Seaon and spatial variability of IRS-P4 OCM (Oceansat-1) derived aerosol and its impact on surface water chlorophyll-a in the Bay of Bengal

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Observation made to study the aerosol pattern retrieved from the 865nm central wavelength band of Indian Remote Sensing satellite, IRS-P4 OCM (Oceansat-1) images. Aerosol concentration found higher during December (Northeast monsoon) over Bay of Bengal off Sundarbans with distinct plume. The aerosol optical depth (AOD) ranged 0.2-0.85 in the image of December 24, 2002. Decreasing-trend observed towards offshore with AOD ~0.45. To understand its link with biological productivity, the ocean surface chlorophyll retrieved from seasonal datasets during April, June, October and December 2002. December has shown very high chlorophyll >2.0mg/m³, compared to other seasonal-months with aerosol plume from west to east, towards offshore. High wind speed (~6-8m/sec) and its direction played the role to move the aerosol towards offshore. Similar aerosol plumes observed during December 2003 and 2004.

[Keywords: Oceansat-1 OCM, aerosol, chlorophyll, Bay of Bengal]

Introduction

An aerosol is a colloid of fine solid particles or liquid droplets, in air or another gas. Examples of aerosols include haze, dust, sea salts/sprays, particulate air pollutants and smoke. In the open ocean, dust falling on the sea surface supplies much of the additional iron required for photosynthetic production. Large spatial and temporal variations in this aeolian input occur annually and over glacial-interglacial cycles. The fluxes of Aeolian iron and aluminum to surface waters in the North Pacific Gyre are, in particular, highly seasonal with large maxima in spring due to mobilization of dust from Asia during storms and subsequent transport to the northeast were studied. This variability in external iron inputs may have subsequent impacts on ecosystem processes.

Surface ocean concentrations of dissolved aluminum, a relatively inert tracer for aeolian deposition, are correlated with dust input on a global scale. The correlation of dust input with surface iron concentrations is not as clear, presumably because biological activity rapidly depletes iron concentrations. In high dust input regions of the Atlantic and Arabian Sea, there are difficulties in understanding the composition of aerosol and its role on biological productivity with the limited works carried out globally. Sources are from iron, sulfate ions, shoot, etc. The episodes of dust deposition are believed to impact upper Ocean biogeochemical processes, especially coupled primary production and carbon export. Studies have been carried out on global distribution of atmospheric phosphorus sources, concentrations and deposition rates and predicted that total phosphorus (TP) and phosphate (PO₄) concentration may contribute as much as 50% to the deposition over the oligotrophic ocean where productivity may be phosphorus-limited.

There are several sources of supply of nutrients in the sea around India. Like the Arabian Sea is triggered with nutrients by upwelling during the summer monsoon and convection during winter monsoon causes algal bloom. Biological productivity or photosynthesis is controlled, apart from PAR and nutrients (nitrate, phosphate, silicate etc.), by the availability of other essential micro-constituent nutrients such as iron. Most studies on the North Indian Ocean productivity and chlorophyll have focused on nutrient inputs to the mixed layer from deep. Nitrate deposition over the eastern Arabian Sea has been noted to be far lower than supplied by
vertical mixing\(^2\). Only recently the significance of atmospheric inputs of nutrients and micro-nutrients to the surface ocean is increasingly being emphasized\(^2\). But the northern Bay of Bengal is influenced by fluxes from rivers carrying nutrients and minerals\(^2\). Aerosol optical depth is a measure of the extinction of the solar beam by dust and haze. In other words, particles in the atmosphere (dust, smoke, pollution) can block sunlight by absorbing or by scattering light. AOD tells us how much direct sunlight is prevented from reaching the ground by these aerosol particles. It is a dimensionless number that is related to the amount of aerosol in the vertical column of atmosphere over the observation location. The global distribution of desert dust is estimated from a combination of observations of dust from \textit{in situ} concentration, optical depth, and deposition data; observations from satellite; and global atmospheric models\(^3\).

