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Satellite remote sensing of space–time plankton variability in the Bay of Bengal: Connections to cholera outbreaks

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Cholera bacteria exhibit strong association with coastal plankton. Characterization of space–time variability of chlorophyll, a surrogate for plankton abundance, in the northern Bay of Bengal is an essential first step to develop any methodology for predicting cholera outbreaks in the Bengal Delta region using remote sensing. This study quantifies the space–time distribution of chlorophyll, using the data from SeaWiFS, in the Bay of Bengal region using 10 years of satellite data. Variability of chlorophyll at daily scale, irrespective of spatial averaging, resembles white noise. At a monthly scale, chlorophyll shows distinct seasonality and chlorophyll values are significantly higher close to the coast than in the offshore regions. At pixel level (9 km) on monthly scale, on the other hand, chlorophyll does not exhibit much persistence in time. With increased spatial averaging, temporal persistence of chlorophyll increases and lag 1 autocorrelation stabilizes around 0.60 for 1296 km^2 or larger areal averages. In contrast to the offshore regions, spatial analyses of chlorophyll suggest that only coastal region has a stable correlation length of 100 km. Presence (absence) of correlation length in the coastal (offshore) regions indicate that the two regions may have two separate processes controlling the production of phytoplankton. This study puts a lower limit on space–time averaging of satellite measured plankton at 1296 km^2 monthly scale to establish relationships with cholera incidence in Bengal Delta.

1. Introduction

There is growing evidence that cholera, coastal waters, and marine plankton are strongly related. Cholera bacteria, a causative agent for cholera outbreaks, are known to survive and thrive in brackish waters, particularly in the presence of abundant zooplankton and phytoplankton; suggesting a high correlation between plankton abundance and disease outbreaks (Alam et al., 2006; Epstein, 1993; Huq et al., 1984; Reidl & Klose, 2002). The disease remains endemic in many regions of the world, specifically in coastal areas of South Asia, Africa and Latin America (Jutla et al., 2010). Northern Bay of Bengal, adjacent to the Bengal Delta, the native homeland of cholera (Akanda et al., 2009), is the focus region of this study.

Laboratory studies suggest a significant positive correlation between plankton abundance and pathogenic cholera bacteria (Alam et al., 2007; Colwell et al., 2003; Huq et al., 2005; Seeligmann et al., 2008; Tamplin et al., 1990). The complexity and costs involved in in-situ measurement of plankton abundance and cholera bacteria did not allow generalization of these laboratory findings over large spatial and temporal scales. Recently available satellite data provide space–time measurements of plankton abundance in terms of chlorophyll content (the greenness of ocean water) over large areas. As the availability and length of satellite data products increase, it is now possible to explore variability of plankton over large regions of the oceans and relate such variability with cholera outbreaks (Jutla et al., 2010). Satellite derived chlorophyll has been a subject of interest for several cholera–chlorophyll related studies. Olsson (1996) was perhaps the first study to document plankton–cholera connection using satellite data. Huq and Colwell (1996) suggested that remote sensing may be useful to study cholera outbreaks using ocean chlorophyll signatures. Lobitz et al. (2000) used Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data and explored the potential role of remotely sensed chlorophyll for understanding plankton–cholera relationships. However, it was difficult to establish any conclusive relationship, given the limited availability of SeaWiFS data at the time of the study (16 months) and for one 18-km pixel. Recently, Magny et al. (2008) proposed a generalized linear regression model with embedded Poisson distribution for simulating monthly cholera outbreaks using previous season cholera incidences and chlorophyll estimated on a 100 km aggregated pixel scale. They concluded that there is approximately a month lag between cholera outbreaks

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in Bangladesh and plankton blooms in the Bay of Bengal. They recommended that finer temporal scale chlorophyll data would be required for developing models for simulation of cholera incidence, but did not elaborate on identifying the spatial zones or temporal scales of the required data. Emch et al. (2008) have used several environmental variables as well as chlorophyll measurements from the coastal region in South Asia and reported a two-month lag between coastal plankton blooms and cholera outbreaks inside Bangladesh.

Given the range of space–time variability of coastal ecological processes related to cholera, it is important to examine at what scales this variability is linked with the dynamics of cholera. More importantly, it is necessary to identify key variables that are related to cholera outbreaks and are measurable over large regions. From this perspective, two empirical observations encourage us to explore temporal and spatial variability of chlorophyll, a surrogate for phytoplankton, in the Bay of Bengal: (a) cholera and plankton show strong association yet the temporal and spatial quantification of phytoplankton in the northern Bay of Bengal remains elusive, and (b) satellite remote sensing is the most effective and efficient way to quantify large scale temporal and spatial variability of phytoplankton across coastal areas of cholera endemic regions. With increased availability of satellite derived chlorophyll data, several studies have analyzed data from different regions and suggested a wide scale of chlorophyll variability across time and space (e.g., Legaard & Thomas, 2006; Uz & Yoder, 2004). Recently, Abreu et al. (2009) reported a possibility of two drivers for long and short term variability of chlorophyll in Patos Estuary in Brazil. They suggested that short term chlorophyll variability (daily or weekly scale) may be controlled by winds whereas the long term (monthly) variation in chlorophyll may mainly be due to influx of nutrients from terrestrial river discharges.

Our recent review study (Jutla et al., 2010), investigated relationship(s) between cholera incidence and coastal processes, and explored possible utility of using remote sensing data to track coastal plankton blooms, using chlorophyll as a surrogate variable for plankton abundance, and subsequent cholera outbreaks in vulnerable regions. The present study will quantitatively characterize the space–time variability of chlorophyll in the northern Bay of Bengal over a range of space and time scales. In particular, we will examine the (1) temporal (daily to seasonal) and spatial (pixel to regional) variability of chlorophyll in the Bay of Bengal; and (2) identify relevant spatial and temporal scales to be able to track cholera–chlorophyll relationships from satellites.

