSO impacts may have exacerbated cholera transmission in vulnerable places within the subregion of Piura, Peru. Furthermore ENSO impacts on cholera may have affected some places more than others depending on the characteristics of social vulnerability in those places.

According to the Rocky Ethics Institute (http://rockblogs.psu.edu/climate/), the magnitude of impact from a changing climate will be catastrophic for the most vulnerable populations, and thus it is an ethical reason for society to respond. Although the context of this statement is a changing climate and what we should do about greenhouse gas emissions, it can also be applied to ENSO and its impacts on the cholera epidemic in Piura. ENSO alters climate patterns around the world and those changes in climate have been associated with hazards that affect the health of vulnerable populations (Kovats et al. 2003; Glantz 2001; 2003).

Evidence in this dissertation suggested that indeed ENSO may have increased the burden of cholera transmission on the west coast of the subregion of Piura, Peru, namely through flooding, for example, because of heavy rains and the subsequent collapse of sanitation infrastructure and/or contamination of the public water supply. Moreover, cholera impacts were experienced differentially based on the social vulnerability of water and sanitation infrastructure within that place. Many people may have been exposed because they purchased water or food from street vendors influenced by socioeconomic constraints or unavailability of potable water in their homes. From a climate ethics and capability approach, it suggests that cholera transmission increased in Piura in places characterized by deprivation of capabilities associated with limited access to food and water and public services, which protect people from waterborne diseases.

This underlying context of the cholera epidemic in Piura, specifically during the 1997-98 El Niño, brings to light the human development and the social environment in Piura. The setting suggests that conditions in Piura were not so good to begin with and that some people in Piura were already living in socially marginal conditions that created the setting for potential infectious disease transmission. When El Niño conditions developed in April-May of 1997 followed by El Niño-related teleconnections in the December of 1997, extreme weather and climate contributed to ecologically favorable conditions for bacteria and pathogens that intersected with the development context in Piura which led to subsequent exposure to cholera and social harm during that austral summer.

During the 1997-98 El Niño, there were also reports of climate-related impacts on other infectious diseases, which are typically reported during extreme climate events in Piura, and coincidently are associated with poverty in the region. For example, from January to March of 1998, when El Niño conditions were peaking, there were 42,000 cases of malaria (i.e., based on two types: *P. falciparum* and *P. vivax*) and 3,200 cases of conjunctivitis because of ecological changes in local aquatic environments and impacts on disease vectors.[26] In addition there were economic impacts on infrastructure in multiple sectors. Estimated losses ($ U.S. in millions) were reported in agriculture (41.5), sanitation (13.0), and health (0.5) (Sandoval 1999). Although the health sector

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[26] According to Norma Ordinola at UDEP, during the summers and particularly during El Niños, there are plagues of insects. Apparently, there are so many that people have the tendency to scratch their more often which can lead to infection if there hands are dirty.

appeared to be the least affected, the damages incurred by extreme weather on health infrastructure may have impeded society's capacity to respond in Piura during that time.

The broader implication of this story is that populations within the subregion of Piura may have experienced a confluence of climate extremes, infrastructure deprivation, and an environment conducive to infectious disease transmission. Within such a context, the study of the cholera epidemic in Piura does not only raise questions about distributive justice (e.g., how are impacts distributed); it also raises questions about the type of hazards and impacts that populations experienced (e.g., co-exposures to climate and social hazards and co-infectious disease morbidities) and the relationship of these experiences to human capabilities and development. One important question to consider is to understand how human capabilities change as the hazards and impacts change across time and space.

6.5.2.2 Ethical Geography 2

Making the research process and collaborations with partners in Piura equitable and participatory.

My dissertation fieldwork in Piura and Lima exposed me to several interrelated ethical challenges associated with what I term 'inequity in scholarship' which could also be linked to the North-South divide. Before I begin describing these challenges, I would like to first reiterate the purpose of my field work in Peru to set the context for these challenges.

In the summers of 2008 and 2009 I visited Piura and Lima to collect data including documents in order to develop my conceptual and empirical models in my dissertation. I also collected anecdotal information from many officials at institutions in Lima and Piura. This was important because I needed to understand how the data were collected and interpreted. I was also looking for social and political dimensions of the cholera epidemic to inform my analysis. Many of the documents I obtained were in Spanish so I needed to communicate frequently with my collaborators in Piura during and after my visits. I also needed a guide to help me navigate through the institutions as well as keep an eye on me since I was a foreigner (i.e., for safety reasons). My main contact in Piura was Prof. Norma Ordinola of the University of Piura (UDEP) via a referral by Dr. Michael H. Glantz at CCB. Therefore, my collaborators were essential to this dissertation.

As a researcher and graduate student of an American University, I entered the collaborative process under the naïve guise that this research experience would be reciprocal and mutually beneficial. By this I am referring to one of the principles of community engagement as defined by Fitzgerald et al. (2005). Reciprocal and mutually beneficial refers to a bi-directional relationship of information and benefits derived from the scholarship. It suggests that knowledge is generated with partners and that this process is transformational for society. However, as I would learn thereafter, achieving equity in scholarship as an American conducting research in a developed country setting was not so easy.

To begin, I entered the research process with a certain set of goals that would hopefully advance my career and capabilities. It was apparent to me what I could gain from the experience. For my partners in Piura, however, it may not have been so clear. I am not sure that they were even concerned about gaining. In my project, my partners were clearly interested in helping me the graduate student and fellow South American. I am an American but also one with a background and ethnicity that may have given me some advantages for collaboration. I also came into the process with advantages in terms of socioeconomic status. As I recall, Prof. Norma Ordinola pointed this fact out, and stated that even as a graduate student my social conditions were better than a Professor's in Piura. Therefore, I should be careful when I communicate with officials and other academics in Piura. Overall my experience was positive when I worked with institutions in Piura.

My collaborators were invaluable to my dissertation research. They trusted me and invested a great deal of time and effort to assist me. Furthermore, they collected and handed me what appeared to be their entire dataset. One ethical geography that arised from this experience was whether my partners were trading off important time and resources to communicate and work with me. Dr. Stephen Esquith of the Philosophy Department at MSU alerted me to this type of opportunity cost which collaborators/ partners in developing countries may face.   This question leads to a subsequent consideration of the usability of my research and my relationship to Piura. The former is more difficult to answer and likely requires a forum for participation and feedback. It could be true that my approach to understanding the cholera epidemic may only be useful to academic circles. That is, since cholera is no longer present and current health challenges may seem of greater import (e.g., dengue).[27]

Another ethical geography associated with fieldwork was communicating with my partners in Piura. I found that infrastructure and language were barriers. I realize that my partners in Piura do not always have access to good internet service. They are also likely to be busy with their own projects. I also find that since I am no longer a native speaker of Spanish, I am less engaged because it takes much longer time to develop a message to my partners. It is much easier to communicate in person in Spanish. Although I was able to obtain enough information about my project, I felt that it was not the most effective or equitable way to work on a research project. My work could have been better informed with more communication and more direct communication (e.g., phone instead of internet). Moreover, it was difficult to sustain (in my opinion) a working relationship this way.

6.5.2.3 Ethical Geography 3

Local understandings of El Niño in Peru are marginalized.

The last ethical geography refers to the marginalization of Peru's scientific understandings of El Niño and impacts. Currently, the definition of El Niño-Southern Oscillation is based upon NOAA's interpretation which relies on the Niño 3.4 region in

[27] The number of classic dengue fever cases rose from 495 in 1999 to 9,739 in 2004 (MINSA 2005a).

the equatorial Pacific Ocean. The importance of sea surface temperatures in this region which straddles the Niño 4 and Niño 3 regions is it has been shown to allow for a better predictability of ENSO's global teleconnections. While I acknowledge that the NOAA definition is important, I also recognize that Peruvian scientists, as well as the South American scientific community, have their own interpretation of ENSO. In fact, for Peruvians, it could be argued that the El Niño phenomenon, as they refer to it, is important to their society because they are sensitive to its associated environmental changes since generally conditions off the coast of Peru are typically in a neutral state of ENSO. Therefore, while Peruvians consider the NOAA definition, they also rely upon their own criteria using monitoring stations spanning the coast of Peru (see Chapter 2, footnote 4). This definition known as the SCOR definition was proposed by South American scientists in 1983 and was subsequently rejected by the international scientific community (Trenberth 1997; Lagos et al. 2008). It is my assumption that this community was largely made up of Americans and Europeans who influenced this decision.