Present study consists the following (1) To study the variability of aerosol (AOD) and chlorophyll on seasonal dates over the northwest Bay of Bengal region using IRS-P4 OCM (Oceansat-1) data, (2) To find out the relationship of aerosol with chlorophyll concentration over the Bay of Bengal off Sundarbans and (3) To understand the movement of aerosol and chlorophyll features and its direction and their relationship with wind speed.

\textbf{Materials and Methods}

Bay of Bengal is unique due to the seasonal reversing monsoon winds. Due to this, the ocean productivity is enhanced in the two major monsoon systems, the southwest monsoon and the northeast monsoon. Bay of Bengal is poured with large volume of fresh water from rainfall and from the rivers like Hoogly, Ganges, Brahmaputra, Airawati, Mahandi, Godavari, Krishna, Kaveri and so on\(^2\). The riverine inputs are a major potential source of nutrients such as nitrate, phosphate and silica to the Bay. One of the major suppliers of the nutrients to the surface in BoB is mixing due to cyclones, frequent during post-monsoon season\(^3\). The formation of localized intense blooms and also the intensification of bloom generated by anti-cyclonic gyre are known due to injection of nutrients by cyclonic activity\(^3\). Specifically, the strong stratification due to the barrier layer impedes the transfer of nutrients into the euphotic zone from below\(^3\).

Indian Remote Sensing satellite IRS-P4 (Oceansat-1) Ocean Color Monitor (OCM) sensor derived aerosol optical depth (AOD-865nm) and chlorophyll images have been generated during the year 2002 covering four seasonal months with respective dates (April 26, June 17, October 05 and December 24). Datasets during December 2003 and 2004 in the northwestern part of the Bay of Benga have been incorporated. The study area comprised of the co-ordinates ranging Latitude 16.62-22.48\(^\circ\)N and Longitude 83.45-92.10\(^\circ\)E viewed by OCM path 10 and row 13. Transect data has been retrieved and analyzed for the different dates aerosol and chlorophyll images.

Aerosols are responsible for a number of physical effects in the atmosphere, the most important being modifying the atmospheric radiation balance\(^3\) by reflecting away the incoming solar radiation and retaining the outgoing terrestrial radiation (greenhouse effect). Aerosols also reduce visibility, cause air pollution and influence the cloud formation microphysics by acting as condensation nuclei. Satellites, with their capability for large area coverage and short-term repeatability are the most ideal means for acquiring global information on aerosols\(^3\). The currently orbiting ocean color sensors like Oceansat-1 OCM, SeaWiFS, MODIS, MERIS and Oceansat-2 though primarily meant for ocean color remote sensing, have the additional capability for monitoring of global distribution of marine aerosols\(^3\).

Space borne ocean-color remote sensor detected radiance is heavily contaminated by solar radiation backscattered by the atmosphere air molecules & aerosols. This radiance is called the atmospheric radiance. So for the detection of the oceanic constituents first step is therefore the removal of the atmospheric contribution from the sensor radiances. For this NIR channel (\(\lambda>700\text{nm}\)) is used as ocean surface acts as a dark background due to the high absorption by water. Therefore, the sensor-detected radiances (\(L_s\)) can be considered as the atmospheric radiance, which can be treated just the sum of the Rayleigh (\(L_r\)) & Aerosol path radiance (\(L_a\)) produced by the scattering of light by air molecules & aerosols. So, the radiances detected by a space borne sensor at top of atmosphere (TOA) at wavelength \(\lambda>700\text{nm}\) can be split into\(^3\).
With necessary approximations and formulations\(^3\), the aerosol optical depth (AOD) from the sensor detected radiance has obtained the final form:

\[
\tau_a = \frac{(L_t - L_r) \cdot 4\pi \cdot \cos\Theta}{F_o \cdot \omega_{oa} \cdot P_a(\Theta)} \quad \text{(2)}
\]

In the above equation, \(F_o\) is extra-terrestrial solar flux, \(\Theta\) is Satellite viewing angle; \(\omega_{oa}\) is Aerosol single scattering albedo and \(P_a(\Theta)\) function related to Aerosol scattering Phase function.

