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# Cholera resurgence in Piura, Peru: examining climate associations during the 1997–1998 El Niño

**Iván J. Ramírez**

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**Abstract** In Peru, the climate pattern El Niño-Southern Oscillation (ENSO) was linked to a resurgence of cholera in 1998. While previous studies found a temperature connection, El Niño's impact on cholera in Peru has not been fully explored. In this study, climate associations with cholera incidence during the 1997–1998 El Niño are examined at a district-level in Piura, a coastal area located in northern Peru. Piura is important to study because it was one of the most affected areas by cholera and El Niño in 1998. The approach taken in this study is a "multiple pathways" perspective, which highlights various dimensions of ENSO to explain cholera linkages. Associations were estimated at various temporal lags using bivariate regression and then mapped in ArcGIS. The results show significant cholera associations with SST in the central equatorial Pacific and on the coast (0–1 month lag), rainfall (1 month lag), and mean and maximum temperatures (5 month lags). Overall, the strongest consistent impact was rainfall, which supports the notion that flooding was a pathway for cholera exposure in Piura. Local sea and air temperature associations also suggest that exposure was potentially linked to vibrio proliferation, which increased the probability of cholera risk. Furthermore, this study shows that climate impacts on cholera were unevenly distributed across Piura, indicating that some districts were more vulnerable than others, possibly related to infrastructure deprivation. In conclusion, the study provides a basis for future investigations, which may be useful for epidemic preparedness during future El Niños and other extreme climate events.

**Keywords** Cholera · El Niño · ENSO · Climate variability · Peru · Vibrio cholerae · Disease

I. J. Ramírez (✉)
Interdisciplinary Science Program, Eugene Lang College, The New School, New York, NY, USA
e-mail: ramirezi@newschool.edu

## Introduction

Cholera is a global health problem that afflicts an estimated 3–5 million people annually (World Health Organization [WHO] 2012). It is a diarrheal disease caused by the ingestion of the bacteria *Vibrio cholerae* found in contaminated water sources or food, including raw/undercooked seafood (Tauxe et al. 1995). In recent decades, it has been established that aquatic organisms, such as phytoplankton, in addition to humans, are reservoirs for *V. cholerae* (Colwell and Spira 1992; Colwell and Huq 2001). Phytoplankton are consumed by upper-level trophic communities, including copepods and crustaceans (e.g., shellfish), which facilitate the movement of *V. cholerae* within the marine food chain (Lipp et al. 2002). Moreover, it is known that *V. cholerae* are autochthonous in estuaries and brackish waters, meaning the bacteria have the ability to reproduce without human fecal contamination, particularly in coastal environments (Colwell and Spira 1992; Colwell and Huq 2001).

Growing evidence suggests that climate variability and extremes are important factors in the ecology of cholera (Constantin de Magny and Colwell 2009). In particular, global patterns such as El Niño-Southern Oscillation (ENSO) have been linked to cholera incidence in South Asia (Pascual et al. 2000; Koelle et al. 2005; Cash et al. 2008), Latin America (Speelmon et al. 2000; Gil et al. 2004), and more recently, the Great Lakes region of Africa (Nkoko et al. 2011). ENSO can influence cholera dynamics through multiple pathways, including by alteration of marine ecosystems and global to local weather patterns (Ramirez et al. 2013). It was first proposed as a climate mechanism for cholera epidemics in Peru (Epstein 1992; Colwell 1996), and later demonstrated in Bangladesh, where correlations were found between ENSO (represented by a sea surface temperature index) and cholera incidence (Pascual et al. 2000). The ENSO link is explained through air–sea interactions in the equatorial Pacific Ocean, which cause basin-wide effects, including pressure changes and a shift of warm water towards the western coast of South America during its warm phase, El Niño. During such events, sea surface temperatures (SST) in the central and eastern Pacific (Niño regions) become anomalously warm, impacting marine and coastal waters (National Oceanic and Atmospheric Research [NOAA] 2012). Elevated SST along with changes in salinity, pH, and nutrient availability in water environments create favorable conditions for plankton populations and *V. cholerae* to thrive (Lobitz et al. 2000; Lipp et al. 2002; Gil et al. 2004). Furthermore, ENSO contributes to rising sea-surface levels and storm surges during El Niño (Philander 1985), which may provide a pathway for intrusion of waters carrying-vibrios to inland environments.

ENSO air–sea interactions also influence global to local climate anomalies, known as teleconnections, which have implications for human health (Nicholls 1991; Kovats et al. 2003). Teleconnections are statistically proven linkages between climate stemming from the central equatorial Pacific and regional climate in distant locations (Glantz 1991). It has been suggested that teleconnections potentially link ENSO to local cholera incidence in places, such as Bangladesh (Pascual et al. 2000; Cash et al. 2008; Hashizume et al. 2013). Temperature and rainfall are important climate pathways in this regard. Elevated sea and air temperatures are associated with the multiplication of aquatic reservoirs and *V. cholerae* found in coastal zones (Lobitz et al. 2000; Lipp et al. 2002; Gil et al. 2004) and inland water sources, such as rivers, lakes and sewage ponds (Franco et al. 1997; Speelmon et al. 2000; Huq et al. 2005; Nkoko et al. 2011; Kaddumukasa et al. 2012). In addition, rainfall has the potential to affect the distribution of *V. cholerae* in water bodies (Ruiz-Moreno et al. 2007). When rain is abundant, it can dilute the concentration of vibrios or transport vibrios (Ruiz-Moreno et al. 2007). The latter pathway occurs during flooding associated with river-levels (Hashizume et al. 2008). Subsequently, surface and ground water contamination may occur if water and sanitation infrastructures collapse. Furthermore, storm run-off can carry waste and contaminants into drinking water sources (Curriero et al. 2001; Rose et al. 2001), thereby increasing human exposure to *V. cholerae* (Saskai et al. 2009; Luques-Fernandez et al. 2012). Alternatively, heavy rains can increase river-flow and enhance the flux of terrestrial nutrients into coastal environments, which is also suspected to influence proliferation of reservoirs and vibrios (Jutla et al. 2011).

