Satellite remote sensing-based forecasting of cholera outbreaks in the Bengal Delta

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THE WICKED WATER PROBLEM

Cholera, one of the oldest known waterborne diseases, is examined as a wicked water problem in this study. The ongoing seventh pandemic of this infectious disease started in the 1960s and has been reported in over 50 countries, affecting over 7 million people (Gleick, 2008). The pattern and magnitude of the global pandemics suggest that cholera outbreaks primarily originate in coastal regions and spread inland via secondary means. Cholera bacteria survive and revive in two distinctly different environments: the micro-environment of the human intestine and the macro-environment of plankton-laden coastal and estuarine water. We recognize the importance of the micro-environmental understanding of cholera to develop effective vaccines or treatment protocols. However, it is the macro-environment that provides the natural ecological niche for the endemicity of *Vibrio cholerae*; with powerful evidence of new biotypes emerging, it is thus highly unlikely that cholera will be eradicated (Jutla *et al.*, 2010). Therefore, we need to develop alternative mechanisms for cholera prediction for effective intervention and mitigation of this disease.

Cholera bacteria are autochthonous to brackish, estuarine and coastal waters, and exhibit coherence with coastal phytoplankton; thus, a strong relationship between plankton abundance and cholera incidence is expected (Colwell, 1996). Satellite remote sensing is the most cost-effective and efficient way to monitor coastal plankton signatures over a range of temporal and spatial scales. With the availability of longer data sets from satellites, it is now possible to envision prediction schemes for cholera outbreaks. Very few studies have attempted to develop a forecast model for cholera outbreaks using satellite-derived chlorophyll, a surrogate for plankton abundance. Such studies have had limited success due to the fact that cholera outbreaks in the Bengal Delta show a double seasonal outbreak peak, whereas all the environmental variables (such as phytoplankton, air temperature, river discharge) show a single seasonal peak, and the role of hydrological and coastal processes were underrepresented. Our previous studies have established that cholera in the Bengal Delta is governed by two asymmetric hydrological conditions where floods and droughts are responsible for autumn and spring cholera outbreaks, respectively (Akanda *et al*., 2009). Our goal in this study is to build upon the existing understanding and to develop a forecasting modelling framework for cholera outbreaks in the Bengal Delta using satellite remote sensing data with a prediction lead time of 2 to 3 months. The objective of this study is to demonstrate how prediction of spring cholera (defined as average cholera incidence in March–April–May: MAM) is possible by using understanding gained from large-scale hydro-coastal processes combined with the latest advances in remote sensing.

TOOLS USED TO SOLVE THE WICKED WATER PROBLEM

Using satellites, we cannot directly detect *Vibrio cholerae*, but we can obtain estimates of chlorophyll. Monthly chlorophyll data at 9-km spatial resolution over the Bay of Bengal (BoB) were obtained from SeaWiFS (Sea-viewing Wide Field-of-view Sensor) from 1997 to 2008. Figure 1 shows seasonal September–October–November (SON) chlorophyll in coastal BoB, indicating that chlorophyll concentration is high close to the coastal regions. The SON season shows a very strong correlation with MAM cholera incidence ($r = 0.85$; $p < 0.05$), which is also the highest chlorophyll season in coastal BoB. Akanda *et al*. (2009) suggested that low flows may contribute to MAM cholera outbreaks. Low flows cannot be measured from satellites as well. Therefore, we relied on the NCEP air temperature data as a surrogate for low flows. Our working hypothesis is that if air temperature is high in the Himalayan foothills (Fig. 2), then more rainfall than snowfall is expected in the region. If our hypothesis is valid then we should observe a statistically-significant correlation between October–November–December (OND) air temperature and February–March–April (FMA) low river discharge ($r = 0.65$; $p < 0.01$). A statistically significant correlation is observed between OND air temperature over the Himalayas where the Ganges and the Brahmaputra rivers originate, and MAM cholera outbreaks (Fig. 2). Based on correlative strength, we have constructed a series of multiple regression models with several variables using statistical relationships between phytoplankton, air temperature, river discharge and cholera incidences. Based on our preliminary results, we can adequately predict MAM cholera outbreaks with a 2-month lead time using SON chlorophyll and OND air temperature with a

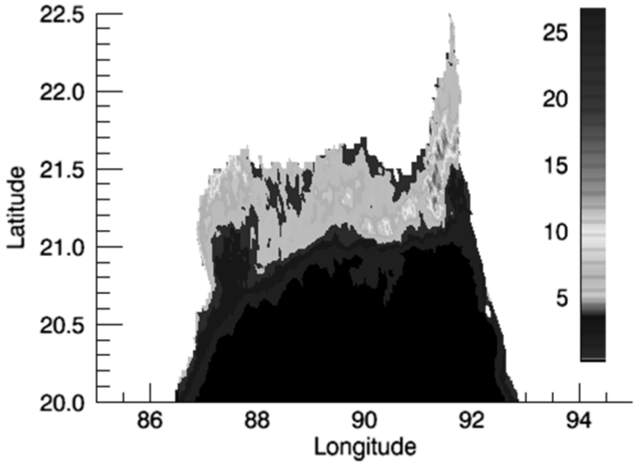

Fig. 1 Climatological SON chlorophyll (mg/m^3) in coastal BoB.