This algorithm was also successfully used\(^3\) with Oceansat-1 OCM data for the estimation of AOD over the oceanic areas with correlation \(-0.90\). Same algorithm is being proposed to be used with Oceansat-2 OCM data\(^4\).

The ocean color monitor (OCM) of the Indian Remote Sensing satellite IRS-P4 is optimally designed for the estimation of chlorophyll in coastal and oceanic waters, detection and monitoring of phytoplankton blooms, studying the suspended sediment dynamics and the characterization of the atmospheric aerosols. Retrieval of ocean color parameters such as phytoplankton pigment (chlorophyll-a) in oceanic waters, involves two major steps like atmospheric correction of visible channels to obtain normalized water leaving radiances in shorter wavelengths and second application of the bio-optical algorithm for retrieval of phytoplankton pigment concentration.

In the ocean remote sensing, the signal received at the satellite altitude is dominated by radiances contribution through atmospheric scattering processes and only 8-10 % signal corresponds to oceanic reflectance. The OCM scenes were corrected for atmospheric effects of Rayleigh and aerosol scattering using an approach called long wavelength atmospheric correction method. Approach used the two near infra-red channels at 765 and 865 nm to correct for the contribution of molecular and aerosol scattering in visible wavelengths at 412, 443, 490, 510, and 555nm\(^3\). The water leaving radiances derived from atmospheric correction procedure was used to compute chlorophyll-a pigment concentration.

The Ocean Chlorophyll 2 or OC2 algorithm\(^4\) has been utilized for chlorophyll retrieval utilizing OCM channels. Algorithm captures the inherent sigmoid relationship between \(R_{a490}/R_{a555}\) band ratio and chlorophyll concentration \(C\) Where \(R_{a}\) is the remote sensing reflectance. The algorithm operates with five coefficients and has following mathematical form.

\[
C = 10^{[0.319 - 2.336 \times X + 0.879 \times X^2 - 0.135 \times X^3 - 0.071 - \quad \text{(3)}}
\]

Results

The four seasonal months (April, June, October and December 2002) have been displayed (Fig.1). Concentration of AOD has been fixed in range 0.05-1.0. The AOD in April was high and well spread. Similar trend was seen in June, even if it was cloudy. The spreading of AOD was observed in October 2002. But, the December month showed typical plume pattern of AOD from the Sundarban coast towards the Bay of Bengal (here onwards BoB). It moved about 300-400 km distance from the coast with high AOD concentration \(-0.4\). There has been distinct feature of aerosol plume (Fig.1).
Fig. 1 IRS-P4 OCM derived synchronous aerosol optical depth (AOD) and chlorophyll concentration images during four seasonal months around northwest Bay of Bengal.
High chlorophyll concentration (here onwards CC) seen spreading in the northwest BoB coast during June 2002. In October, high CC (>2.0 mg/m$^3$) was seen around Sundarban coast. During December, the coastal Sundarban was seen with high CC increasing up to 5.0 mg/m$^3$ and plume like spreading with moderate concentration 0.4 mg/m$^3$. So, the plume of aerosol has triggered the CC, depicting similar plume in aerosol images, leaving the imprint of plume in chlorophyll image (Fig.1).