In Peru, it was hypothesized that El Niño influenced cholera epidemics in the 1990s (Epstein 1992; Colwell 1996; Mourino-Perez 1998; Seas et al. 2000; Gil et al. 2004; Salazar-Lindo et al. 2008). In that decade, Peru experienced epidemic waves in the onset years, followed by decaying rates of incidence in mid-decade, and a notable resurgence of cholera in 1998 (Fig. 1). Although the El Niño link in 1991 (the onset) has been questioned (Ramirez et al. 2013), there is notable evidence that the 1998 event contributed to a significant rise in cholera incidence, not only in Peru (Ministry of Health, Peru [MINSA] 1998; Speelmon et al. 2000; Gil et al. 2004), but globally (Griffith et al. 2006). Previous studies suggested El Niño-related climate was correlated with excess cholera incidence in Peru during the Southern Hemisphere (SH) summer of 1998 (Speelmon et al. 2000; Gil et al. 2004; Huanca 2004), as well as overall diarrheal disease in SH winter of 1997 (Salazar-Lindo et al. 1997; Checkley et al. 2000; Lama et al. 2004). According to Speelmon et al. (2000), elevated air temperatures influenced by the 1997–1998 El Niño preceded the rise in cholera incidence in Lima, Peru. It was also shown that peaks

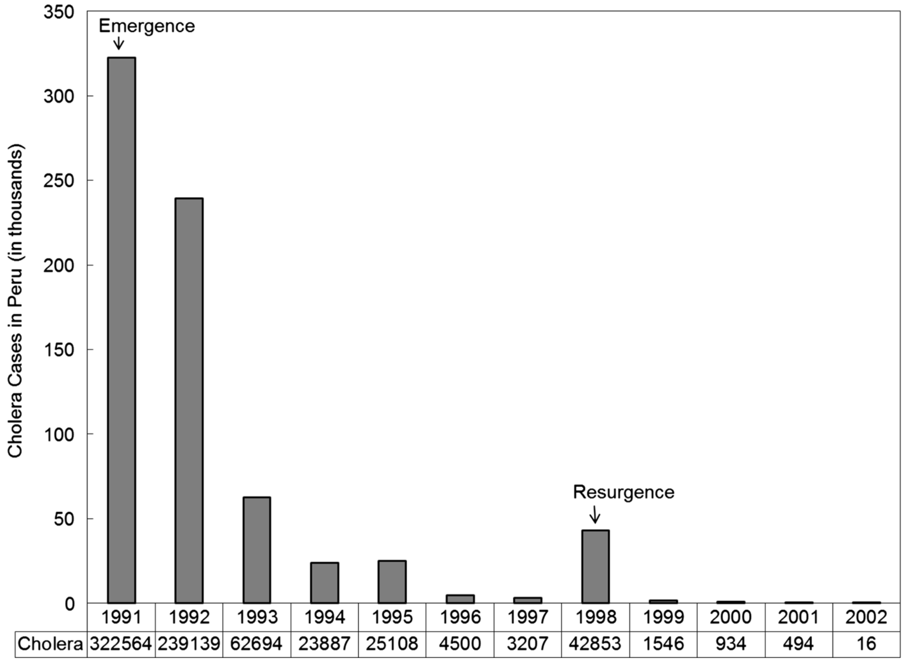


**Fig. 1** Cholera cases (suspected and confirmed, in thousands) in Peru from 1991 to 2002. Highlighted is the emergence and resurgence of cholera in 1991 and 1998. *Data source* The Department of Epidemiology in Lima, Peru; Pan American Health Organization

in coastal seawater temperature (off of Lima) coincided with cholera outbreaks (Gil et al. 2004). Both studies and another (Lipp et al. 2003) detected *V. cholerae* in inland water bodies, sewer sea outlets and the coastal offshore ($\sim$0.5–1.0 km), suggesting that anomalous temperatures propagated the growth of *V. cholerae*, which may have enhanced cholera transmission in coastal Lima.

While a temperature connection was demonstrated in 1998, the pathways by which El Niño and climate impacted cholera in Peru have not been fully explored. In a prior study, using a holistic approach, Ramirez et al. (2013) outlined multiple pathways through which ENSO may have been linked to cholera in Peru. First, it was identified that findings were generally limited to the capital of Lima, located on the central coast. El Niño teleconnections within Peru vary by geography, and therefore, it was argued that regional variations of climate pathways may have existed. In particular, El Niño's influence on local climate is strongest in Peru's northern coastal area. There, El Niño not only influences air temperatures, but also brings storms and rains (Woodman 1999; Takahashi 2004; Lagos et al. 2008). Therefore, one important climate pathway in 1998, which has yet to be examined, is heavy rainfall (Ramirez et al. 2013). Furthermore, the association between SST in the Niño regions and cholera incidence in Peru has not been investigated. SST is important because it a direct indicator of El Niño (NOAA 2012), linked to coastal conditions near Peru and its local climate (Caviedes 1984; Woodman 1999; Ordinola 2002; Lagos et al. 2008). Despite their relevant importance to cholera, the impacts of rainfall and SST during the 1997–1998 El Niño remain unknown in Peru.

