Biological response of the sea around Sri Lanka to summer monsoon

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Received 3 September 2003; accepted 3 December 2003; published 3 January 2004.

[1] Chlorophyll-a concentration (chl *a*) maps derived from the Ocean Color Monitor (OCM) on board Indian Remote Sensing Satellite (IRS-P4) and Seaviewing Wide field of View sensor (SeaWiFS) show increased chl *a* in the waters around Sri Lanka during summer monsoon. Physical processes that can lead to the phytoplankton bloom are investigated using upper ocean temperature profiles and satellite derived winds, sea surface temperature (SST) and sea level anomalies (SLA). There is a chl *a* bloom attached to the southern coast of Sri Lanka accompanied by cool SST, low SLA and upsloping of isotherms towards the coast. Coastal upwelling driven by monsoon winds is identified as the physical mechanism causing nutrient enrichment in the surface layer. The Southwest Monsoon Current (SMC) which flows eastward south of Sri Lanka and then into the Bay of Bengal advects the upwelled water eastward along its path. The chl *a* rich waters from the Indian coast also advects along with the SMC towards Sri Lanka. East of Sri Lanka the open ocean upwelling associated with the Sri Lanka Dome is also found to be an important process that upwell nutrients. *INDEX TERMS:* 4572 Oceanography: Physical: Upper ocean processes; 4223 Oceanography: General: Descriptive and regional oceanography; 4855 Oceanography: Biological and Chemical: Plankton; 4279 Oceanography: General: Upwelling and convergences. **Citation:** Vinayachandran, P. N., P. Chauhan, M. Mohan, and S. Nayak (2004), Biological response of the sea around Sri Lanka to summer monsoon, *Geophys. Res. Lett.*, *31*, L01302, doi:10.1029/2003GL018533.

1. Introduction

[2] The extremely intense biological production occurring in the western Arabian Sea, in response to the summer monsoon is well known [*Banse and English*, 2000]. Upwelling, driven either by alongshore winds [*McCreary et al.*, 1996] or by open ocean Ekman pumping [*Bauer et al.*, 1991], entrains nutrients into the mixed layer. Phytoplankton blooms of lesser intensity are also known to occur along the west coast of India during summer monsoon [*Lierheimer and Banse*, 2002] as a result of coastal upwelling [*Shetye et al.*, 1990; *McCreary et al.*, 1996]. Relatively, very little is known about the eastern part of the Indian Ocean and this may be attributed to the inadequate coverage by the Coastal Zone Color Scanner (CZCS) which helped in the early detection of the chl *a* blooms of the Arabian Sea. Shipboard observations off the east coast of India and along 88°E suggest that the primary productivity in the Bay of Bengal is considerably lower than that in the Arabian Sea [*Gomes et al.*, 2000; *Kumar et al.*, 2002; *Madhupratap et al.*, 2003]. Physical processes, however, can lead to high chl *a* in the western Bay of Bengal [*Gomes et al.*, 2000]. Elsewhere, a map of chl *a* distribution around Sri Lanka during the summer monsoon could not be obtained even from composites made using eight years of CZCS images [*Yapa*, 2000].

[3] The oceanic region around Sri Lanka (Figure 1) is a highly energetic physical environment during the summer monsoon. The southwest monsoon current (SMC) flows eastward south of Sri Lanka [*Schott et al.*, 1994] and is fed by a westward flow from the southcentral Arabian Sea and a southeastward flow from the southeastern Arabian Sea [*Shankar et al.*, 2002]. East of Sri Lanka, the SMC turns towards northeast and flows into the Bay of Bengal [*Vinayachandran et al.*, 1999]. Parts of the SMC also extends into northern and southeastern Bay of Bengal (Figure 1). The open ocean Ekman pumping drives a cyclonic gyre known as Sri Lanka Dome (SLD) east of Sri Lanka [*Vinayachandran and Yamagata*, 1998 (hereafter VY98)] and the western arm of the SLD is a southward current along the east coast of Sri Lanka. Model results also show that there is a large anticyclonic vortex south of Sri Lanka [VY98]. SeaWiFS images for the summer monsoon of 1998 [*Murtugudde et al.*, 1999] indicate a seasonal bloom south of Sri Lanka. In this paper, we present evidences from ocean color images (see section 2) for the occurrence of phytoplankton blooms in the oceanic region around Sri Lanka during summer monsoon (section 3). The role of physical processes on the bloom generation and its advection is examined in section 4 and the summary and conclusions are presented in the last section.

2. Data

[4] We have used ocean color images obtained by the Ocean Color Monitor (OCM) on board the IRS-P4 which was launched on May 26, 1999. IRS-P4 had a repeat cycle of 2 days and it was placed at an altitude of 720 km. OCM was designed to measure the spectral variation of water leaving irradiances in 8 spectral channels in the range of 404–887 nm which can be used for calculating the phytoplankton pigment concentration in the ocean. It has a spatial resolution of 360 m × 236 m and a swath of 1420 km. Chl *a* is calculated using the OC2 algorithm [*O'Riley et al.*, 1998; *Chauhan et al.*, 2002, 2003]. *Chauhan et al.* [2002] have validated the OCM data with in situ observations in the Arabian Sea. They found that the chl *a* derived from OCM

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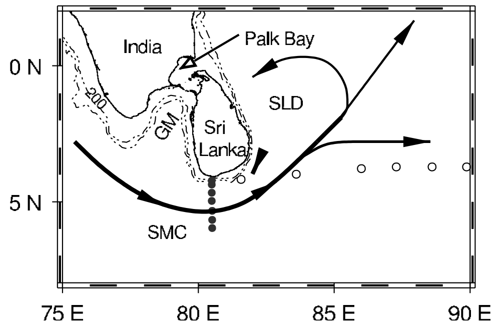

Figure 1. Map of the study area. Open circles correspond to the location of XBT stations used in Figure 5a and filled circles are locations of CTD sampling used in Figure 5b. GM, SLD and SMC are Gulf of Mannar, Sri Lanka Dome and Southwest Monsoon Current, respectively. 200 m and 1000 m isobaths are also shown.

and in situ measurements had a correlation of 0.90 with an rms error of 0.125 mg m^{-3}. *Dey and Singh* [2003] obtained a correlation of 0.93 between chl *a* measurement from OCM and in situ measurements in the Gulf of Mannar (Figure 1). We have also used Level-3 (GAC) chl *a* images with a spatial resolution of 9 km from SeaWiFS.