The transect line (17-21$^\circ$N and 90.50$^\circ$E) has been sampled for collecting data points from the 4 seasonal monthly images:
April- Spring Inter-monsoon (SIM), June-South-west monsoon (SWM), October- Fall Inter-monsoon (FIM) and December-Northeast monsoon (NEM) during 2002. During April AOD ranged 0.42 - 0.72 and during June 0.2-0.8. April-June-October doesn’t show any significant trend in AOD distribution. But, the AOD of December showed somewhat linear gradient with respect to latitude with few noisy points (Fig.2). The chlorophyll images showed likely linear trend with the increase in latitude, the CC tends to increase to small extent. But, the trend saturated in coastal water (Fig. 3), between 20-21°N latitude. December 2002 chlorophyll plot shows very clear graph almost without noisy points ranging 0.05 – 6.0 mg/m³. Coastal region indicated CC ranging 0.5-5.0 mg/m³ between 20-21°N. The interpretation can be made that with the increase in AOD, there has been increase in CC. The December 2002 AOD and chlorophyll plots confirm the existing relationship. There has been aerosol induced phytoplankton growth and biological productivity in the northwest BoB off Sundarban coast for about 400km (17-21°N).

Fig.3 Aerosol and chlorophyll data points distribution trend during April-June-October-December 2002 in the Bay of Bengal covering all 4 seasonal dates, along the transect line 17.0-21.0°N and 90.50°E (displayed in Fig.1).
Strong aerosol plume of AOD ~0.80 has been observed during December 2002, 2003 and 2004 in IRS-P4 OCM derived AOD-865 nm. The year 2003 showed strongest aerosol plume >400 km, from the coastline off Sundarban into BoB (Fig.2). There has been increase in CC off the Sundarban in the BoB and plume with moderate CC ~ 0.4 mg/m³ has been drifted towards offshore during the three years (Fig.3).
Fig.5 IRS-P4 OCM derived aerosol optical depth (AOD) and chlorophyll concentration relationship shown during December 2002, 2003 and 2004 in the Bay of Bengal, data points retrieved from transect line covering 17.0-21.0°N and 90.50°E (shown in Fig.1).
During December month 2002-2004 the AOD and chlorophyll distribution has been observed in terms of the plots from the data retrieved from transact line (Fig.1). The chlorophyll plots showed almost similar trend during three years ranging 0.05-6.0 mg/m$^3$ and high concentration in coastal water (20-21°N latitude). AOD trend wasn’t similar. There was noisy points during December 2002 and 2003 and plot resembling to the trend. But, the December 2004 showed the matching trend with the chlorophyll with almost noise free data sets. So, the trend has been observed between aerosol and chlorophyll during December month (2002-2004) (Fig.4). There has been proven relationship between AOD and chlorophyll from the current study. So, the phytoplankton growth and chlorophyll pigment accumulation has been triggered due to the increase in AOD. The phenomenon holds good for the northwest BoB (Fig.5). During December 2002, the $R^2$ found to be 0.486, during December 2003, $R^2$ found to be 0.25 and during December 2004, $R^2$ found to be 0.866 with around 1000 points in each year with 2nd order polynomial relationship. The December 2004 has noise free data points, so the best relationship observed. Aerosol during December needs to be studied in more details, which enhances the phytoplankton biomass and increase in CC. So, there would be more primary production and export flux from the food chain, needs to be studies. There is very less number of studies as far as BoB is concerned. The peak in AOD has been reflected up to 400 km seawards off Sundarban coast. Extensive study is needed. The wind direction/vector and speed plays a role to carry on the aerosol towards the BoB from coast to seawards in southerly direction (Fig. 6). Wind speed was moderate and high (1-10 m/sec). Maximum wind speed (~10 m/sec) was during December 2003, so the largest AOD plume seen during December 2003 in AOD image. So, there is relationship between AOD with wind speed, wind vector and wind stress. The Quicksat scatterometer retrieved wind information has been shown in Fig.6.