In this study, climate associations with cholera incidence during the 1997–1998 El Niño are examined in Piura, Peru. Piura is a coastal region located in northern Peru, approximately 900 km from Lima. It is important to study because it was one of three locations where cholera first emerged in 1991 (Ries et al. 1992; MINSA 1994), and was one of the most affected areas during cholera resurgence in 1998. It is also a place historically associated with El Niño and its impacts on Peruvian society (Caviedes 1984; Woodman 1999; Ordinola 2002). Using retrospective secondary data and health bulletins and governmental documents, this study estimates associations between global and local climate parameters, including SST, air temperature and rainfall, and cholera incidence at a district-level in Piura, Peru from January to December of 1998. The approach taken in this study is a “multiple pathways” perspective, described in Ramirez et al. (2013), which focuses on various dimensions of ENSO to explain cholera linkages, rather than solely focusing on temperature. A multiple pathways approach highlights key characteristics of ENSO that may be important to understanding disease transmission, including air–sea interactions, geography of teleconnections, definition of an ENSO event, and underlying social vulnerability. For public health measures, this study offers new insights which will be useful for prevention and control strategies during future El Niños and other extreme climate events. Although it has been fifteen years since the epidemic, understanding how El Niño and climate influenced cholera in Peru remains important today, particularly as the disease threatens the region amid a new resurgence which began in Haiti in 2010 (PAHO 2013).

## Methods

### Study area

The study site is the subregion of Piura, which is one of two health administrative units located in the Department of Piura in northwest Peru (Fig. 2). The region’s physical geography ranges from semi-arid flora including shrub and woodlands on the low-lying coast in the west, to dry and mountainous forests in the east (foothills of the Andes). Its climate is principally modulated by coastal and equatorial upwelling, the Humboldt current, and importantly, conditions in the central and eastern equatorial Pacific Ocean (Woodman 1999; Rodriguez et al. 2005; Lagos et al. 2008). On the coast, the average annual temperature is 24.0 °C with an average annual maximum and minimum of 37.0 °C and 15.0 °C. Rainfall is highly seasonal, and the annual average is less than 40 mm (mm) on the coast (PAEN Piura/GTZ 2003). The study area also has one major river (Piura), which is intermittently seasonal because it is typically dry or at low levels. However, during El Niños, the region experiences torrential rains and flooding (Woodman 1999; Lagos et al. 2008). Rainfall estimates have been reported as great as 30 times the annual average (Takahashi 2004). In 1998, the study area had an estimated population of 591,175 (Instituto Nacional de Estadistica y Informacion [INEI] 2000). Ninety-three percent of residents lived in urban areas and 59.3 % and 38.5 % had access to potable water and a toilet, respectively, in their households (INEI 1994).

### Data

#### *Cholera*

Weekly cholera data by district for the subregion of Piura from January 1997 to December 1998 were obtained from the Department of Epidemiology at the Ministry of Health in Lima, Peru. These data were comprised of suspected and laboratory-confirmed case-counts. Because the study area reported less than 30 cases in 1997, this study focused on cholera incidence in 1998. Eight districts in the subregion were selected for analysis based on the number of cholera cases ($n \geq 40$) and months of reported cholera ($n \geq 5$). It was important to have at least 40 cases of cholera and 5 months of cholera data in each district in order to have an adequate sample for analyses. In addition, one district (Paita) from the subregion of Luciano Castilla was included because of its geographic location which is adjacent to Piura’s coastal Port of Paita. Figure 3 shows the districts included in the study and the weather stations in the study area (discussed in the following section). For analysis, these cholera data were aggregated to monthly case-counts. Monthly incidence rates were then calculated by dividing the total number of new cholera cases for each month by the 1998 population of each district obtained from INEI. Finally, cholera incidence rates were normalized by square-root transformation.

#### *Climate*

Monthly SST anomaly data for the Niño 3.4 and Niño 1 + 2 regions from 1971 to 2001 were downloaded from the NOAA website (http://www.cpc.ncep.noaa.gov/data/indices/). The Niño region parameters represent global SST conditions in the central equatorial Pacific Ocean and eastern equatorial Pacific Ocean (Niño 3.4), including equatorial and coastal upwelling, near Ecuador and Peru (Niño 1 + 2). The El Niño period in this study is defined as May 1997 to May 1998, based on the Niño 3.4 index available at NOAA (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears_1971-2000_climo.shtml). In addition, monthly data for SST anomaly at


**Fig. 2** Map of the study area (*shaded*) in the Department of Piura, northern Peru. Map produced by Ivan J. Ramirez. *Data source*: University of Piura (Private)

the Paita coastal weather station from 1971 to 2001 were acquired from the University of Piura (Private [UDEP]). Paita represents local SST conditions in the coastal zone of Piura, Peru. Finally, data for monthly air temperature (mean, maximum and minimum) and rainfall (total mm) were acquired from UDEP for Miraflores, a weather station located in the district of Castilla (altitude = 30 m above sea level). Climate data were also collected from a nearby station (CORPAC, altitude = 49 m above sea level), also in Castilla, to supplement a small number of missing values in the Miraflores record (refer to Fig. 3 for all weather station sites). For each temperature parameter (maximum anomaly [Tmax], mean anomaly [Tmean], and minimum anomaly [Tmin]), standardized anomalies were calculated by subtracting the mean for each month and then dividing by the monthly standard deviation for the base period 1971–2000. Rainfall data were normalized using square-root transformation.