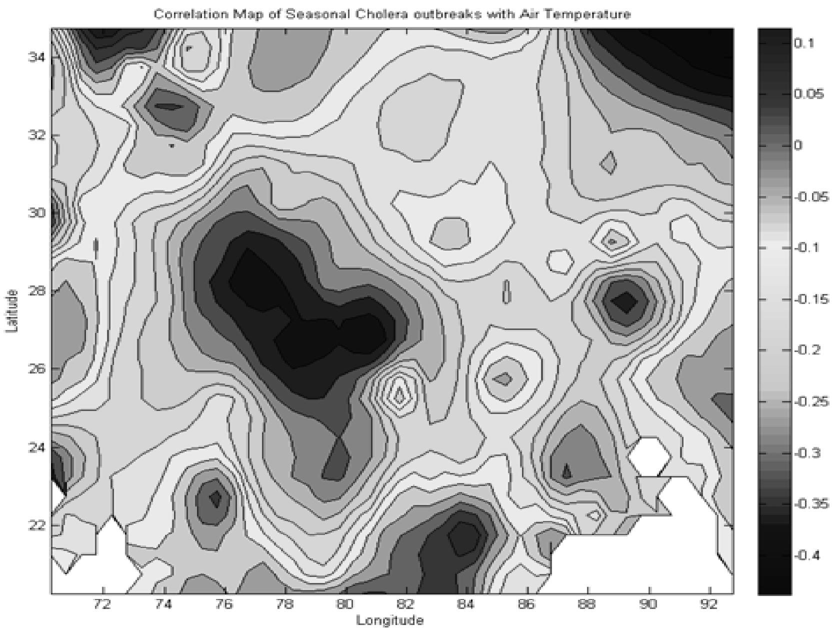

Fig. 2 Correlation between OND air temperature and MAM cholera outbreaks.

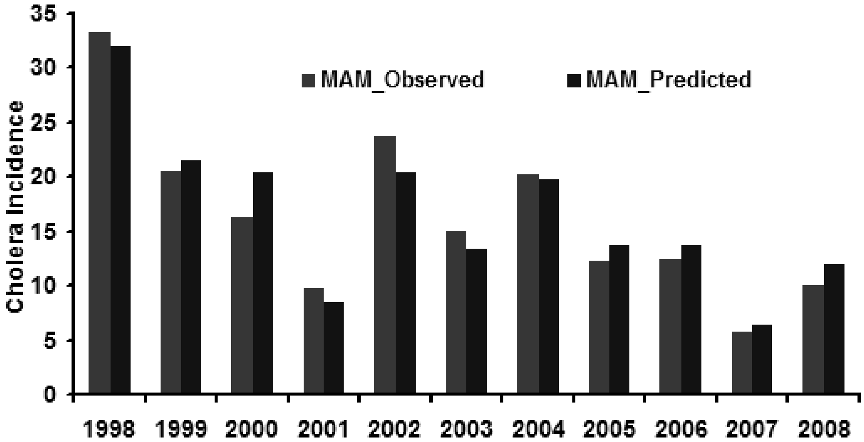

Fig. 3 Predicted and observed spring cholera incidence.

predicted r^2 of 0.80. Figure 3 shows predicted *versus* observed MAM cholera incidence. Correlation, bias, root mean square error, and Nash-Sutcliffe efficiency between MAM predicted and observed cholera incidence are 0.87, –0.37, 1.67 and 0.89, respectively. This is arguably one of the first "actionable" cholera prediction models using satellite data that will have the capability to predict spring cholera outbreaks in coastal Bangladesh 2–3 months in advance.

KEY LESSONS LEARNED

Two key findings from our study are: (i) prediction of MAM cholera outbreaks with reasonable accuracy is possible using SON chlorophyll and OND air temperature; and (ii) satellites, with their recent availability of high quality data products, are one of the most promising tools for the development of prediction schemes and actionable knowledge to intervene and mitigate cholera outbreaks in resource constrained regions around the world.

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