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Examining rainfall and cholera dynamics in Haiti using statistical and dynamic modeling approaches

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ABSTRACT

Haiti has been in the midst of a cholera epidemic since October 2010. Rainfall is thought to be associated with cholera here, but this relationship has only begun to be quantitatively examined. In this paper, we quantitatively examine the link between rainfall and cholera in Haiti for several different settings (including urban, rural, and displaced person camps) and spatial scales, using a combination of statistical and dynamic models.

Statistical analysis of the lagged relationship between rainfall and cholera incidence was conducted using case crossover analysis and distributed lag nonlinear models. Dynamic models consisted of compartmental differential equation models including direct (fast) and indirect (delayed) disease transmission, where indirect transmission was forced by empirical rainfall data. Data sources include cholera case and hospitalization time series from the Haitian Ministry of Public Health, the United Nations Water, Sanitation and Health Cluster, International Organization for Migration, and Hôpital Albert Schweitzer. Rainfall data was obtained from rain gauges from the U.S. Geological Survey and Haiti Regeneration Initiative, and remote sensing rainfall data from the National Aeronautics and Space Administration Tropical Rainfall Measuring Mission.

A strong relationship between rainfall and cholera was found for all spatial scales and locations examined. Increased rainfall was significantly correlated with increased cholera incidence 4–7 days later. Forcing the dynamic models with rainfall data resulted in good fits to the cholera case data, and rainfall-based predictions from the dynamic models closely matched observed cholera cases. These models provide a tool for planning and managing the epidemic as it continues.

Introduction

Haiti has been in the grip of a cholera epidemic since October 2010. As of July 1, 2013, the Haitian Ministere de la Sante Publique et de la Population (MSPP) has reported 664,259 cases and 8169 deaths.[1] Much attention has been paid to the early stages of the epidemic, including the origin of the epidemic strain (Chin et al., 2011; Cravioto et al., 2011; Piarroux et al., 2011), and the continuing threat posed by cholera to the current health and welfare of Haitians is of paramount concern. Although research efforts have evaluated the impact of water treatment practices, hand washing, and diet in urban (Dunkle et al., 2011) and rural (O'Connor et al., 2011) settings on cholera risk, have assessed the burden of *Vibrio cholerae* in water and food sources (Hill et al., 2011), and have evaluated such intervention efforts as opening of cholera treatment centers, education campaigns, and building of latrines (De Rochars et al., 2011; Ernst et al., 2011), case counts continue to rise more than two years after the epidemic began.

As intervention efforts grapple with a disease which is rapidly becoming endemic, understanding the role of the physical environment, including rainfall at both short-term time scales, and at a seasonal level, in the spread of cholera is crucial. Anecdotally, it has been noted that cholera case counts, which had been declining, rose sharply with the onset of seasonal heavy rains in the spring of 2011 (Adams, 2012; Periago et al., 2012). A better understanding

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[1] July 1 report from MSPP.

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of the role of the physical environment in general, and rainfall in particular, in cholera dynamics in Haiti may lead to both improvement in the ability to forecast disease incidence, and would also help inform disease control interventions. Rinaldo et al. (2012) include rainfall in a complex model of cholera in Haiti, involving more than 300 spatial locations and including movement of both people and water. We take a simpler approach here, using a combination of statistical models and basic dynamic models to examine the relationship between rainfall with cholera case data from several different settings and spatial scales. Previous models of cholera in Haiti and elsewhere have incorporated varying degrees of spatial structure (Tuite et al., 2011; Chao et al., 2011; Reiner et al., 2012; Rinaldo et al., 2012; Bertuzzo et al., 2010, 2011; Gatto et al., 2012). In this paper, neither the statistical nor the dynamic models include an explicit spatial component. This bare-bones approach is intended to allow the model to be focused on the role of rainfall.

Previous studies have examined the role of weather and rainfall on cholera dynamics in Haiti (Rinaldo et al., 2012) and there have been many previous examinations of these effects in countries other than Haiti (Reiner et al., 2012; Altizer et al., 2006; Constantin de Magny et al., 2008; Emch et al., 2008; Faruque et al., 2005; Fernandez et al., 2009; Hashizume et al., 2010; Koelle, 2009; Lipp et al., 2002; Longini et al., 2002; Pascual et al., 2000; Ruiz-Moreno et al., 2007). Most countries in which the influence of rainfall on cholera incidence has been studied experience endemic cholera. Haiti, by contrast, has been cholera free for the past century, with the pathogen introduced from elsewhere. Associations between rainfall and cholera risk in other countries have shown a range of effects, with both positive and negative correlations having been reported at time lags varying from weeks to months (Emch et al., 2008; Fernandez et al., 2009; Hashizume et al., 2008, 2010; Mendelsohn and Dawson, 2008; Ruiz-Moreno et al., 2007). This may reflect the variety of potential mechanisms whereby rainfall may alter cholera risk, including via flooding leading to raw sewage contamination of water sources (Hashizume et al., 2008; Ruiz-Moreno et al., 2007), increased rainfall leading to increased iron availability, which in turn improves *V. cholerae* survival and expression of cholera toxin (Faruque et al., 2005; Lipp et al., 2002), and decreased water levels leading to increased usage of existing water sources and thus increased risk of contamination and disease transmission (Lipp et al., 2002; Ruiz-Moreno et al., 2007). Ruiz-Moreno et al. (2007) suggest a dual role for rainfall and cholera, with both high and low rainfall leading to increased transmission through different mechanisms. This variation between studies emphasizes the need for quantitative examination of site-specific case and environmental data in order to understand cholera dynamics in a given region.