I became aware of the importance of this issue while reviewing the literature and conducting fieldwork in Piura. As I began to have conversations with Prof. Norma Ordinola, my contacts at various institutions, and even local people (e.g., cab drivers) about El Niño in the early 1990s, I realized that an El Niño in 1991 was not remembered by anyone that I spoke with. It suggested that Piurans did not experience an El Niño during that time. What many remembered, however, was the experience of heavy rains in Piura in the austral summer of 1992, which local data confirms. It is this piece of information that helped inform my hypotheses. It also supported my doubts that an El Niño had occurred in the initial stages of the epidemic in 1991. Therefore, Colwell's hypothesis (1996) may have been based on the global understanding of ENSO. Well, why do I consider this an ethical issue? These insights from my fieldwork raise questions about knowledge inequalities between the North and South scientific communities. It could be argued that knowledge generated about El Niño in Peru is not widely known, and therefore, not as widely accepted (e.g., as NOAA), because of resources disparities and perhaps even language barriers. This speaks to the fact that in order for scientific knowledge to become widely accepted, one must publish in peer-reviewed journals, most likely, in English. In order to do so, funding and fluency in English is necessary.

6.5.3 Conclusions

Using the combined perspectives of climate and development ethics, this coda highlighted several ethical geographies that arose from the findings in this dissertation and the research process itself. The first ethical geography associated the findings with issues of distributive justice and suggested that the cholera outbreak in Piura was actually part of a broader social and environmental crisis with implications for the geography of human capabilities and development. The second and third ethical geographies raised questions about inequity in climate impacts scholarship. These issues illuminated disparities that existed in the study area, and suggested that future scholarship be mindful of this context and work towards minimizing this type of injustice.

CHAPTER 7: CONCLUSIONS

Using a climate affairs approach, I reconstructed the temporal and spatial associations among ENSO, social vulnerability and cholera incidence in Piura, Peru from 1991 to 2001 in order to better understand El Niño's impact on the cholera epidemic in Peru. Moreover, I explored what more can be learned about cholera emergence and transmission if we considered the broader aspects of the ENSO cycle including social dimensions. My findings suggested that cholera's temporal association with ENSO was transient throughout the 1990s; the strongest associations were found during the 1997-98 El Niño, supporting previous studies in Peru. I also found that an important temporal pathway in cholera transmission occurred through the interactions of global and local sea surface temperatures with rainfall. Furthermore, I showed that the spatial distribution of social vulnerability by district can in part explain the associations between global and local climate and cholera during the 1997-98 El Niño; the findings also suggested that social vulnerability modifies the climate-cholera relationship based on the type of water-infrastructure vulnerability. Moreover, at a district-level analysis (i.e., distinguishing the wavelet analysis from the regression analysis), it was revealed that the associations between climate and cholera varied by time lag, district and climate variable. In terms of geographic patterns, it appears that districts on the west coast of the subregion of Piura were the most vulnerable to climate-cholera impacts. In addition, the spatial analysis provided further support for the role of rainfall on cholera transmission within Piura. Lastly, important to the understanding of these findings is that interpretation of ENSO and its association with cholera will depend highly on the Niño region chosen for analysis, as Trenberth (1997) had demonstrated previously.

Dissemination of findings

I plan to disseminate and share my findings with scholars, public health practicioners, policymakers, and civil society by presenting at conferences, such as the Association of American Geographers (AAG) Annual Meeting, the International Medical Geography Symposium (IMGS) (at MSU in 2013), and the American Meteorological Society (AMS), and at workshops, such as NOAA's Annual Climate Prediction Applications Science Workshop (CPASW). I will also prepare several manuscripts for publication including: a wavelet anaylsis of climate and cholera in Piura; an assessment of the impacts of global and local climate anomalies on cholera incidence in Piura, Peru during the 1997-98 El Niño; a geographically weighted regression analysis of social vulnerability and cholera incidence in Piura; and the importance of definition and region in understanding the relationship between sea surface temperature and cholera in Peru. I will also pursue a research grant so that I may return to Peru to share my findings with MINSA and my institutional collaborators in Piura and Lima, Peru. This activity will also contribute to future collaborations and capacity in Piura. In addition, I will integrate my study knowledge including my fieldwork experiences into undergraduate and graduate coursework materials and lectures, as well as outreach and engagement activities that foster capacity building.

Future areas of scholarship: implications for research, policy and ethics

Understanding the climate dimension of cholera transmission in Peru remains an important topic today because, although, the last confirmed cases of cholera (related to the El Tor strain) were reported in 2002, the first case of the epidemic strain *V. cholerae* 0139, previously reported in Bangladesh (WHO 2009), was documented in South Lima in 2004 (Instituto Nacional de Salud 2006). Furthermore, a cholera epidemic in Haiti that erupted in October 2010 revealed that cholera remains a potential threat not only to Peru but to other parts of the region; and maybe more so in the face of a changing warming climate (Shah 2011).

Below are several implications that can be drawn from this study to build capacity and contribute to the future prevention of cholera and other climate-sensitive diseases in Piura and the Latin American region.

a) Building capacity through impacts and time-lag information

One important finding which warrants further investigation is the associations among Niño 3.4 sea surface temperatures, local sea surface temperatures in Paita, and rainfall in Piura. We should learn more about the pathways in which each variable was associated with cholera incidence and how each may have interacted with one another to impact disease transmission. For example, how are the time-lag associations among the climate variables related? Furthermore, what are the characteristics of rainfall impacts (e.g., abundant versus deficient) by place (e.g., coast versus mountain or areas away from coast)? Understanding these important pieces of information could inform future public health responses in Piura to ENSO and other climate-related extremes. Moreover, such information could improve current early warning systems in Piura for climate-sensitive diseases, such as diarrheal (non-cholera), mosquito-borne and respiratory diseases. This endeavor would enhance Piura's El Niño contingency plan which is organized through several institutions including the Ministry of Health and UDEP (Sandoval 1999; MINSA 2005a; Rodriguez, personal communication 2009).

b) Understanding the first few years of the outbreak

My study was unable to fully examine the initial cholera outbreak in Piura from 1991 to 1992, and therefore it is crucial to gain a better understanding of this time period because it may help to understand the origin of the epidemic. I highlight two points of investigation. One is to understand how cholera incidence diffused within and across Piura. Another is to understand how climate impacted the emergence of cholera. One research suggestion is to conduct a qualitative analysis that retraces the first suspected cases of cholera by place through newspapers (e.g., the local newspaper *El Tiempo*) and other documents that may be available at local health outposts and census offices in Piura. Using these sources, it may also be possible to identify if there were any extreme climate-related events that coincide with incidence. Important to this endeavor will be to sustain collaborations with the University of Piura (UDEP), the Ministries of Health in Piura and Lima, and the local census offices.

c) ENSO and attribution

The study of the cholera epidemic in Piura offers lessons about ENSO and disease attribution. In order to fully understand an association between ENSO and infectious diseases, researchers and public health practitioners should take into account the importance of understanding the ENSO definition and Niño region in climate-health impact studies. Identifying El Niño periods is not a simple task given that there are many definitions that exist and can be applied; the association with infectious disease can vary by the criteria of the definition (e.g., anomaly thresholds) and the region chosen to represent climate anomalies (e.g., Niño 3.4 or or Niño 1+2). As such, the researcher should carefully interpret and assess which region data is appropriate for the area of study. Furthermore, ENSO has many characteristics, which should be fully explored if possible, to assess an association. In my study, two important characteristics were rainfall teleconnections and social dimensions.

d) Unexplained social vulnerability

As this dissertation has demonstrated, there are geographic differences of social vulnerability to cholera that require better understanding. For example, what were the contributing factors in districts where river and rural water vulnerability lessened the likelihood of transmission? In addition, can we identify the transmission pathways in districts where 'other water' sources vulnerability increased the risk for transmission? In order to further understand these findings and their application in future prevention of cholera, it may prove useful to examine the contribution of population immunity on cholera incidence. This would require obtaining birth rates and vaccination coverage information, two variables used by Koelle and Pascual (2004) to assess herd immunity in Bangladesh. Furthermore, this new information on immunity should take into account that 75.0% of infected persons are asymptomatic (WHO 2009). Another factor which may be important is migration (urban to rural or mountain to coast). In my analysis of MINSA epidemiology reports, I noticed that alerts were posted about the potential risk of cholera transmission during the summer season (e.g., agricultural migrants), coincidently when cholera incidence increased at a national level.