## Data analysis

Ordinary Least Squares (OLS) regression was used to estimate the associations between climate and cholera, where monthly incidence (per 1,000 persons) was the dependent variable and global and local climate parameters (Niño 3.4 SST; Niño 1 + 2 SST; Paita

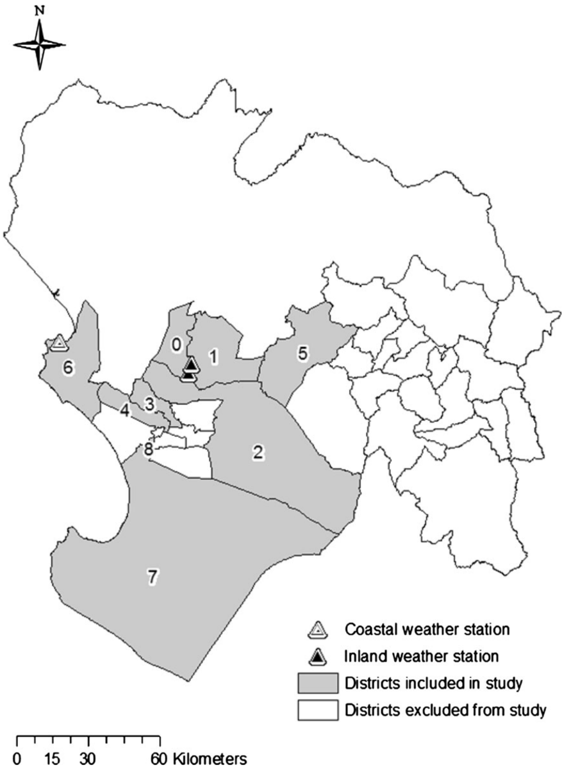


**Fig. 3** Map of districts (ID) included in the study: (*0*) Piura; (*1*) Castilla; (*2*) Catacaos; (*3*) La Arena; (*4*) La Union; (*5*) Chulucanas; (*6*) Paita; (*7*) Sechura; and (*8*) Rinconada Llicuar. Coastal (Paita) and inland (Miraflores and CORPAC) weather stations are also shown. *Data source* University of Piura (Private)

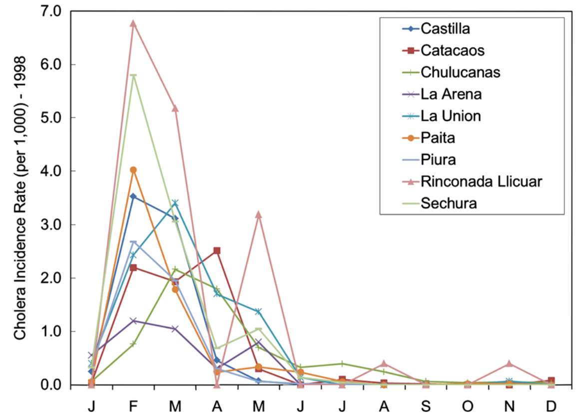


**Fig. 4** Monthly time plot of cholera incidence rate (per 1,000) by districts for January to December 1998. *Data source* The Department of Epidemiology, Lima, Peru

SST; Tmax; Tmin; Tmean; and Rainfall) were the explanatory variables. The strength of each association was estimated using the coefficient of determination ($r^2 > 0.65$) and statistical significance ($p$ value $>0.05$). Similar criteria were used by Mendelsohn and Dawson (2008) to study a cholera epidemic in KwaZulu-Natal, South Africa from 2000 to 2001. Temporal lag associations between monthly cholera incidence and global and local climate parameters were also estimated from zero to 12 months in order to explore a range of potential temporal patterns. Understanding temporal lags is important to explain the timing of impacts associated with different climate pathways; such information could be useful for an early warning system in public health. Analyses were performed in IBM SPSS Statistics 20.0 and graphic time plots were created in Microsoft Excel. In addition, the spatial variability of climate-cholera relationships was visualized by mapping the climate parameters with the strongest associations ($r^2$ values) in ArcGIS version 10.1.

## Results

In 1998, there were 3,897 confirmed and suspected cases of cholera reported across the study area in Piura. This total represented 58.0 % of cholera cases in the Department of Piura and 9.1 % of all cases in Peru. The overall incidence rate for the area was 659.20 per 100,000, which, during the course of the year, reached a maximum of 267.43 per 100,000 in February (SH summer) and a minimum of 0.85 per 100,000 in October (SH spring). At the district-level, cholera incidence per 1,000 was highest in the west coast districts of Rinconada Llicuar (15.94 per 1,000) and Sechura (11.11 per 1,000), as well as La Union (9.51 per 1,000), which borders the district of Paita. Figure 4 shows the temporal pattern of cholera incidence from January to December 1998. Although incidence was most notable in February (e.g., Rinconada Llicuar, 6.77 per 1,000; Sechura, 5.80 per 1,000; and Paita, 4.03 per 1,000), peaks in cholera rates were also observed in March (La Union, 3.40 per 1,000; and Chulucanas, 2.17 per 1,000), April (Catacaos, 2.51 per 1,000), and May (second peak in Rinconada Llicuar, 3.19 per 1,000). By June (winter), cholera incidence across the study area had declined at rates below 1.00 per 1,000.