We examine the relationship between cholera and rainfall in Haiti using several different approaches, including both statistical models (distributed lag nonlinear models (Gasparrini et al., 2010) and case-crossover analysis (Maclure, 1991)) and dynamic models ("SIWR" model (Tien and Earn, 2010) forced by rainfall time series data). The statistical models we use are flexible in how rainfall at different time lags affect cholera incidence (Gasparrini et al., 2010), and controls for systematic differences between individuals for risk factors such as water treatment practices and access to improved sanitation (Fisman et al., 2005; Maclure, 1991). For our dynamic models, we force our differential equation models directly with empirical rainfall data. This approach is different than previous work which first estimates time-varying transmission rates from case data, and then compares these transmission rates with environmental data (Koelle et al., 2005). We find a strong relationship between rainfall and cholera incidence for all methods used and spatial scales examined. A larger goal is to develop predictive models for cholera in Haiti on both the short and long term. Our dynamic models are promising for use in this regard – we present results on this below.

Data sets

We present here case data from several different sources (locations are shown in Fig. 1): MSPP data at the country-wide, Department (Sud), and city (Port-au-Prince) levels, cholera cases seen at Hôpital Albert Schweitzer (HAS), originating from four communes in a rural area of the Artibonite Department, and data from oral rehydration posts (ORPs) located in internally displaced persons camps (IDPs). These data encompass a wide range of spatial scales, and include three distinct types of settings (urban/rural/IDP), each with their own unique challenges for dealing with cholera.

Case data

Hôpital Albert Schweitzer Data. Data for cholera patients treated at Hôpital Albert Schweitzer (Fig. 1, red circle) as part of the hospital's routine clinical practices were provided from October 17, 2010 through July 11, 2011, under IRB protocol 2011H0197 (Ohio State University) and REB protocol 27264 (U. Toronto). Hospital Albert Schweitzer (HAS) is located in Deschapelles, Artibonite, near the epicenter of the Haitian cholera outbreak along the Artibonite river (shown in blue in Fig. 1). HAS is one of the largest hospitals in Haiti, providing care for over 345,000 people living in their 610 square mile service area. In response to the cholera epidemic, HAS established a 6-tent cholera ward adjacent to the hospital (Ernst et al., 2011). Provided data include date of admission, gender, age, and home location. These data comprise 4,662 total cases from 4 different communes (Verrettes, Dessalines, Petite Riviere de l'Artibonite, and La Chapelle) within the Artibonite Department.

Internally Displaced Person (IDP) Camp Data. A large number of IDP camps were set up to house Haitians whose homes were destroyed by the January 2010 earthquake, primarily in the greater Port au Prince region (Fig. 1, red star). As of May 4, 2011, the United Nations (UN) Water and Sanitation Health Cluster (WASH Cluster) listed 1001 IDP camps distributed over 13 communes (Carrefour, Cite Soleil, Croix-des-Boquets, Delmas, Ganthier, Grand Goave, Gressier, Jacmel, Leogane, Petionville, Petit Goave, Port-au-Prince, and Tabarre). Oral rehydration posts (ORPs) were established in more than 140 IDPs in early 2011 in response to cholera affecting the camps. Weekly case counts from March 14, 2011 through July 4, 2011 for 112 ORPs in the Port-au-Prince area were provided by the WASH Cluster and the International Organization for Migration (IOM-Haiti).

Ministere de la Sante Publique et de la Population (MSPP) Data. MSPP cholera case data were obtained from the publicly availably MSPP website (Ministere de la Sante Publique et de la Population). Daily cholera cases ("cas vus") reported by the MSPP were analyzed nationally from November 20, 2010 to June 4, 2011, for the Sud Department from November 18, 2010 to December 26, 2011, and for Port-au-Prince from June 26, 2011 to October 23, 2011 (dates were dependent on the range of case and rainfall data available for the region).

Rainfall data

Rainfall data came from rain gauges operated by the U.S. Geological Survey and the Haiti Regeneration Initiative, as well as from satellite measurements through the NASA Tropical Rainfall Measuring Mission.

United States Geological Survey Rainfall Data. The U.S. Geological Survey (USGS) maintains rain gauges in the Morne Gentilehomme (U.S. Geological Survey) and Foret de Pins (U.S. Geological Survey)