Yet another factor to understand is water infrastructure and human-environment interactions which led to transmission in Piura. Specifially, in regards to 'other water' sources vulnerability, I suspected that water from street vendors was the source of transmission based on previous evidence in Peru (Tauxe et al. 1995) and Piura (Ries et al. 1992). The latter study was based on the city of Piura and, therefore, it may not have represented the source of transmission in other areas within the subregion of Piura. Thus, additional knowledge about water sources and transmission in Piura should be pursued. These data could be obtained by interviewing officials at MINSA. As I discovered during fieldwork, there are still many public health staff at MINSA in Piura, which were present during the years of cholera epidemics in Piura. Learning about these factors would enable us to better estimate incidence, understand societal factors, and enhance prevention efforts.

e) Resilience actions

One important aspect of vulnerability which was not addressed in this study is resilience. During the cholera epidemics in 1991 and 1998, there were also reports of societal responses to mitigate the impacts of cholera. In addition to education programs to prevent diarrheal disease and cholera, MINSA set up sanitary and oral rehydration posts (MINSA 1994b). Furthermore, given Peru's past history with El Niño, several actions from different public sectors were taken to respond to emerging El Niño threats in 1997 (Sandoval 1999; MINSA Piura 2005a), which may have contributed to cholera prevention too. Therefore, I recommend that practitioners and policymakers in Piura that are responsible for public health and development initiatives consider understanding actions that enhance both health and development by not only considering the multiple ways that societies can become exposed to infectious diseases, but also actions that promote capacities to cope.

f) Cholera as part of broader health crisis

Future health and development policies should also consider that the Ministry of Health in Piura may be facing several concurrent health and social crises at multiple scales. From this perspective, policy, practice, and research should consider a more holistic approach to society, health and disease, such as the 'syndemic' perspective which is currently being promoted at the CDC (http://www.cdc.gov/syndemics/). Syndemic environments are places where social, economic, political, and environmental factors interact and contribute to an excess burden of disease in vulnerable populations. The concept of "syndemics" was first introduced by Singer (1994) to capture and understand how poverty, poor nutrition, and socioeconomic stressors increased the risk for exposure to HIV transmission and related opportunistic infections in Harlem, NYC. Utilizing this orientation of analysis to understand cholera within a medical geographic tradition would greatly compliment my findings on social vulnerability. Moreover, if a political ecology of health approach were integrated too, this would greatly enhance our understanding of scalar interactions including those related to global development (Mayer 2000).

g) Addressing inequity in scholarship

One ethical issue that arose during this dissertation research was inequity in scholarship. In order to address this problem, I acknowledged and credited my partners in Piura in presentations and papers. I also intend to publish articles with them, as well as work with these partners more equitably (e.g., from the beginning of the research process) in the future. I have already published one editorial with Prof. Norma Ordinola, my collaborator in Piura (http://ccb.colorado.edu/enos/editorials/sept09.html). Also, through my work at CCB with Dr. Michael H. Glantz, I developed a bibliography of El Niño-related works that include the materials I collected in Peru and links to webpages from various Latin American institutions that address El Niño and climate impacts (This information is available online at: http://ccb.colorado.edu/enos/comunidad.html). The collection and sharing of El Niño-related materials from Latin America addresses the problem of marginalized ENSO-society science in Latin America. This is an important future area of research which I intend to pursue.

h) Climate, cholera and marine reservoirs

Lastly, in order to further link my findings to the broader knowledge of climate/environmental factors of cholera transmission, it is necessary to examine the association between potential marine reservoirs off the coast of Piura and cholera incidence. Through UDEP partnerships, it may be possible to collect marine environmental data as well as remote sensing data that measures biological productivity (e.g., chlorophyll, which serves as a proxy for plankton) in the equatorial Pacific Ocean. This would link my findings to previous work in Lima (Gil et al. 2004). Furthermore, collaborations with researchers that examine climate and cholera incidence in Bangladesh (e.g., Dr. Mercedes Pascual [University of Michigan] and Dr. Michael Emch [University of North Carolina]) should be fostered in order to compare results in Peru.

In closing, I identified important areas of future scholarship and their relevance to research, policy and ethics. They highlight the importance of retrospective analyses in climate-health impacts research and the multidisciplinary nature of this work. It is hoped that this research will contribute to future climate-informed initiatives that enhance societal capacities while focusing on population health and the monitoring of populations during future climate events in Piura, Peru and the Latin American region.

APPENDICES

APPENDIX 1

Table A-1 Time Lag Associations in Climate Cholera Studies

Authors	Year	Study Area	Time Period	Cholera Variable	Climate Variables	Lag	S
Lobitz et al.	2000	Bangladesh	1992-1995	% cholera	SSH	1 month	P
Hashizume et al.	2008	Bangladesh, Dhaka	1996-2002	Cholera rate	High rainfall	1-5 weeks	P
Hashizume et al.	2008	Bangladesh, Dhaka	1996-2002	Cholera rate	Low rainfall	1-16 weeks	P
Hashizume et al.	2010	Bangladesh, Dhaka	1983-2008	% cholera	High rainfall	29-31 weeks	P
Hashizume et al.	2010	Bangladesh, Dhaka	1983-2008	% cholera	Low rainfall	10 weeks	P
Pascual et al.	2000	Bangladesh, Dhaka	1980-1998	% cholera	Niño 3.4 SST	11 months	P
Pascual et al.	2000	Bangladesh, Dhaka	1980-1998	% cholera	Temperature	4-6 months	P
Rodo et al.	2002	Bangladesh, Dhaka	1893-1940	% cholera death	Niño 3.4 SST	10 months	P
Huq et al.	2005	Bangladesh, L. Bakerhganj	1997-2000	Cholera	Lake water cond	zero month	P
Huq et al.	2005	Bangladesh, L. Bakerhganj	1997-2000	Cholera	Rainfall	8 week	N
Huq et al.	2005	Bangladesh, L. Bakerhganj	1997-2000	Cholera	Water temp	4-8 weeks	P
Huq et al.	2005	Bangladesh, L. Bakerhganj	1997-2000	Cholera	Water temp	6 weeks	P
Constantin de Magny et al.	2008	Bangladesh, Matlab	1997-2006	Cholera	Chlorophyll	1 month	P
Emch et al.	2008	Bangladesh, Matlab	1983-2003	Cholera outbreak	Chlorophyll	2 months	P
Emch et al.	2008	Bangladesh, Matlab	1983-2003	Cholera outbreak	Chlorophyll	zero month	P

Table A-1 (cont'd)

Authors	**Year**	**Study Area**	**Time Period**	**Cholera Variable**	**Climate Variables**	**Lag**	**S**
Constantin de Magny et al.	2007	Ghana	1975-1995	Cholera	Indian Ocean I	16 months	P
Constantin de Magny et al.	2007	Ghana	1975-1995	Cholera	Temperature	12 months	N
Constantin de Magny et al.	2007	Ghana	1975-1995	Cholera	Rainfall	.75 month	N
Constantin de Magny et al.	2007	Ghana	1975-1995	Cholera	Rainfall	16 months	N
Ruiz Moreno et al.	2007	India - NE, Madras	1901-1940	Cholera deaths	Rainfall	zero month	P
Ruiz Moreno et al.	2007	India - S, Madras	1901-1940	Cholera deaths	Rainfall	3-7 months	P
Ruiz Moreno et al.	2007	India - S, Madras	1901-1940	Cholera deaths	Rainfall	zero month	N
Emch et al.	2008	Vietnam, Hue	1985-2003	Cholera outbreak	SSH	2 months	N
Emch et al.	2008	Vietnam, Hue	1985-2003	Cholera outbreak	SSH	zero month	N
Emch et al.	2008	Vietnam, Nha Trang	1985-1995	Cholera outbreak	Cai River disc	zero month	P
Emch et al.	2008	Vietnam, Nha Trang	1985-1995	Cholera outbreak	Cai River height	zero month	P
Emch et al.	2008	Vietnam, Nha Trang	1985-1995	Cholera outbreak	Dinh River height	2 months	P
Emch et al.	2008	Vietnam, Nha Trang	1985-1995	Cholera outbreak	Dinh River height	zero month	P
Emch et al.	2008	Vietnam, Nha Trang	1985-1995	Cholera outbreak	Rainfall	zero month	P
Koelle et al.	2005	Bangladesh, Matlab	1966-2002	Cholera	BOB SST	0-9 months	P
Koelle et al.	2005	Bangladesh, Matlab	1966-2002	Niño 3.4 SSTA	BOB SST	2-3 months	P
Koelle et al.	2005	Bangladesh, Matlab	1966-2002	Cholera	NE India rainfall	14 months	N
Koelle et al.	2005	Bangladesh, Matlab	1966-2002	Cholera	Niño 3.4 SSTA	8-10 months	P
Koelle et al.	2005	Bangladesh, Matlab	1966-2002	Cholera	River disch. A	7 months	N
Bouma & Pascual	2001	Bengal	1891-1940	Cholera deaths	BOB SST	zero month	P
Bouma & Pascual	2001	Bengal	1891-1940	Cholera deaths	Niño Year	12 months	P

APPENDIX 2

IRB#X08-724 – Questions and Consent Form

List of Questions that I will ask individuals at Peruvian institutions:

Please note that these questions will be adapted to each type of institution I will approach for data.