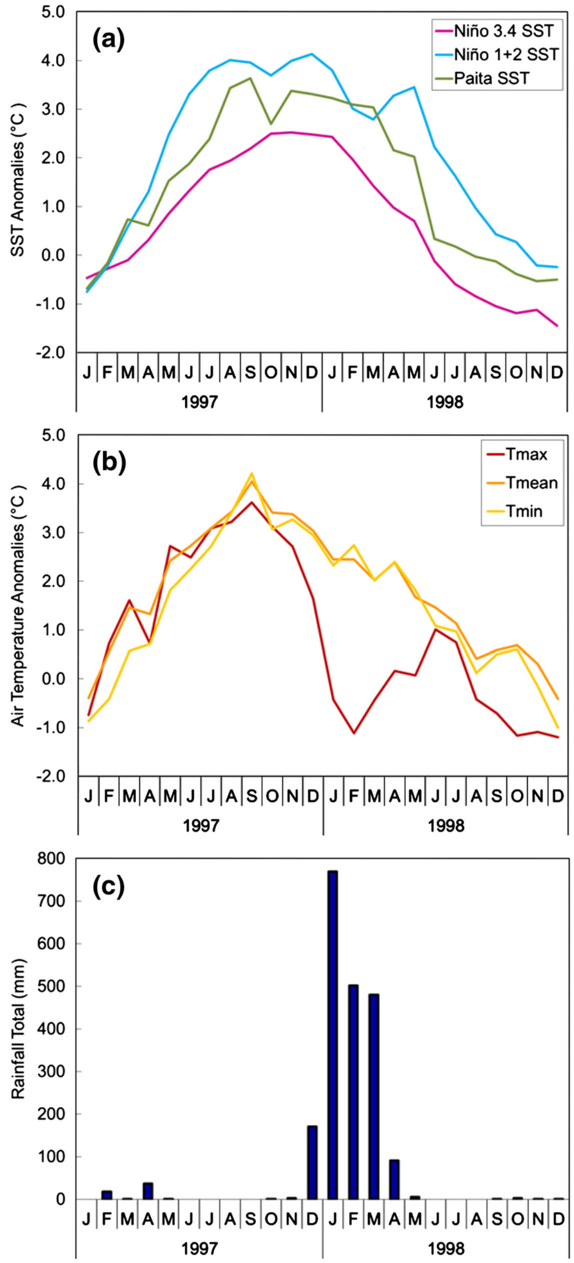


**Fig. 5** Monthly time plots of climate parameters for 1997–1998: **a** SST anomalies; **b** air temperature anomalies; and **c** rainfall total. *Data sources* National Oceanic and Atmospheric Administration; University of Piura (Private)

Figure 5a–c shows time plots of climate parameters from January 1997 to December 1998. The preceding year is shown to illustrate the impact of the 1997–1998 El Niño on global and regional climate, which is well documented in the literature (World Meteorological Organization [WMO] 1999), and to demonstrate the potential time-lagged relationships between climate and cholera. As Fig. 5a indicates, beginning in May of 1997 with the onset of El Niño, a significant rise in SST was observed in the Niño 3.4 and Niño 1 + 2 regions in the Pacific Ocean and coastal near shore of Piura, Peru (Paita). For approximately 11 consecutive months, elevated SST anomalies were equal to or greater than 1.0 °C. SST anomalies peaked in December of 1997: Niño 3.4, 2.5 °C; Niño 1 + 2, 4.1 °C; and Paita, 3.3 °C. During this time period, inland, Tmean and Tmin in Piura were also positively anomalous with values equal to or greater than 2.0 °C, which peaked in September (~4.0 °C) (Fig. 5b). Tmax in Piura followed a similar pattern; however, Tmax values declined rapidly by January 1998. For the next 2 months (February to March), Tmax anomalies were negative, which coincided with heavy rainfall during summer in Piura. Rainfall values peaked in January (769 mm) and subsided by June (0 mm) (Fig. 5 [c]). In total, from December 1997 to March 1998, an estimated 1,921 mm of rain fell in Piura, which was approximately 9 times the annual average at the Miraflores station. In summary, elevated sea surface and air temperatures observed during the 1997–1998 El Niño preceded the rise of cholera in Piura in 1998 (by several months); whilst, a rise in total rainfall and decline in maximum air temperature was concurrent with cholera incidence in Piura.

Table 1 shows the strongest associations, denoted by the coefficient of determination ($r^2 > 0.65$), between global and local climate parameters and cholera incidence rates at the district level in Piura. The climate parameters with the strongest significant relationships with cholera were: Niño 3.4 SST (1 month lag), Paita SST (0 month lag), Tmax (5 month lag), Tmean (5 month lag), and Rainfall (1 month lag). The parameter with the weakest cholera associations was Niño 1 + 2 SST ($r^2 < 0.60$). Overall, the sign direction of relationships was positive, suggesting that with each unit increase of climate parameter, cholera incidence increased. Furthermore, the strong temporal lag associations indicated suggest differences in the timing of potential impacts on cholera between climate parameters. For example, SST and Rainfall associations were strongest and significant at 0–1 month, whereas air temperature associations peaked at 5–6 months.

The spatial distribution of climate-cholera associations is displayed in Fig. 6. The most distinct climate

**Table 1** Strongest climate-cholera associations ($r^2$) by district and climate parameter

| District | Niño3.4 SST 1 month | Paita SST 0 month | Tmax 5 month | Tmean 5 month | Rainfall 1 month |
|---|---|---|---|---|---|
| Castilla | 0.60** | **0.65**** | 0.64** | 0.60** | **0.85**** |
| Catacaos | 0.46* | 0.53** | 0.53** | 0.54** | **0.84**** |
| Chulucanas | 0.41* | 0.43* | 0.26 | 0.47* | 0.59** |
| La Arena | **0.74**** | **0.87**** | **0.81**** | **0.70**** | **0.81**** |
| La Union | **0.69**** | **0.77**** | **0.71**** | **0.68**** | **0.89**** |
| Paita | 0.53** | 0.53** | 0.46* | 0.58** | **0.72**** |
| Piura | **0.68**** | **0.71**** | **0.65**** | **0.67**** | **0.85**** |
| Rinconada Llicuar | 0.28 | 0.36* | 0.34* | 0.32 | 0.44* |
| Sechura | **0.67**** | **0.71**** | 0.60** | **0.71*** | **0.84**** |

Associations greater than 0.65 are noted in bold. Statistical significance at the 95.0 % (*) and 99.0 % (**) levels are indicated, respectively

relationship across the study area, determined by the number of districts and level of association, was Rainfall at a 1 month lag (Fig. 6a). Rainfall-cholera associations (1 month lag) were consistently strong ($r^2 > 0.80$, $p$ value $= 0.000$) in 7 out of 9 districts. Sea and air temperature associations at 0–1 and 5 month lags (Fig. 6b–e), on the other hand, suggest some spatial variability across the study area. It is also observed that strong associations were concentrated in a few districts. These districts potentially signify impact hotspots based on the number of climate associations in each place. They include the inland districts of La Arena (5 impacts) and La Union (5 impacts), which border each other, Piura (5 impacts), and Sechura (4 impacts), which is located on the immediate coast. Interestingly, Rinconada Llicuar, which had the highest incidence rate in the study area, had the weakest associations with climate parameters ($r^2 < 0.45$).

