SEASONAL VARIABILITY OF CHLOROPHYLL-A IN THE GANGES RIVER DELTA

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INTRODUCTION
The Ganges River Delta forms the northern boundary of the Bay of Bengal and is one of the world’s largest river outflows. This delta, along with the greater Bay of Bengal, are a dynamically coupled ocean-atmosphere system where many physical and biological processes exhibit seasonal variations. These changes are induced by a reversal of winds between the summer and winter monsoon seasons, as well as other climatologic factors like rainfall and temperature. These factors lead to detectable changes in ocean surface chlorophyll-a concentration, a proxy for biological production.

In this study, the seasonal variation of chlorophyll-a concentration is analyzed qualitatively using Sentinel-2 and MODIS imagery. Additionally, a quantitative analysis of the MODIS data is included.

DATA & METHODS

A variety of open-access datasets were used in this study. These include Sentinel-2 imagery, Open Street Map data, and chlorophyll concentration imagery and data. The Sentinel-2 images used are 100 km² tiles of the eastern-most portion of the Ganges River Delta (Meghna River outflow). Sentinel images from January 2019 and October 2019 are compared and analyzed using various bands and methods. These include near-infrared (NIR), normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and a variety of difference maps. These months were chosen to show the differences before and after the summer monsoon season.

The NIR band from Sentinel-2 is useful in showing the changes in vegetation concentration between seasons. NDVI images are traditionally used to show the health of vegetation in a region, and are created using the following equation:
\[ NDVI = \frac{(NIR-Red)}{(NIR+Red)} \] (1)

Here, the difference of NDVIs from January and October is found and the land is masked. This allows for changes in vegetation within the water, which would usually be suppressed by the degree of change on land, to make use of the full color scale chosen to show seasonal variations. A similar process is done for the NDWI images, which show water content and are derived by the following equation:

\[ NDWI = \frac{(Green-NIR)}{(Green+NIR)} \] (2)

Open Street Map is a vector dataset that shows important features such as roads, buildings, and fields. This data is used as an overlay for the Sentinel-2 images and shows the extent of manmade structures, which provides an idea of how humans may be influencing the environment.

The chlorophyll-a concentration imagery and data used is from NASA’s MODIS project. The Moderate Resolution Imaging Spectroradiometer (MODIS) is an instrument onboard the AQUA satellite. This data set is provided on a global scale and has a resolution of 0.1°. In this study, monthly chlorophyll-a concentrations from January 2019 and October 2019 are used to limit missing data caused by daily cloud cover. An analysis of the raw data was done using MATLAB, and the mean difference of chlorophyll-a concentration (in mg/m³) for the Ganges River Delta was found.

RESULTS

Several images from the Sentinel-2 product have been prepared and analyzed. Figure 1 shows the NIR band for January 2019 and October 2019 at the Meghna River outflow, the
eastern-most portion of the Ganges Delta. Even though these images are in the same 3 bands, there is a stark contrast between January and October, to include the land and water. There is a much greater density of vegetation in October, indicated by the red coloration. The water is also more of a cyan color in October, an indicator that changes in vegetation are present in the outflow as well.

**Figure 1.** Sentinel-2 NIR band for January 2019 (A) and October 2019 (B) at the Meghna River outflow.

**Figure 2** shows NDVI maps for January and October. As was shown in the NIR images, there appears to be a much higher concentration of vegetation in October, indicated here by the darker shades of green and higher corresponding NDVI values. There also appears to be differences in the water, but they are not well defined, as NDVI is not traditionally used to analyze biological production in water. A solution to this can be achieved by masking the land. **Figure 3** shows a difference map between October and January with the land masked. Doing this
allows the full set of color bar values to be utilized in the water. This figure shows an increase in NDVI value throughout a majority of the outflow and surrounding area.

**Figure 2.** NDVI maps for January 2019 (A) and October 2019 (B) at the Meghna River outflow.
**Figure 3.** Difference map of NDVIs (Oct. 2019 and Jan. 2019) at the Meghna River outflow.

**Figure 4** shows NDWI maps for January and October. NDWI maps are used to show changes in water content, on a scale of -1 to +1. Higher values are indicative of light being absorbed by water. The difference map, with the land masked, shows negative values throughout most of the outflow (Fig. 5). These values mean that the water was absorbing less light in October, which supports the higher NDVI values found in **Figure 3**.
Figure 4. NDWI maps for January 2019 (A) and October 2019 (B) at the Meghna River outflow.
**Figure 5.** Difference map of NDWIs (Oct. 2019 and Jan. 2019) at the Meghna River outflow.

Figure 6 shows Sentinel-2 imagery with Open Street Map data overlaid. This shows a digitization of key features in the area. For example, waterways are marked in blue and points of interest are indicated by red squares. Here, two of the points of interest shown in **Figure 6B**
likely mark the locations of Bangladesh Krishi Bank and Pubali Bank Limited in Mirzaganj, Bangladesh.

**Figure 6.** Sentinel-2 imagery with Open Street Map overlay for Meghna River outflow (A) and Mirzaganj, Bangladesh (B).

The imagery and data from the MODIS sensor on NASA’s AQUA satellite provides a direct description of chlorophyll-a concentration. **Figure 7** shows monthly averages of chlorophyll-a concentration for January and October across the entire Ganges Delta. The coastline varies slightly between the images, which may be due to cloud cover or resolution discrepancies (the resolution in both images is 0.1°, about 10 km). Despite the relatively poor resolution for a region of this size, a higher concentration of chlorophyll-a remains visible in October. This visualization can be further improved by taking the difference between October and January (**Fig. 8**).
Figure 7. Chlorophyll-a concentration (mg/m$^3$) from AQUA/MODIS for January 2019 (A) and October 2019 (B) at the Ganges River Delta.
Figure 8. Difference map of chlorophyll-a concentration (Oct. 2019 and Jan. 2019) at the Ganges River Delta. Unit values are in mg/m³.