What kinds of data are available at your institution?

If data are available, are they accessible?

If data are available, how are they organized?

If data are available, in what format do the data exist?

If data are available, at what scales and time periods are the data available for?

If data are available, may I review the data?

If data are available, how may I obtain the data?

If data are not available, can you refer me to an institution, which have these types of data available?

Consent Form

I, ______________________, at the institution _____________________, on this date _______________________, agree to participate in a discussion about data sources relevant to the pertinent research study that Ivan Ramirez, a PhD student in the Dept. of Geography at Michigan State University, is conducting for his dissertation while in Peru. Participation is voluntary, you may choose not to participate at all, or you may refuse to answer certain questions or discontinue your participation at any time without consequence. I acknowledge that the information generated from this discussion may be used for research purposes and will be properly cited and acknowledged. If I wish to remain as an anonymous source, then I will inform Mr. Ramirez.

If you have concerns or questions about this study, such as scientific issues, how to do any part of it, or to report an injury, please contact the researchers:

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APPENDIX 3

Wavelet Transform Script

%WAVETEST Example Matlab script for WAVELET, using Cholera (Square root transformed) Anomaly dataset
 cholera = cholera_sqrt_a;
 Script developed by Torrence and Compo (1998) found at:
http://paos.colorado.edu/research/wavelets/
%-- Computation
 % normalize by standard deviation (not necessary, but makes it easier% to compare with plot on Interactive Wavelet page, at
% http://paos.colorado.edu/research/wavelets/plot/ (this was excluded from the script because the climate datasets I used were already standardized anomalies.
variance = std(cholera)^2;
 n = length(cholera); %length of dataseries
dt = 0.083; %amount of time between each Y value, i.e. the sampling time. this says 1 month
time = [0:length(cholera)-1]*dt + 1991.0 ; % construct time array
xlim = [1991,2001]; % plotting range
pad = 1; % pad the time series with zeroes (recommended)
dj = 0.25; % this will do 4 sub-octaves per octave
s0 = 2*dt; % the smallest scale of the wavelet. this says start at a scale of 2 months
j1 = 5/dj; % the # of scales minus one. this says do 5 powers-of-two with dj sub-octaves each
lag1 = 0.72; % lag-1 autocorrelation for red noise background
mother = 'Morlet'; %the mother wavelet function.
% Wavelet transform:
[wave,period,scale,coi] = wavelet(cholera,dt,pad,dj,s0,j1,mother);
power = (abs(wave)).^2 ; % compute wavelet power spectrum
% Significance levels: (variance=1 for the normalized cholera)
[signif,fft_theor] = wave_signif(1.0,dt,scale,0,lag1,-1,-1,mother);
sig95 = (signif')*(ones(1,n)); % expand signif --> (J+1)x(N) array
sig95 = power ./ sig95; % where ratio > 1, power is significant
% Global wavelet spectrum & significance levels:
global_ws = variance*(sum(power')/n); % time-average over all times
dof = n - scale; % the -scale corrects for padding at edges

Wavelet Transform Script (cont'd)

```
global_signif = wave_signif(variance,dt,scale,1,lag1,-1,dof,mother);
whos
%------------------------------------------------------ Plotting
%--- Contour plot wavelet power spectrum
subplot('position',[0.1 0.37 0.65 0.28])
levels = [0.0625,0.125,0.25,0.5,1,2,4,8,16,32,64] ;
Yticks = 2.^(fix(log2(min(period))):fix(log2(max(period))));
contourf(time,log2(period),log2(power),log2(levels));  %*** or use 'contourfill'

%imagesc(time,log2(period),log2(power));  %*** uncomment for 'image' plot
ylabel('Period (Year)')
set(gca,'XLim',xlim(:))
set(gca,'YLim',log2([min(period),max(period)]), ...
   'YDir','reverse', ...
   'YTick',log2(Yticks(:)), ...
   'YTickLabel',Yticks)

% 95% significance contour, levels at -99 (fake) and 1 (95% signif)
hold on
contour(time,log2(period),sig95,[-99,1],'k');
hold on
% cone-of-influence, anything "below" is dubious
plot(time,log2(coi),'k')
hold off

%--- Plot global wavelet spectrum
subplot('position',[0.77 0.37 0.2 0.28])
plot(global_ws,log2(period))
hold on
plot(global_signif,log2(period),'--')
hold off
set(gca,'YLim',log2([min(period),max(period)]), ...
   'YDir','reverse', ...
   'YTick',log2(Yticks(:)), ...
   'YTickLabel','')
set(gca,'XLim',[0,1.25*max(global_ws)])
```

Wavelet Coherence Script

```
%% Wavelet coherence Example
%
% USAGE: [Rsq,period,scale,coi,sig95]=wtc(x,y,[,settings])
%
% Settings: Pad: pad the time series with zeros?
% .        Dj: Octaves per scale (default: '1/12')
% .        S0: Minimum scale
% .        J1: Total number of scales
% .        Mother: Mother wavelet (default 'morlet')
% .        MaxScale: An easier way of specifying J1
% .        MakeFigure: Make a figure or simply return the output.
% .        BlackandWhite: Create black and white figures
% .        AR1: the ar1 coefficients of the series
% .           (default='auto' using a naive ar1 estimator.  See ar1nv.m)
% .        MonteCarloCount: Number of surrogate data sets in the significance
calculation.  (default=300)
% .        ArrowDensity (default: [30 30])
% .        ArrowSize (default: 1)
% .        ArrowHeadSize (default: 1)
%
% Settings can also be specified using abbreviations.  e.g.  ms=MaxScale.
% For detailed help on some parameters type help wavelet.
%
% Example:
%    t=1:200;
%    wtc(sin(t),sin(t.*cos(t*.01)),'ms',16)
%
% Phase arrows indicate the relative phase relationship between the series
% (pointing right: in-phase; left: anti-phase; down: series1 leading
% series2 by 90°)
%
% Please acknowledge the use of this software in any publications:
%   "Crosswavelet and wavelet coherence software were provided by
%   A.  Grinsted."
%
% (C) Aslak Grinsted 2002-2004
%
% http://www.pol.ac.uk/home/research/waveletcoherence/
```

Wavelet Coherence Script (cont'd)

```
% ------------------------------------------------------------------------
%   Copyright (C) 2002-2004, Aslak Grinsted
%   This software may be used, copied, or redistributed as long as it is not
%   sold and this copyright notice is reproduced on each copy made.   This
%   routine is provided as is without any express or implied warranties
%   whatsoever.

% ------validate and reformat timeseries.
[x,dt]=formatts(x);
[y,dty]=formatts(y);
if dt~=dty
   error('timestep must be equal between time series')
end
t=(max(x(1,1),y(1,1)):dt:min(x(end,1),y(end,1)))'; %common time period
if length(t)<4
   error('The two time series must overlap.')
end

n=length(t);

%----------default arguments for the wavelet transform-----------
Args=struct('Pad',1,...       % pad the time series with zeroes (recommended)
          'Dj',1/12, ...     % this will do 12 sub-octaves per octave
          'S0',2*dt,...     % this says start at a scale of 2 months
          'J1',[],...
          'Mother','Morlet', ...
          'MaxScale',[],...    %a more simple way to specify J1
          'MakeFigure',(nargout==0),...
          'MonteCarloCount',300,...
          'BlackandWhite',0,...
          'AR1','auto',...
          'ArrowDensity',[30 30],...
          'ArrowSize',1,...
          'ArrowHeadSize',1);
Args=parseArgs(varargin,Args,{'BlackandWhite'});
if isempty(Args.J1)
   if isempty(Args.MaxScale)
      Args.MaxScale=(n*.17)*2*dt; %auto maxscale
   end
   Args.J1=round(log2(Args.MaxScale/Args.S0)/Args.Dj);
end
```