## Discussion

The goal of this study was to examine associations between global and local climate during the 1997–1998 El Niño and cholera incidence at a district-level in Piura, Peru. Using bivariate regression analyses, it was shown that some climate parameters were linked to cholera rates. The analysis found important associations between cholera and rainfall, SST in the central equatorial Pacific Ocean (Niño 3.4) and off the coast of Paita, and mean and maximum air temperatures in Piura. The sign direction of associations were generally positive, however, the strength of relationships varied by climate parameter, temporal lag, and district. Overall, the climate parameter with the strongest positive impact was rainfall when it preceded cholera by 1 month ($r^2 > 0.80$, $p$ value $= 0.000$). The impact of rainfall on cholera transmission has been demonstrated in numerous studies (Hashizume et al. 2008; Mendelsohn and Dawson 2008; Luques-Fernandez et al. 2009; Rinaldo et al. 2012). Rain-related disasters were documented widely in northern coastal Peru in 1998 as a consequence of El Niño (Sandoval 1999; MINSA 1998; PAHO 1998), and thus this work supports the notion that flooding may have provided pathways for cholera exposure in Piura. In the study area, in particular, reports indicated that enhanced riverflow destroyed two bridges (including the Piura and Bolognesis in the capital) and that the Piura River overflowed its banks, which in turn flooded city streets and homes (INEI 1998; Sandoval 1999). One specific pathway of exposure, therefore, may have been contaminated water as drainage networks became overwhelmed with rainwater, bringing to surface sewer water and waste (Saskai et al. 2009). In addition, within areas of poor water and sanitation infrastructures (e.g., shallow wells and open latrines), cholera exposure may have occurred as flood waters and rain-related run-off transported waste from exposed pit latrines, which in turn contaminated open water wells and other drinking water sources. Saskai et al. (2009) and Rinaldo et al. (2012) reported similar climate mechanisms in Zambia and Haiti during cholera outbreaks.

Cholera incidence in Piura was also linked to SST in the Niño 3.4 region and coast of Paita at temporal

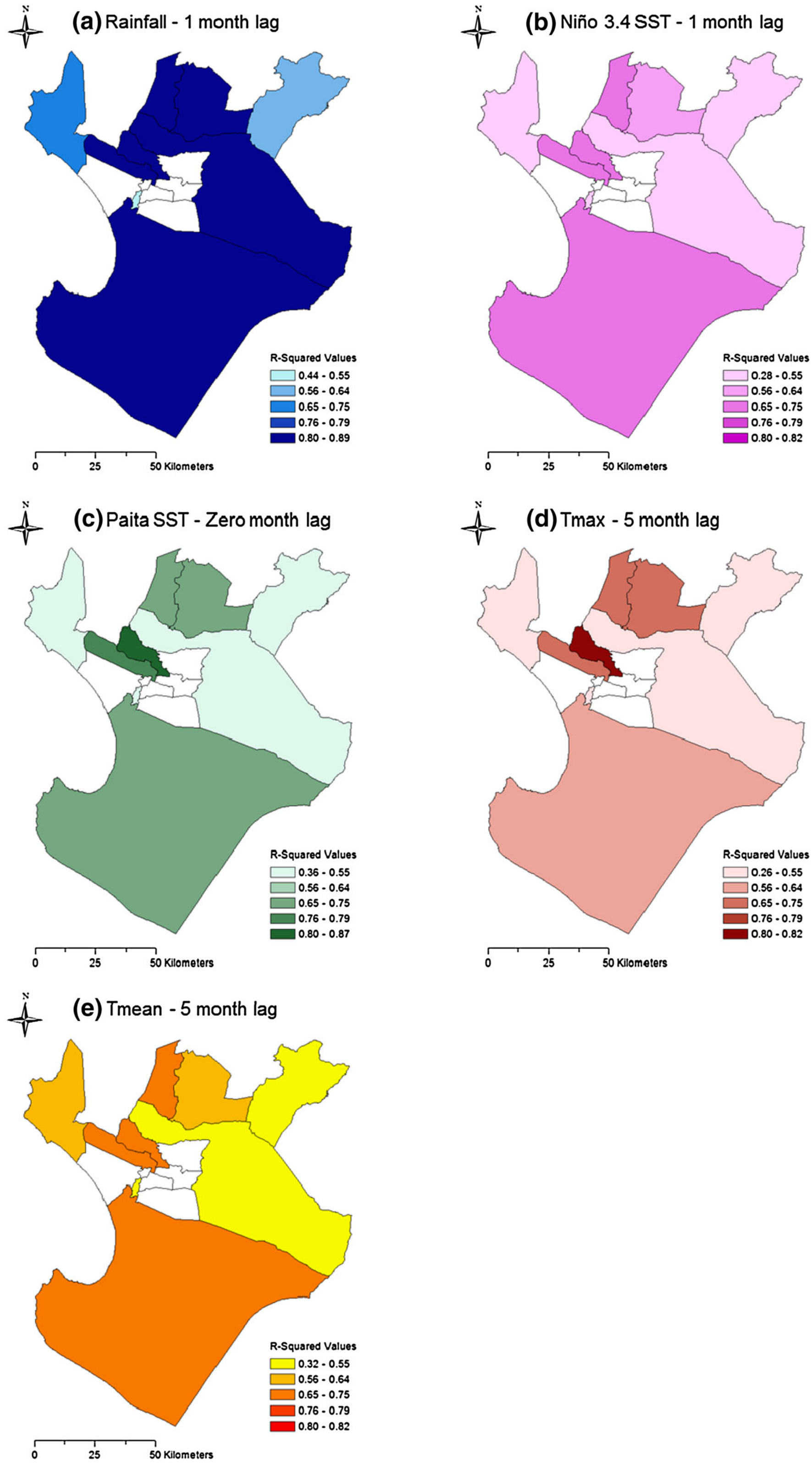


**Fig. 6** Spatial distribution of cholera incidence (per 1,000) associations with (**a**) rainfall (1 month lag); (**b**) Niño 3.4 SST (1 month lag); (**c**) Paita SST (Zero month lag); (**d**) Tmax (5 month lag); and (**e**) Tmean (5 month lag), based on R-squared values