![Dec 2002](image1)

![Dec 2003](image2)

![Dec 2004](image3)

Fig.6 Quicksat scatterometer retrieved monthly scale wind speed and wind vector maps off Sundarban coast during December 2002, 2003 and 2004.
Discussion

Earlier studies\textsuperscript{16,47} report that there is no increasing trend during December. But, the current study disagrees and show significant aerosol peak \(\sim 0.85\) and distribution pattern during December 2002-2004. As per the earlier work\textsuperscript{47,48}, the increase in aerosol in the BoB is due to anthropogenic source, needs to be verified again. As per earlier study\textsuperscript{16} during October-December, both oceanic basins receive low inputs of land-originated aerosols as seen from the aerosol index, but the current study show the reverse trend during the December month. It has the triggering role to enhance the biological productivity in terms of surface ocean chlorophyll, as observed using the IRS-P4 OCM images. Sources in the Arabian Sea, marked from Saharan and African dusts induce the productivity in Arabian Sea during June-August. Wind speed and its relationship also plays role in the movement/transport of aerosols. The effect of wind on aerosol index from the Total Ozone Mapping Spectrometer (TOMS) data has been observed in two peaks during March-May and June-August in Arabian Sea\textsuperscript{25,49}.

Earlier study says, in the BoB one aerosol peak is observed during the spring season (pre-monsoon), March-May. This is primarily due to the transport of aerosols from the Indian sub-continent\textsuperscript{46}. As mentioned that the aerosol from North Africa and the Gulf region are transported to Arabian Sea, are predominantly naturally produced soil or desert dusts, but those from the Indian sub-continent to BoB are rich in anthropogenic compounds\textsuperscript{48}. Therefore the Ocean fertilization capacity of the aerosols transported from desert to the Arabian Sea could be higher compared to that carried over to the BoB. Iron concentrations in aerosols collected over Arabian Sea \((\sim 600 \text{ ng m}^{-3})\) is about twice higher than in those found over the BoB \((\sim 300 \text{ ng m}^{-3})\). The nitrate concentration is also comparatively higher in aerosols over the Arabian Sea. These results of differences in aerosol composition are obtained during February-April period\textsuperscript{50}. So, the detailed study about the source, composition and flux would bring more impetus.

So, the current study indicates that there is strong relationship of atmospheric aerosol with Ocean surface CC in the northwest BoB, as being evidenced with 3 years datasets. Intra-annual, seasonal-monthly data set shows their distribution pattern and confirms that December month depicts unique pattern, which links to the enhancement in chlorophyll variability. Aerosol plume is related to chlorophyll plume with similar pattern. The regression coefficient peaks to \(R^2 = 0.86\) during December 2004 with 972 data points. There has been observation of wind direction from coast towards offshore around Sundarban, similar direction of aerosol movement has been observed in the AOD images. The detailed and seasonal wind analysis would reflect more about the aerosol transport mechanism.

Conclusion

The IRS-P4 OCM derived aerosol optical depth (AOD) pattern seemed to be decreasing from coastal to offshore water. Strong plume has been observed around the water off Sundarban coast. Aerosol plume concentration found to be around 0.85. In the offshore water the concentration reduced to 0.40 in deeper water. Similar high chlorophyll concentration patches and plume was seen in the coastal water of Bay of Bengal off Sundarbans. It signifies the distribution of the aerosol was from the terrestrial source from the west to eastward direction during December month, the northeast monsoon season. Source of mineral dust with the composition of iron and sulfur compound, etc. might have been the cause to enhance the chlorophyll concentration and biological productivity in the northwest Bay of Bengal. The other seasonal months like April, June and October does not show significant AOD variability trend, but the December month indicates significant distribution trend. Aerosol particle distribution and plume has blown from the west towards the east into the Bay of Bengal coast as the Quicksat scatterometer wind vector image portraits. Details intra-annual, monthly and seasonal study with the \textit{in situ} aerosol concentration and composition would provide the clear-cut view about the algal blooming like phenomenon due to aerosol plume. Even the particular species of phytoplankton and its densification can be studied. The sources of aerosol from any industry or from natural source can be confirmed.

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