Wavelet Coherence Script (cont'd)

```
ad=mean(Args.ArrowDensity);
Args.ArrowSize=Args.ArrowSize*30*.03/ad;
%Args.ArrowHeadSize=Args.ArrowHeadSize*Args.ArrowSize*220;
Args.ArrowHeadSize=Args.ArrowHeadSize*120/ad;

if ~strcmpi(Args.Mother,'morlet')
   warning('WTC:InappropriateSmoothingOperator','Smoothing operator is designed for
morlet wavelet.')
end

if strcmpi(Args.AR1,'auto')
   Args.AR1=[ar1nv(x(:,2)) ar1nv(y(:,2))];
   if any(isnan(Args.AR1))
      error('Automatic AR1 estimation failed.  Specify it manually (use arcov or arburg).')
   end
end

nx=size(x,1);
%sigmax=std(x(:,2));
 ny=size(y,1);
%sigmay=std(y(:,2));

%-----------:::::::::::::--------- ANALYZE ----------::::::::::::------------

[X,period,scale,coix] =
wavelet(x(:,2),dt,Args.Pad,Args.Dj,Args.S0,Args.J1,Args.Mother);%#ok
[Y,period,scale,coiy] = wavelet(y(:,2),dt,Args.Pad,Args.Dj,Args.S0,Args.J1,Args.Mother);

%Smooth X and Y before truncating!  (minimize coi)
sinv=1./(scale');

sX=smoothwavelet(sinv(:,ones(1,nx)).*(abs(X).^2),dt,period,Args.Dj,scale);
sY=smoothwavelet(sinv(:,ones(1,ny)).*(abs(Y).^2),dt,period,Args.Dj,scale);

% truncate X,Y to common time interval (this is first done here so that the coi is
minimized)
dte=dt*.01; %to cricumvent round off errors with fractional timesteps
idx=find((x(:,1)>=(t(1)-dte))&(x(:,1)<=(t(end)+dte)));
X=X(:,idx);
sX=sX(:,idx);
coix=coix(idx);
```

Wavelet Coherence Script (cont'd)

```
idx=find((y(:,1)>=(t(1))-dte)&(y(:,1)<=(t(end)+dte)));
Y=Y(:,idx);
sY=sY(:,idx);
coiy=coiy(idx);

coi=min(coix,coiy);

% -------- Cross wavelet -------
Wxy=X.*conj(Y);

% ---------------------- Wavelet coherence ---------------------------------
sWxy=smoothwavelet(sinv(:,ones(1,n)).*Wxy,dt,period,Args.Dj,scale);
Rsq=abs(sWxy).^2./(sX.*sY);

if (nargout>0)||(Args.MakeFigure)

wtcsig=wtcsignif(Args.MonteCarloCount,Args.AR1,dt,length(t)*2,Args.Pad,Args.Dj,Args.S
0,Args.J1,Args.Mother,.6);
   wtcsig=(wtcsig(:,2))*(ones(1,n));
   wtcsig=Rsq./wtcsig;
end

if Args.MakeFigure

   Yticks = 2.^(fix(log2(min(period))):fix(log2(max(period))));

   if Args.BlackandWhite
      levels = [0 0.5 0.7 0.8 0.9 1];
       [cout,H]=safecontourf(t,log2(period),Rsq,levels);

      colorbarf(cout,H)
      cmap=[0 1;.5 .9;.8 .8;.9 .6;1 .5];
      cmap=interp1(cmap(:,1),cmap(:,2),(0:.1:1)');
      cmap=cmap(:,[1 1 1]);
      colormap(cmap)
      set(gca,'YLim',log2([min(period),max(period)]), ...
         'YDir','reverse', 'layer','top', ...
         'YTick',log2(Yticks(:)), ...
         'YTickLabel',num2str(Yticks'), ...
         'layer','top')
      ylabel('Period')
      hold on
```

Wavelet Coherence Script (cont'd)

```
      %phase plot
    aWxy=angle(Wxy);
      aaa=aWxy;
      aaa(Rsq<.5)=NaN;
      %[xx,yy]=meshgrid(t(1:5:end),log2(period));

      phs_dt=round(length(t)/Args.ArrowDensity(1));
tidx=max(floor(phs_dt/2),1):phs_dt:length(t);
      phs_dp=round(length(period)/Args.ArrowDensity(2));
pidx=max(floor(phs_dp/2),1):phs_dp:length(period);

phaseplot(t(tidx),log2(period(pidx)),aaa(pidx,tidx),Args.ArrowSize,Args.ArrowHeadSize);

      if ~all(isnan(wtcsig))
         [c,h] = contour(t,log2(period),wtcsig,[1 1],'k');%#ok
         set(h,'linewidth',2)
      end
      %suptitle([sTitle ' coherence']);
      plot(t,log2(coi),'k','linewidth',3)
      hold off
   else
      H=imagesc(t,log2(period),Rsq);%#ok
      %[c,H]=safecontourf(t,log2(period),Rsq,[0:.05:1]);
      %set(H,'linestyle','none')

      set(gca,'clim',[0 1])

HCB=safecolorbar;%#ok

      set(gca,'YLim',log2([min(period),max(period)]), ...
         'YDir','reverse', 'layer','top', ...
         'YTick',log2(Yticks(:)), ...
         'YTickLabel',num2str(Yticks'), ...
         'layer','top')
      ylabel('Period')
      hold on

      %phase plot
      aWxy=angle(Wxy);
      aaa=aWxy;
      aaa(Rsq<.5)=NaN; %remove phase indication where Rsq is low
      %[xx,yy]=meshgrid(t(1:5:end),log2(period));
```

Wavelet Coherence Script (cont'd)

```
        phs_dt=round(length(t)/Args.ArrowDensity(1));
tidx=max(floor(phs_dt/2),1):phs_dt:length(t);
        phs_dp=round(length(period)/Args.ArrowDensity(2));
pidx=max(floor(phs_dp/2),1):phs_dp:length(period);

phaseplot(t(tidx),log2(period(pidx)),aaa(pidx,tidx),Args.ArrowSize,Args.ArrowHeadSize);

        if ~all(isnan(wtcsig))
            [c,h] = contour(t,log2(period),wtcsig,[1 1],'k');%#ok
            set(h,'linewidth',2)
        end
        %suptitle([sTitle ' coherence']);
        tt=[t([1 1])-dt*.5;t;t([end end])+dt*.5];
        hcoi=fill(tt,log2([period([end 1]) coi period([1 end])]),'w');
        set(hcoi,'alphadatamapping','direct','facealpha',.5)
        hold off
    end
end

varargout={Rsq,period,scale,coi,wtcsig};
varargout=varargout(1:nargout);

function [cout,H]=safecontourf(varargin)
vv=sscanf(version,'%i.');
if (version('-release')<14)|(vv(1)<7)
    [cout,H]=contourf(varargin{:});
else
    [cout,H]=contourf('v6',varargin{:});

end

function hcb=safecolorbar(varargin)
vv=sscanf(version,'%i.');

if (version('-release')<14)|(vv(1)<7)
    hcb=colorbar(varargin{:});
else
    hcb=colorbar('v6',varargin{:});
end
```

APPENDIX 4

Table A-2 Comparison of Social Vulnerability Index and Sub-Indices from High Social Vulnerability (+) to Low Social Vulnerability (-) and Cholera Incidence by District ID

ID	SVI	C	ID	SVIF1	C	ID	SVIF2	C
32	1.30	15.9	8	1.54	0.0	31	2.59	3.7
31	0.87	3.7	16	1.44	0.6	27	2.12	11.1
30	0.59	12.1	12	1.43	1.2	29	2.01	5.8
27	0.53	11.1	15	0.95	0.1	2	1.10	7.2
20	0.48	1.4	11	0.89	0.4	17	0.84	6.6
12	0.42	1.2	7	0.69	0.4	5	0.64	3.9
29	0.37	5.8	20	0.58	1.4	12	0.49	1.2
6	0.29	9.5	13	0.56	0.8	11	0.45	0.4
16	0.28	0.6	26	0.56	0.3	14	0.40	1.5
28	0.26	3.3	31	0.56	3.7	15	0.40	0.1
3	0.19	2.3	14	0.47	1.5	6	0.36	9.5
4	0.18	2.2	9	0.42	1.7	3	0.17	2.3
5	0.14	3.9	19	0.32	3.9	13	0.10	0.8
17	0.12	6.6	32	0.25	15.9	26	0.09	0.3
22	0.12	6.5	4	0.20	2.2	22	0.07	6.5
15	0.09	0.1	30	0.17	12.1	32	0.01	15.9
8	0.06	0.0	3	0.11	2.3	23	-0.06	13.8
2	0.04	7.2	25	0.00	1.4	8	-0.09	0.0
11	-0.06	0.4	6	-0.04	9.5	16	-0.13	0.6
14	-0.13	1.5	22	-0.06	6.5	1	-0.16	7.4
23	-0.15	13.8	5	-0.08	3.9	10	-0.21	1.5
13	-0.19	0.8	10	-0.08	1.5	21	-0.29	0.7
9	-0.24	1.7	23	-0.15	13.8	30	-0.37	12.1
26	-0.26	0.3	28	-0.24	3.3	0	-0.42	5.4
7	-0.29	0.4	24	-0.35	4.0	9	-0.44	1.7
10	-0.32	1.5	17	-0.37	6.6	28	-0.56	3.3
21	-0.44	0.7	29	-0.53	5.8	20	-0.70	1.4
18	-0.49	0.5	18	-0.71	0.5	18	-1.17	0.5
19	-0.49	3.9	27	-0.79	11.1	24	-1.31	4.0
24	-0.64	4.0	2	-0.88	7.2	7	-1.35	0.4
25	-0.64	1.4	21	-0.92	0.7	19	-1.43	3.9
1	-0.74	7.4	1	-2.55	7.4	25	-1.47	1.4
0	-1.26	5.4	0	-3.39	5.4	4	-1.69	2.2