lags of 1 and 0 month, which may associate teleconnections with ecosystem changes in coastal Piura. As mentioned earlier, Pascual et al. (2000) postulated that El Niño influenced the ecology of cholera through interactions with local sea and air temperatures in Bangladesh. It was also proposed that rainfall mediated the relationship between SST and cholera incidence (Pascual et al. 2002; Koelle et al. 2005). According to Cash et al. (2008), basin-wide changes (in the Pacific Ocean) during El Niños lead to impacts on the regional climate of Bangladesh, including enhanced monsoon rains, which in turn influence cholera transmission in the region. It is well documented that conditions in the central and eastern equatorial Pacific strongly influence local climate in coastal Piura (Caviedes 1984; Horel and Cornejo-Garrido 1986; Woodman 1999; Ordinola 2002; Lagos et al. 2008). During El Niños, as warm waters shift from the western end to the eastern end of the Pacific Ocean basin, convective activity and below average air pressure bring warmer temperatures, rains, and storms to this region. Therefore, one pathway of exposure associated with El Niño teleconnections may have been elevated sea surface conditions off the coast of Paita which led to the proliferation of *V. cholerae* and/or aquatic reservoirs near shore. Previous studies in Lima, which also documented the presence of vibrios in coastal waters preceding outbreaks (Lipp et al. 2002; Gil et al. 2004), support these associations. Subsequently, contaminated coastal waters may have been carried inland by tidal intrusion, caused by rising sea levels and storm surges associated with El Niño (Ramirez et al. 2013). Thus, Paita may have been one coastal entry point in Piura for cholera transmission in 1998, which then diffused to neighboring districts.

Furthermore, other pathways of exposure associated with El Niño teleconnections may have occurred via air temperature and rainfall in inland Piura. In other words, the impact of SST on cholera incidence in Piura was also likely mediated by local inland temperature and rainfall mechanisms. In this study, local mean and maximum air temperatures at temporal lags of 5 months were positively associated with cholera incidence in Piura. These results support studies in Lima which also found that elevated inland air temperatures during El Niño increased cholera and diarrheal disease (Franco et al. 1997; Salazar-Lindo et al. 1997; Speelmon et al. 2000; Lama et al. 2004). Unlike studies in Lima, however, this analysis found longer temporal lag relationships (5 months). For example, Speelmon et al. (2000) showed that a rise in mean air temperature preceded cholera by 3 weeks from July 1997 to July 1998. Although it is possible that geography (central vs. north coast) and study design (e.g., time period; variables, mean temperature versus anomaly) account for the difference in lags, longer time delays may also be explained by considering the impact of El Niño on seasonal weather in Piura. Specifically, this refers to the extension of warmer weather in the winter (June to August) and spring (September to November) of 1997, as a result of above average SST in the central equatorial Pacific, which in turn enabled *V. cholerae* to flourish in local water bodies (Speelmon et al. 2000; Lipp et al. 2003; Gil et al. 2004). When El Niño matured in December of 1997, mean and maximum air temperature conditions in Piura had been elevated for several consecutive months, as mentioned earlier. By January, however, while mean air temperature remained high (positive anomaly of 2.4 °C), maximum air temperature values declined rapidly (negative anomaly of 0.4 °C), most likely because of cloud cover and the commencement of torrential rains in Piura. Subsequently, a cycle of enhanced cholera transmission may have occurred as exposure increased because of bacterial replication (due to elevated water temperatures) (Franco et al. 1997), exacerbated by the effects of heavy rains, described earlier.

Lastly, this study showed descriptively that climate associations with cholera were not evenly distributed across the study area in 1998. Except for rainfall (1 month lag)—which was consistently strong in most districts, sea and air temperature associations were spatially variable in terms of the strength of relationship by district, suggesting that other factors, unaccounted for in this analysis, influenced transmission. It was also shown that the strongest climate associations were concentrated in four districts: La Arena, La Union, Piura, and Sechura. According to INEI (1994), all of these districts, except for Piura,[1] reported that more than 60.0 % of the population may not have had access to potable water and 90.0 % did not have a toilet in their households. These observations highlight the importance of social vulnerability associated

[1] Piura reported 26.0 and 39.0 % of the population without access to potable water or a toilet in their households (INEI 1994).

with infrastructure deprivation, which may have contributed to preventable exposure to cholera in 1998. Moreover, it alludes to the potential interactions of social vulnerability with climate extremes, which may have been most evident in Sechura and La Union, where the highest cholera rates were reported in the study area in 1998.

This study faced several challenges. Although several climate datasets were acquired during fieldwork in 2008 and 2009, many were incomplete, except for two stations located in the district of Castilla, which were employed for the study. Therefore, it was difficult to conduct an analysis that captured the spatial variability of climate on cholera within the region. Another challenge was the length of the cholera data series, which was limited to 12 out of 24 months because most districts did not report cholera in 1997. Furthermore, data prior to 1997 at the local level were unavailable. According to public health personnel at MINSA in Piura, El Niño-related flooding in 1998 destroyed data records including cholera reports that were not digitized (anecdotal). Therefore, this study was only able to examine cholera associations during one El Niño event, which means that these results cannot be generalized to represent the entire decade (1990s) or other time segments when cholera was endemic. El Niño events can differ in their development, including magnitude and timing of impacts, and therefore, the potential for regional impacts can vary between ENSO episodes. Examining a longer series at a local level would have enabled this study to better gauge the strength and consistency of climate associations in Piura, Peru. Thus, it could help explain why Niño 1 + 2 SST, in particular, was weakly associated with cholera incidence even though the geography of this parameter (represents sea conditions near Peru where vibrios may have been present) suggests the potential for a stronger relationship.