2. Data

The Bay of Bengal is a semi enclosed tropical ocean basin, situated between 0° and 23°N and 80° and 100°E, occupying an area of 4.087×10^6 km^2. It has a unique system of coupled oceanographic and sedimentary processes which is caused by the seasonally reversing monsoon winds and an enormous supply of fresh water from several rivers (Shetye, 1996). The monsoon river discharge plays an important role in governing the surface as well as the coastal hydrology in the bay. During monsoons, large volumes of fresh water discharge from the Ganges–Brahmaputra–Meghna rivers lower the salinity substantially and also reduce the intensity of upwelling at a distance of up to ~40 km from the coast (Shetye, 1996). We have used daily and monthly SeaWiFS chlorophyll pixel level (9×9km) data, which were obtained from NASA/Goddard Earth Sciences/Distributed Active Archive Center for 1998–2007. The selection of regions from the Bay of Bengal is described in the following sections. Relevant details of the data are mentioned in the result section as well. We have divided our region of analysis (Fig. 1a) into six latitudinal bands: LB1, from 21°N to 22.5 N and LB2 to LB6 are one-degree bands down to 16 N. The longitudinal spread of each band is from 86 E to 93 E.

3. Remote sensing of plankton using chlorophyll

Remote sensing of ocean started with the launch of the Coastal Zone Color Scanner on Nimbus7 in 1978, which was followed by the SeaWiFS mission in 1997. Chlorophyll measured by SeaWiFS has been used in several studies ranging from detection of harmful algal blooms (Stumpf et al., 2003; Tang et al., 2003), coastal pollution (Chen et al., 2007), oceanic processes (Danling et al., 2002; Tang et al., 2003; Yoder et al., 1987; Yuras et al., 2005), to land–ocean interaction (D'Sa & Miller, 2003; Jutla et al., 2009; Lopez & Hidalgo, 2009) and marine fauna (Labiosa & Arrigo, 2003; Polovina et al., 2003; Solanki et al., 2001; Turley et al., 2000). The SeaWiFS consists of eight channels at: 412, 443, 490, 510, 555, 670, 765, and 865 nm (nanometers: 1 μm = 1000 nm), each with bandwidths of 20 or 40 nm (O'Reilly et al., 2000). The orbital altitude of SeaWiFS is about 705 km (438 mi) with spatial resolution in the Local Area Coverage of about 1.1 km (0.68 mi). The optimal resolution is 0.6 km at the nadir. Currently, SeaWiFS data offer the longest available ocean color records for more than 10 years (1997 till date) at various spatial (4 km, 9 km) and temporal scales (daily, monthly, annual). Current global SeaWiFS chlorophyll algorithm, OC4V4, is a fourth-order polynomial (Eq. (1)) of the maximum band ratio of four bands (O'Reilly et al., 2000), and can be represented as:

$$\begin{aligned} Chl &= 10^{0.366-3.067X+1.930X^2+0.649X^3-1.532X^4} \\ \text{where } X &= \log_{10}(\max[R_{rs}(443)/(R_{rs}(555), R_{rs}(490) \\ &\quad /(R_{rs}(555), R_{rs}(510)/(R_{rs}(555)]) \end{aligned} \tag{1}$$

where, Chl is the chlorophyll in mg/m^3 and $R_{rs}(\ )$ is the wavelength in nm.

Satellite remote sensing is perhaps the best way to study and quantify large scale monitoring and variability of phytoplankton in the absence of in-situ plankton data, which is prohibitively expensive to obtain. A recent study by Gregg and Casey (2004) observed a correlation of 0.78 between in-situ chlorophyll and SeaWiFS derived chlorophyll using over 2400 coastal region stations. Our study region experiences discharge from the large Ganges, Brahmaputra and Meghna (GBM),river system, which brings huge amounts of freshwater containing terrestrial nutrients to the coastal waters during the summer monsoon months. There is no in-situ plankton data in the GBM coastal region; consequently we have used a proxy region for comparing applicability of SeaWiFS algorithm for the Bay of Bengal. Using a subset of the chlorophyll data from SeaWiFS, Gregg and Casey (2004) reported a correlation of 0.61 between observed and measured chlorophyll close to the mouth where Amazon River discharges into the Atlantic Ocean. Amazon is one of the largest rivers discharging freshwater into the ocean, a feature similar to the GBM river system.

Remote sensing measurements of other relevant variables (e.g., sea surface temperature; sea surface height) may also help in understanding the possible controls on chlorophyll production in the coastal regions and its links to terrestrial hydrology. For example, using satellite measured chlorophyll from various ocean basins across the globe, several recent studies suggest an inverse relationship between chlorophyll (and hence phytoplankton) and SST (e.g., Legaard & Thomas, 2006; Smyth et al., 2001; Solanki et al., 2001; Uz & Yoder, 2004). In the Bay of Bengal, however, a positive relationship between phytoplankton and SST is observed (Chaturvedi, 2005; Emch et al., 2008; Lobitz et al., 2000; Magny et al., 2008). Our preliminary analyses, using SeaWiFS data, suggest that terrestrial nutrient transport through fresh water discharge from the Ganges and the Brahmaputra rivers may affect phytoplankton production in the coastal Bay of Bengal region (Jutla et al., 2011), which may also alter the usually observed inverse relationship between SST and chlorophyll. Increase in phytoplankton through freshwater discharge has been observed