C represents the total cholera incidence rate for 1997 and 1998 for comparison

Table A-2 (cont'd)

ID	SVIF3	C	ID	SVIF4	C
20	2.66	1.4	32	4.60	15.9
4	2.45	2.2	30	1.38	12.1
5	1.34	3.9	28	1.33	3.3
6	1.30	9.5	31	0.51	3.7
30	1.19	12.1	27	0.41	11.1
16	0.64	0.6	18	0.24	0.5
3	0.54	2.3	13	0.15	0.8
22	0.52	6.5	25	0.11	1.4
28	0.50	3.3	24	0.10	4.0
21	0.39	0.7	2	0.09	7.2
27	0.39	11.1	7	0.09	0.4
32	0.35	15.9	19	0.06	3.9
12	0.31	1.2	9	0.03	1.7
17	0.18	6.6	29	0.01	5.8
29	-0.03	5.8	3	-0.05	2.3
2	-0.15	7.2	22	-0.07	6.5
31	-0.16	3.7	1	-0.08	7.4
1	-0.17	7.4	11	-0.16	0.4
23	-0.22	13.8	23	-0.16	13.8
18	-0.30	0.5	17	-0.18	6.6
8	-0.50	0.0	4	-0.25	2.2
0	-0.51	5.4	15	-0.33	0.1
7	-0.58	0.4	10	-0.34	1.5
14	-0.64	1.5	6	-0.46	9.5
15	-0.64	0.1	12	-0.56	1.2
10	-0.67	1.5	26	-0.56	0.3
19	-0.93	3.9	20	-0.62	1.4
9	-0.97	1.7	8	-0.70	0.0
24	-1.00	4.0	0	-0.71	5.4
26	-1.12	0.3	14	-0.76	1.5
25	-1.20	1.4	16	-0.84	0.6
11	-1.41	0.4	21	-0.94	0.7
13	-1.56	0.8	5	-1.34	3.9

C represents the total cholera incidence rate for 1997 and 1998 for comparison

APPENDIX 5

Table A-3 Climate-cholera Associations by R-Squared and P-Values from Ordinary Least Squares Regression (OLS) by District

ID	District	Variable	Lag	r^2	*p* value
0	PIURA	Rainfall	1	0.85	0.0000
0	PIURA	PAITA SSTA	0	0.71	0.0006
0	PIURA	Rainfall	0	0.71	0.0006
0	PIURA	NIÑO 3.4 SSTA	1	0.68	0.0010
0	PIURA	TMEANA	5	0.67	0.0012
0	PIURA	TMAXA	5	0.65	0.0014
0	PIURA	NIÑO 3.4 SSTA	0	0.65	0.0016
0	PIURA	NIÑO 3.4 SSTA	2	0.63	0.0021
0	PIURA	PAITA SSTA	1	0.61	0.0026
0	PIURA	TMINA	5	0.58	0.0038
0	PIURA	TMAXA	4	0.58	0.0039
0	PIURA	TMEANA	3	0.58	0.0043
0	PIURA	TMAXA	6	0.57	0.0043
0	PIURA	TMEANA	6	0.57	0.0045
0	PIURA	TMINA	0	0.56	0.0050
0	PIURA	TMINA	6	0.56	0.0054
0	PIURA	TMEANA	0	0.54	0.0065
0	PIURA	NIÑO 3.4 SSTA	3	0.54	0.0068
0	PIURA	TMINA	3	0.52	0.0080
0	PIURA	TMEANA	4	0.52	0.0085
0	PIURA	PAITA SSTA	2	0.51	0.0086
0	PIURA	TMINA	1	0.50	0.0101
0	PIURA	TMEANA	2	0.50	0.0102
0	PIURA	TMEANA	1	0.49	0.0112
0	PIURA	NIÑO 1+2 SSTA	2	0.48	0.0128
0	PIURA	TMINA	2	0.46	0.0161
0	PIURA	NIÑO 1+2 SSTA	3	0.45	0.0163
0	PIURA	NIÑO 3.4 SSTA	4	0.44	0.0189
0	PIURA	PAITA SSTA	3	0.44	0.0189
0	PIURA	TMAXA	7	0.44	0.0189
0	PIURA	TMAXA	3	0.42	0.0222
0	PIURA	Rainfall	2	0.40	0.0264
0	PIURA	NIÑO 1+2 SSTA	1	0.40	0.0271
0	PIURA	NIÑO 1+2 SSTA	0	0.39	0.0295
0	PIURA	TMINA	4	0.39	0.0299

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
1	CASTILLA	Rainfall	1	0.85	0.0000
1	CASTILLA	PAITA SSTA	0	0.65	0.0015
1	CASTILLA	Rainfall	0	0.65	0.0016
1	CASTILLA	TMAXA	5	0.64	0.0017
1	CASTILLA	TMEANA	5	0.60	0.0031
1	CASTILLA	NIÑO 3.4 SSTA	1	0.60	0.0031
1	CASTILLA	NIÑO 3.4 SSTA	0	0.57	0.0046
1	CASTILLA	TMAXA	6	0.56	0.0050
1	CASTILLA	TMAXA	4	0.56	0.0053
1	CASTILLA	TMINA	6	0.56	0.0053
1	CASTILLA	TMEANA	6	0.56	0.0053
1	CASTILLA	NIÑO 3.4 SSTA	2	0.56	0.0054
1	CASTILLA	PAITA SSTA	1	0.55	0.0054
1	CASTILLA	TMINA	0	0.51	0.0088
1	CASTILLA	TMINA	5	0.51	0.0089
1	CASTILLA	TMEANA	3	0.49	0.0114
1	CASTILLA	TMEANA	0	0.48	0.0123
1	CASTILLA	NIÑO 3.4 SSTA	3	0.47	0.0143
1	CASTILLA	PAITA SSTA	2	0.45	0.0172
1	CASTILLA	Rainfall	2	0.45	0.0174
1	CASTILLA	TMINA	3	0.44	0.0185
1	CASTILLA	TMEANA	4	0.44	0.0190
1	CASTILLA	TMINA	1	0.44	0.0191
1	CASTILLA	TMEANA	1	0.41	0.0245
1	CASTILLA	TMEANA	2	0.40	0.0272
1	CASTILLA	TMAXA	7	0.40	0.0277
1	CASTILLA	NIÑO 1+2 SSTA	3	0.39	0.0290
1	CASTILLA	NIÑO 1+2 SSTA	2	0.39	0.0296
1	CASTILLA	NIÑO 3.4 SSTA	4	0.38	0.0320
1	CASTILLA	PAITA SSTA	3	0.38	0.0334
1	CASTILLA	TMAXA	3	0.37	0.0364
1	CASTILLA	TMINA	2	0.36	0.0378

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
2	CATACAOS	Rainfall	1	0.84	0.0000
2	CATACAOS	Rainfall	2	0.64	0.0018
2	CATACAOS	TMEANA	5	0.54	0.0063
2	CATACAOS	TMAXA	5	0.53	0.0071
2	CATACAOS	PAITA SSTA	0	0.53	0.0076
2	CATACAOS	TMAXA	6	0.51	0.0091
2	CATACAOS	TMEANA	6	0.50	0.0105
2	CATACAOS	PAITA SSTA	1	0.48	0.0120
2	CATACAOS	NIÑO 3.4 SSTA	2	0.48	0.0120
2	CATACAOS	TMAXA	7	0.47	0.0133
2	CATACAOS	TMINA	0	0.47	0.0133
2	CATACAOS	NIÑO 3.4 SSTA	3	0.46	0.0148
2	CATACAOS	TMINA	5	0.46	0.0148
2	CATACAOS	NIÑO 3.4 SSTA	1	0.46	0.0159
2	CATACAOS	TMEANA	0	0.44	0.0186
2	CATACAOS	PAITA SSTA	2	0.44	0.0191
2	CATACAOS	TMINA	6	0.43	0.0211
2	CATACAOS	TMEANA	7	0.43	0.0211
2	CATACAOS	TMINA	7	0.41	0.0243
2	CATACAOS	NIÑO 3.4 SSTA	0	0.41	0.0252
2	CATACAOS	PAITA SSTA	3	0.41	0.0260
2	CATACAOS	NIÑO 3.4 SSTA	4	0.40	0.0262
2	CATACAOS	NIÑO 1+2 SSTA	3	0.39	0.0308
2	CATACAOS	TMEANA	3	0.36	0.0383
2	CATACAOS	TMINA	3	0.36	0.0392
2	CATACAOS	NIÑO 1+2 SSTA	0	0.35	0.0444
2	CATACAOS	TMINA	2	0.34	0.0452
2	CATACAOS	Rainfall	0	0.34	0.0471