This study also recognizes that it is possible that people may have been exposed in a different location. Since information about the location of exposure was unavailable, the cholera data used in this study may represent an underestimation or overestimation of cases for each district. In general, surveillance of cholera is challenging given that 75.0 % of population infected do not show symptoms (WHO 2012). In addition, the historical association between cholera and poverty suggests that social mechanisms are important to explaining exposure and vulnerability to cholera (Cueto 2001; Talavera and Perez 2009). However, in this study, the effects of population and social factors on cholera incidence were not investigated. One reason, again, is related to the data limitations mentioned above. While climate data were available across time, social data (e.g., census information) were not. This may explain why only a few climate-cholera studies (see Emch et al. 2010 for an example in Bangladesh) have explored the effects of socioeconomic status and infrastructure on the climate and cholera relationship.

## Summary and conclusions

This study, in addition to supporting previous work in Peru (cholera links with local mean air and SST), revealed that other climate parameters during the 1997–1998 El Niño were also important and that district-level associations varied by parameter and district. In sum, the results show that more than one pathway associated with El Niño may have contributed to cholera incidence, rather than just temperature. In particular, heavy rain was likely an important mechanism in the region of Piura, which increased human exposure and vulnerability to cholera because of flooding in 1998. The results further show that elevated local sea and air temperatures had an impact on cholera incidence, suggesting that disease exposure was also potentially associated with vibrio proliferation. Furthermore, it is possible that these temperature mechanisms took place at differing time points if one considers time lag associations: local sea surface temperature (Paita) was concurrent with cholera incidence; whereas local maximum and mean air temperature preceded cholera by 5 months, which may suggest that air temperatures contributed to an ecological incubation of bacteria due to seasonal disruption (no winter). Alternatively, the local sea surface temperature association could be related to the rainfall mechanism given similar temporal lags (0–1 month). Moreover, although not directly measured, it is suspected that both pathways (rainfall and temperature) were likely mediating factors influenced by the effects of sea surface conditions in the central equatorial Pacific during the 1997–1998 El Niño, which increased the probability of climate anomalies that heightened cholera risk in 1998. In addition, each pathway may have interacted with the other. For example, temperature influence on bacteria, followed by rain-related floods that exposed vulnerable populations. Finally, this study shows that the spatial distribution of climate impacts on cholera were unevenly distributed, indicating that some districts may have been more vulnerable than others, possibly related to infrastructure deprivation.

In conclusion, this study highlights the importance of understanding climate and cholera relationships through multiple pathways, particularly when considering the influence of El Niño (Ramirez et al. 2013). Thus, future research in Peru should consider the independent and interactive effects of each climate pathway described above. In particular, in addition to a much needed longer time series analysis to support the findings here, it will be necessary to examine how the Piura River flow and levels contributed to flooding, which in part, may explain the spread of cholera in 1998. This could be achieved by utilizing river discharge data to measure peak stream flow volume in relation to cholera incidence, as Akanda et al. (2009) have demonstrated in Bangladesh. Also, the role of local SST should be examined further. In a recent study by Jutla et al. (2011), the authors argue that in the Bay of Bengal, SST does not directly impact *V. cholerae* and aquatic reservoirs. Rather it is the influx of terrestrial nutrients associated with high river discharge that influences the local coastal ecology of *V. cholerae*, which suggests that SST is confounding. With this said, in Piura, the role of river discharge is plausible given the extreme rainfall amounts reported during the SH summer in 1998. However, future work should also assess whether both mechanisms (elevated SST and river discharge) could play concurrent roles in cholera transmission due to the complexity of coastal processes during El Niños in Peru (see Ramirez et al. 2013). Furthermore, an examination of parameter interactions and temporal lag associations is needed to better understand pathway dynamics, which can potentially inform a cholera early warning system in Piura and the region.

Importantly, in order to better understand the spatial variation of climate-cholera associations within Piura, a more comprehensive investigation of cholera vulnerability must include not only climate, but also non-climatic variables, such as inequality in socioeconomics and basic infrastructure (e.g., potable water and sanitation access), as well as immunity status among the population. The two former factors, are well known to influence exposure to cholera, as mentioned earlier, and have also been shown to mediate the climate and cholera relationship. For example, Emch et al. (2010) found that socioeconomic status, measured as an index composed of census data, was a stronger driver of cholera relative to environmental factors in the post-monsoon season in Matlab, Bangladesh, supporting the notion that social vulnerability can also explain regional and seasonal differences in disease patterns. Immunity status, on the other hand, provides a better estimation of biological susceptibility to cholera by including previous disease levels, which can explain, in part, temporal patterns of cholera (also in Bangladesh) (Pascual et al. 2002; Koelle et al. 2005). Therefore, considering the modifying effects of these non-climatic variables could possibly explain why and how some districts in this study were more vulnerable to climate impacts and how patterns changed overtime.

Unlike Bangladesh, where climate and cholera dynamics understanding has advanced, much more work remains to be done in Peru. It is hoped that the results in this study, along with the points for inquiry suggested, rekindle interest and motivate future work in the region. Such investigations, which require broad multidisciplinary thinking (including but not limited to epidemiology and climate and social sciences), will lead to an improved understanding of cholera epidemics, and thus, better epidemic preparedness in Piura, Peru and the region, where cholera remains an imminent threat.

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