The chlorophyll-a concentration data from the AQUA/MODIS product has also been quantitatively analyzed in MATLAB. First, a region that encompasses the Ganges Delta was selected. Then, all false values were removed and concentration means were calculated. The January mean chlorophyll-a concentration was 2.0376 mg/m³ and the October mean was 3.5642 mg/m³. Thus, the average chlorophyll-a concentration in the Ganges Delta was 1.5266 mg/m³ higher in October than in January.

DISCUSSION

The seasonal reversal of monsoon winds drives many oceanographic and climatological processes in the Ganges Delta and Bay of Bengal. Amongst these is a seasonal variability of ocean surface chlorophyll concentration. Several factors associated with the monsoon seasons
are responsible for this variability. During the summer monsoon, or “wet season,” winds flow primarily from the southwest and coastward in the Ganges Delta region. Conversely, the winter monsoon, or “dry season,” brings winds that blow to the southwest, away from the coast. This reversal alters the current fields in the Bay of Bengal, resulting in upwelling during the summer monsoon (Potemra et al., 1991). This process carries suspended nutrients from deep in the water column to the surface, where light can penetrate and biological production can occur.

The seasonal monsoons also bring about changes in the extent of nutrients that enter the water, which is a factor of rainfall. The summer monsoon often brings torrential rainfall to Bangladesh and much of the India sub-continent, driving a large increase in river discharge. Kay et al. (2018) state, “The winter discharge rate of the GBM (Ganges-Brahmaputra-Meghna delta) is less than ten percent of its summer peak.” Figures 1 and 2 show how beneficial the rainfall from the summer monsoon season is to vegetation growth on land, which leads to more nutrients being washed into the rivers.

For this study, January and October were chosen to best illustrate the differences in the months prior to and following the summer monsoon. This allows for adequate time after the wet season ends for vegetation growth to occur both on land and in the water. Figure 8 shows the difference in chlorophyll-a concentration between these months, which can be up to ~50 mg/m³ higher in some areas in October. While the mean difference between October and January was just 1.5266 mg/m³, this roughly a 75% increase in chlorophyll-a concentration. A difference of this magnitude can be very impactful to the local communities and fisheries that rely on the ecosystem of the Ganges Delta and Bay of Bengal.
CONCLUSION AND FUTURE WORK

The Ganges River Delta is one of the largest and most fertile river discharge regions in the world. Forming the northern boundary of the Bay of Bengal, the Ganges River Delta is subject to large seasonal variabilities caused by the summer and winter monsoon seasons. The summer monsoon brings heavy rains and wind patterns that beneficially influence nutrient discharge and entrainment. This study explores the extent to which these seasonal processes affect land vegetation growth and water surface chlorophyll-a concentration. These parameters are shown to increase significantly following the summer monsoon and quickly decrease with the onset of the winter monsoon.

While chlorophyll-a in the Bay of Bengal is shown to have seasonal variability based on the monsoon seasons, this region is also subject to more complex and difficult to characterize meteorological events. the Madden-Jullian Oscillation (MJO), a sub-seasonal, equatorial weather system that can influence wind patterns in the Bay of Bengal. Future works will explore the MJO and its impact on the Bay of Bengal, with the goal of identifying sub-seasonal variabilities in ocean currents and chlorophyll-a concentration.
REFERENCES


<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Processing</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sentinel-2 imagery</td>
<td><a href="https://earthexplorer.usgs.gov">https://earthexplorer.usgs.gov</a></td>
<td>Downloaded as geotiff.</td>
<td>Used as the basis of NDVI and NDWI creation.</td>
</tr>
<tr>
<td>Open Street Map data</td>
<td><a href="https://www.openstreetmap.org">https://www.openstreetmap.org</a></td>
<td>Downloaded as shapefile.</td>
<td>Used for roads, buildings, and other features.</td>
</tr>
<tr>
<td>AQUA/MODIS Chlorophyll-a concentration data and imagery</td>
<td><a href="https://neo.sci.gsfc.nasa.gov">https://neo.sci.gsfc.nasa.gov</a></td>
<td>Downloaded as GeoTIFF and CSV</td>
<td>Global coverage. Used the best resolution available (0.1°).</td>
</tr>
</tbody>
</table>
% SO431: Environmental Remote Sensing
% Computes Seasonal Variability of Chlorophyll in
the Ganges River Delta
% Input files are xxxxxxxxxxxx

%% Preliminaries
clear
close all
clc

JanData = csvread('MY1DMM_CHLORA_2019-01-01_rgb_3600x1800.SS.CSV');
OctData = csvread('MY1DMM_CHLORA_2019-10-01_rgb_3600x1800.SS.CSV');

%% Reassign placeholder values as NaN
BoBJanData = JanData(660:700,2690:2720);
BoBJanData(BoBJanData == 99999) = NaN;

BoBOctData = OctData(660:700,2690:2720);
BoBOctData(BoBOctData == 99999) = NaN;

%% Compute mean Chl-a concentration
JanMean = nanmean(BoBJanData,'All');
OctMean = nanmean(BoBOctData,'All');
MeanDiff = OctMean - JanMean;

%% Results
% January, 2019 mean Chl-a concentration = 2.0376 mg/m^3
% October, 2019 mean Chl-a concentration = 3.5642 mg/m^3
% Mean difference (Oct, 2019 - Jan, 2019) = 1.5266 mg/m^3