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
5	LA ARENA	PAITA SSTA	0	0.87	0.0000
5	LA ARENA	TMAXA	5	0.81	0.0001
5	LA ARENA	Rainfall	1	0.81	0.0001
5	LA ARENA	NIÑO 3.4 SSTA	0	0.78	0.0001
5	LA ARENA	TMAXA	6	0.76	0.0002
5	LA ARENA	NIÑO 3.4 SSTA	1	0.74	0.0003
5	LA ARENA	PAITA SSTA	1	0.71	0.0006
5	LA ARENA	TMEANA	5	0.70	0.0006
5	LA ARENA	TMINA	1	0.70	0.0007
5	LA ARENA	TMEANA	1	0.70	0.0007
5	LA ARENA	NIÑO 3.4 SSTA	2	0.69	0.0008
5	LA ARENA	TMINA	0	0.66	0.0013
5	LA ARENA	PAITA SSTA	2	0.66	0.0014
5	LA ARENA	Rainfall	0	0.66	0.0014
5	LA ARENA	TMEANA	6	0.63	0.0020
5	LA ARENA	TMEANA	0	0.63	0.0022
5	LA ARENA	NIÑO 3.4 SSTA	3	0.62	0.0023
5	LA ARENA	NIÑO 1+2 SSTA	0	0.61	0.0026
5	LA ARENA	TMEANA	3	0.58	0.0038
5	LA ARENA	TMINA	5	0.58	0.0041
5	LA ARENA	TMAXA	7	0.58	0.0043
5	LA ARENA	TMINA	3	0.57	0.0047
5	LA ARENA	TMINA	6	0.56	0.0054
5	LA ARENA	Rainfall	2	0.55	0.0055
5	LA ARENA	TMEANA	4	0.54	0.0063
5	LA ARENA	NIÑO 3.4 SSTA	4	0.52	0.0080
5	LA ARENA	TMEANA	2	0.52	0.0081
5	LA ARENA	TMAXA	4	0.51	0.0092
5	LA ARENA	TMINA	2	0.49	0.0108
5	LA ARENA	NIÑO 1+2 SSTA	1	0.49	0.0113
5	LA ARENA	PAITA SSTA	3	0.48	0.0127
5	LA ARENA	TMINA	4	0.42	0.0233
5	LA ARENA	NIÑO 1+2 SSTA	4	0.42	0.0233
5	LA ARENA	NIÑO 1+2 SSTA	2	0.41	0.0242
5	LA ARENA	NIÑO 1+2 SSTA	3	0.40	0.0281
5	LA ARENA	NIÑO 1+2 SSTA	5	0.39	0.0300
5	LA ARENA	NIÑO 1+2 SSTA	6	0.35	0.0409
5	LA ARENA	NIÑO 3.4 SSTA	5	0.34	0.0479

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
6	LA UNION	Rainfall	1	0.89	0.0000
6	LA UNION	Rainfall	2	0.82	0.0001
6	LA UNION	TMAXA	6	0.79	0.0001
6	LA UNION	PAITA SSTA	0	0.77	0.0002
6	LA UNION	TMEANA	6	0.75	0.0003
6	LA UNION	PAITA SSTA	1	0.73	0.0004
6	LA UNION	TMAXA	5	0.71	0.0006
6	LA UNION	NIÑO 3.4 SSTA	1	0.69	0.0009
6	LA UNION	TMAXA	7	0.69	0.0009
6	LA UNION	TMINA	6	0.68	0.0009
6	LA UNION	NIÑO 3.4 SSTA	2	0.68	0.0009
6	LA UNION	TMEANA	5	0.68	0.0010
6	LA UNION	PAITA SSTA	2	0.66	0.0014
6	LA UNION	NIÑO 3.4 SSTA	0	0.66	0.0014
6	LA UNION	TMINA	0	0.65	0.0016
6	LA UNION	TMINA	1	0.65	0.0017
6	LA UNION	NIÑO 3.4 SSTA	3	0.64	0.0018
6	LA UNION	TMEANA	0	0.63	0.0022
6	LA UNION	TMEANA	1	0.59	0.0036
6	LA UNION	NIÑO 3.4 SSTA	4	0.57	0.0043
6	LA UNION	NIÑO 1+2 SSTA	0	0.57	0.0046
6	LA UNION	PAITA SSTA	3	0.56	0.0050
6	LA UNION	TMINA	5	0.52	0.0080
6	LA UNION	TMEANA	7	0.52	0.0085
6	LA UNION	TMINA	3	0.50	0.0101
6	LA UNION	TMEANA	3	0.50	0.0101
6	LA UNION	Rainfall	0	0.50	0.0103
6	LA UNION	TMEANA	4	0.48	0.0120
6	LA UNION	TMINA	2	0.48	0.0126
6	LA UNION	TMEANA	2	0.47	0.0141
6	LA UNION	NIÑO 1+2 SSTA	1	0.45	0.0178
6	LA UNION	NIÑO 1+2 SSTA	4	0.43	0.0206
6	LA UNION	NIÑO 1+2 SSTA	3	0.43	0.0208
6	LA UNION	NIÑO 3.4 SSTA	5	0.43	0.0209
6	LA UNION	NIÑO 1+2 SSTA	2	0.40	0.0265
6	LA UNION	NIÑO 1+2 SSTA	6	0.40	0.0285
6	LA UNION	NIÑO 1+2 SSTA	5	0.39	0.0290
6	LA UNION	TMINA	7	0.38	0.0338
6	LA UNION	TMINA	4	0.37	0.0347
6	LA UNION	TMAXA	4	0.37	0.0355
6	LA UNION	PAITA SSTA	4	0.33	0.0491

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
9	HUANCABAMBA	Rainfall	2	0.67	0.0012
9	HUANCABAMBA	TMINA	7	0.44	0.0180
9	HUANCABAMBA	TMAXA	7	0.44	0.0191
9	HUANCABAMBA	TMAXA	6	0.41	0.0255
9	HUANCABAMBA	Rainfall	3	0.40	0.0273
9	HUANCABAMBA	TMEANA	6	0.38	0.0330
9	HUANCABAMBA	Rainfall	1	0.37	0.0349
9	HUANCABAMBA	TMEANA	7	0.37	0.0355
9	HUANCABAMBA	TMINA	6	0.34	0.0471

ID	District	Variable	Lag	r^2	*p* value
12	HUARMACA	Rainfall	2	0.64	0.0019
12	HUARMACA	TMEANA	6	0.63	0.0021
12	HUARMACA	TMINA	6	0.62	0.0024
12	HUARMACA	PAITA SSTA	0	0.50	0.0098
12	HUARMACA	TMINA	1	0.46	0.0148
12	HUARMACA	TMAXA	6	0.46	0.0151
12	HUARMACA	Rainfall	1	0.45	0.0169
12	HUARMACA	PAITA SSTA	1	0.42	0.0232
12	HUARMACA	TMAXA	5	0.41	0.0252
12	HUARMACA	NIÑO 3.4 SSTA	2	0.40	0.0269
12	HUARMACA	NIÑO 3.4 SSTA	3	0.39	0.0289
12	HUARMACA	TMEANA	1	0.38	0.0315
12	HUARMACA	NIÑO 1+2 SSTA	4	0.37	0.0346
12	HUARMACA	NIÑO 3.4 SSTA	0	0.37	0.0357
12	HUARMACA	NIÑO 3.4 SSTA	1	0.36	0.0383
12	HUARMACA	TMINA	0	0.36	0.0391
12	HUARMACA	PAITA SSTA	2	0.36	0.0393
12	HUARMACA	NIÑO 1+2 SSTA	0	0.36	0.0396
12	HUARMACA	TMEANA	4	0.36	0.0408
12	HUARMACA	NIÑO 3.4 SSTA	4	0.34	0.0451
12	HUARMACA	Rainfall	0	0.34	0.0456
12	HUARMACA	TMEANA	0	0.34	0.0460
12	HUARMACA	NIÑO 1+2 SSTA	3	0.33	0.0489

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
17	CHULUCANAS	Rainfall	2	0.86	0.0000
17	CHULUCANAS	TMEANA	7	0.71	0.0006
17	CHULUCANAS	TMINA	7	0.71	0.0006
17	CHULUCANAS	TMEANA	6	0.68	0.0009
17	CHULUCANAS	TMINA	6	0.66	0.0013
17	CHULUCANAS	PAITA SSTA	3	0.59	0.0035
17	CHULUCANAS	TMAXA	7	0.59	0.0036
17	CHULUCANAS	Rainfall	1	0.59	0.0037
17	CHULUCANAS	NIÑO 3.4 SSTA	4	0.56	0.0051
17	CHULUCANAS	NIÑO 3.4 SSTA	3	0.55	0.0058
17	CHULUCANAS	NIÑO 3.4 SSTA	5	0.54	0.0065
17	CHULUCANAS	PAITA SSTA	2	0.51	0.0087
17	CHULUCANAS	NIÑO 3.4 SSTA	2	0.51	0.0090
17	CHULUCANAS	NIÑO 1+2 SSTA	7	0.51	0.0091
17	CHULUCANAS	NIÑO 1+2 SSTA	3	0.51	0.0094
17	CHULUCANAS	Rainfall	3	0.49	0.0111
17	CHULUCANAS	PAITA SSTA	1	0.49	0.0118
17	CHULUCANAS	TMEANA	5	0.47	0.0133
17	CHULUCANAS	TMINA	0	0.45	0.0174
17	CHULUCANAS	NIÑO 3.4 SSTA	6	0.44	0.0181
17	CHULUCANAS	TMEANA	0	0.44	0.0190
17	CHULUCANAS	PAITA SSTA	0	0.43	0.0204
17	CHULUCANAS	TMAXA	6	0.42	0.0217
17	CHULUCANAS	NIÑO 1+2 SSTA	4	0.42	0.0221
17	CHULUCANAS	NIÑO 1+2 SSTA	0	0.42	0.0226
17	CHULUCANAS	TMINA	1	0.42	0.0235
17	CHULUCANAS	TMINA	3	0.41	0.0240
17	CHULUCANAS	PAITA SSTA	4	0.41	0.0254
17	CHULUCANAS	NIÑO 3.4 SSTA	1	0.41	0.0257
17	CHULUCANAS	NIÑO 1+2 SSTA	2	0.38	0.0327
17	CHULUCANAS	TMINA	5	0.37	0.0348
17	CHULUCANAS	TMEANA	3	0.36	0.0376
17	CHULUCANAS	TMEANA	1	0.36	0.0396
17	CHULUCANAS	TMINA	2	0.35	0.0439

ID	District	Variable	Lag	r^2	*p* value
19	CHALACO	Rainfall	2	0.51	0.0093
19	CHALACO	TMINA	6	0.43	0.0199
19	CHALACO	TMEANA	6	0.36	0.0401

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
22	SALITRAL1	Rainfall	2	0.75	0.0002
22	SALITRAL1	PAITA SSTA	3	0.71	0.0006
22	SALITRAL1	TMEANA	6	0.70	0.0007
22	SALITRAL1	TMINA	6	0.66	0.0012
22	SALITRAL1	TMAXA	7	0.60	0.0029
22	SALITRAL1	NIÑO 3.4 SSTA	4	0.60	0.0031
22	SALITRAL1	NIÑO 1+2 SSTA	7	0.59	0.0035
22	SALITRAL1	NIÑO 3.4 SSTA	3	0.59	0.0036
22	SALITRAL1	NIÑO 3.4 SSTA	5	0.58	0.0040
22	SALITRAL1	TMEANA	7	0.56	0.0054
22	SALITRAL1	TMINA	1	0.55	0.0059
22	SALITRAL1	PAITA SSTA	2	0.53	0.0071
22	SALITRAL1	NIÑO 3.4 SSTA	2	0.52	0.0082
22	SALITRAL1	NIÑO 1+2 SSTA	0	0.51	0.0087
22	SALITRAL1	Rainfall	3	0.51	0.0088
22	SALITRAL1	TMINA	3	0.51	0.0094
22	SALITRAL1	PAITA SSTA	4	0.50	0.0098
22	SALITRAL1	PAITA SSTA	1	0.50	0.0101
22	SALITRAL1	TMEANA	1	0.49	0.0118
22	SALITRAL1	NIÑO 1+2 SSTA	3	0.48	0.0130
22	SALITRAL1	NIÑO 3.4 SSTA	6	0.47	0.0137
22	SALITRAL1	NIÑO 1+2 SSTA	1	0.45	0.0173
22	SALITRAL1	NIÑO 3.4 SSTA	1	0.44	0.0193
22	SALITRAL1	NIÑO 1+2 SSTA	2	0.43	0.0206
22	SALITRAL1	TMAXA	6	0.43	0.0213
22	SALITRAL1	TMINA	7	0.43	0.0213
22	SALITRAL1	PAITA SSTA	0	0.42	0.0222
22	SALITRAL1	TMINA	2	0.39	0.0288
22	SALITRAL1	TMEANA	3	0.39	0.0292
22	SALITRAL1	TMEANA	2	0.39	0.0309
22	SALITRAL1	NIÑO 1+2 SSTA	4	0.38	0.0319
22	SALITRAL1	TMEANA	5	0.37	0.0368
22	SALITRAL1	TMEANA	4	0.36	0.0388
22	SALITRAL1	Rainfall	1	0.36	0.0406
22	SALITRAL1	TMINA	4	0.34	0.0461
22	SALITRAL1	NIÑO 3.4 SSTA	0	0.34	0.0465
22	SALITRAL1	TMEANA	0	0.34	0.0467

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
27	SECHURA	Rainfall	1	0.84	0.0000
27	SECHURA	PAITA SSTA	0	0.71	0.0006
27	SECHURA	TMEANA	5	0.71	0.0006
27	SECHURA	NIÑO 3.4 SSTA	1	0.67	0.0011
27	SECHURA	NIÑO 3.4 SSTA	2	0.64	0.0017
27	SECHURA	PAITA SSTA	1	0.63	0.0019
27	SECHURA	TMEANA	6	0.63	0.0020
27	SECHURA	TMINA	5	0.63	0.0020
27	SECHURA	NIÑO 3.4 SSTA	0	0.63	0.0021
27	SECHURA	TMAXA	6	0.63	0.0021
27	SECHURA	TMINA	0	0.62	0.0025
27	SECHURA	TMINA	6	0.60	0.0030
27	SECHURA	TMAXA	5	0.60	0.0030
27	SECHURA	PAITA SSTA	2	0.59	0.0034
27	SECHURA	NIÑO 3.4 SSTA	3	0.58	0.0041
27	SECHURA	TMEANA	3	0.57	0.0043
27	SECHURA	TMINA	3	0.57	0.0044
27	SECHURA	TMEANA	0	0.57	0.0047
27	SECHURA	TMAXA	7	0.55	0.0056
27	SECHURA	Rainfall	2	0.54	0.0065
27	SECHURA	TMINA	1	0.54	0.0067
27	SECHURA	Rainfall	0	0.53	0.0072
27	SECHURA	TMEANA	1	0.53	0.0074
27	SECHURA	PAITA SSTA	3	0.52	0.0078
27	SECHURA	NIÑO 3.4 SSTA	4	0.52	0.0078
27	SECHURA	TMEANA	2	0.49	0.0114
27	SECHURA	NIÑO 1+2 SSTA	2	0.48	0.0124
27	SECHURA	NIÑO 1+2 SSTA	0	0.47	0.0134
27	SECHURA	TMINA	2	0.47	0.0143
27	SECHURA	NIÑO 1+2 SSTA	1	0.46	0.0149
27	SECHURA	TMEANA	4	0.46	0.0159
27	SECHURA	NIÑO 1+2 SSTA	3	0.43	0.0197
27	SECHURA	TMAXA	4	0.38	0.0324
27	SECHURA	NIÑO 3.4 SSTA	5	0.38	0.0340
27	SECHURA	NIÑO 1+2 SSTA	6	0.37	0.0355
27	SECHURA	NIÑO 1+2 SSTA	5	0.34	0.0449
27	SECHURA	NIÑO 1+2 SSTA	4	0.34	0.0457
27	SECHURA	TMINA	4	0.33	0.0488

Table A-3 (cont'd)

ID	District	Variable	Lag	r^2	*p* value
32	RINCONADA LLICUAR	TMINA	6	0.46	0.0150
32	RINCONADA LLICUAR	Rainfall	1	0.44	0.0179
32	RINCONADA LLICUAR	Rainfall	2	0.39	0.0302
32	RINCONADA LLICUAR	PAITA SSTA	0	0.36	0.0394
32	RINCONADA LLICUAR	TMEANA	6	0.35	0.0417
32	RINCONADA LLICUAR	TMAXA	5	0.34	0.0460

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