[5] Upper ocean temperature profiles are obtained from the WOCE global data set. In addition, sea level anomalies (SLA) from a combined TOPEX/Poseidon - ERS data set [*Le Traon et al.*, 1998], daily scatterometer winds from QuickSCAT (Level 3 gridded product obtained from poddaac.jpl.nasa.gov) and SST from TMI (www.ssmi.com) all at a spatial resolution of 0.25° × 0.25° are also used.

3. Biological Response

[6] The biological response of the sea around Sri Lanka to the summer monsoon is illustrated in Figure 2. During March, there is some amount of chl *a* in the Palk Bay and the rest of the region is almost devoid of any phytoplankton. Chl *a* patches higher than 1 mg m^{-3} appear along the southern coast of Sri Lanka during April. By the month of May, there is high chl *a* along the Indian coast as well as along the southern coast of Sri Lanka (Figure 2). The chl *a* bloom is fully developed during June–July and there is high chl *a* in the Gulf of Mannar, Palk Bay and along the southern coast of Sri Lanka. There are lower concentrations, compared to the coastal region, in the offshore waters to the west and east of Sri Lanka. It is interesting to note that the high chl *a* seen east of Sri Lanka is completely separated from the coast. High chl *a* occurred around Sri Lanka for all the summer monsoons during 1998–2002 suggesting that this is a regular seasonal feature. Although these composite images delineate the seasonal patterns of chl *a*, individual snapshots of ocean color are more instructive about the space-time evolution of the blooms and they are examined below.

[7] We have processed the OCM images of the southern Bay of Bengal (path 10, row 14 of OCM) for the months of July–October, 1999. Due to cloud cover associated with the summer monsoon the data loss was high during this period. However, several images that map the chl *a* around Sri Lanka are available for this period. Three selected images

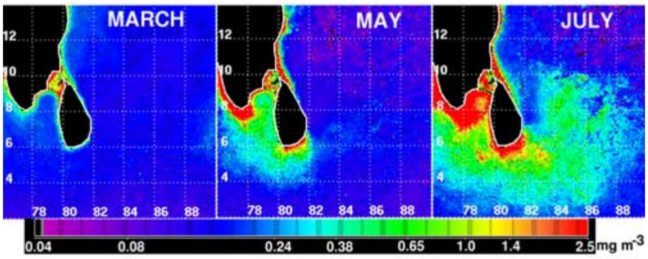

Figure 2. Monthly composite images of chl *a* (mg m^{-3}) derived from SeaWiFS during 1998–2002.

for 1, 19, and 29 July 1999, that provided good coverage are presented in Figure 3. There is high chl *a* along the Indian coast and in the Palk Bay. The chl *a* generated along the Indian coast moves southeastward (Figure 3a) towards Sri Lanka and southward (Figure 3c). The high chl *a* seen along the northern rim of the the Gulf of Mannar extends along the western coast of Sri Lanka (Figure 3b). Similarly, high chl *a* from the Palk Bay appears to spread along the eastern coast of Sri Lanka, but a major part of the east coast of Sri Lanka does not show appreciable levels of chl *a* (Figures 3a–3c). A

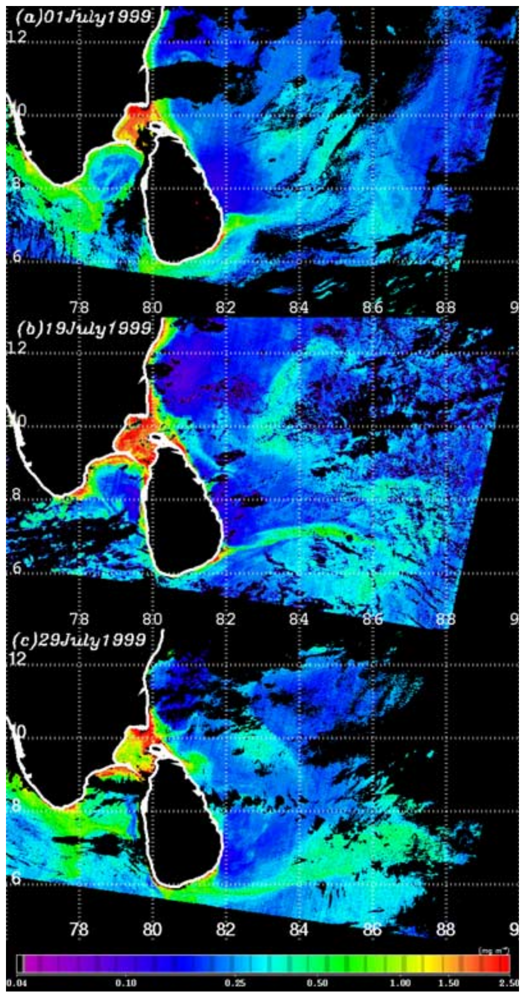

Figure 3. Chl *a* (mg m^{-3}) images around Sri Lanka for (a) 1 July 1999, (b) 19 Jul 1999 and (c) 29 July 1999 obtained from OCM on board IRS-P4 Ocensat.

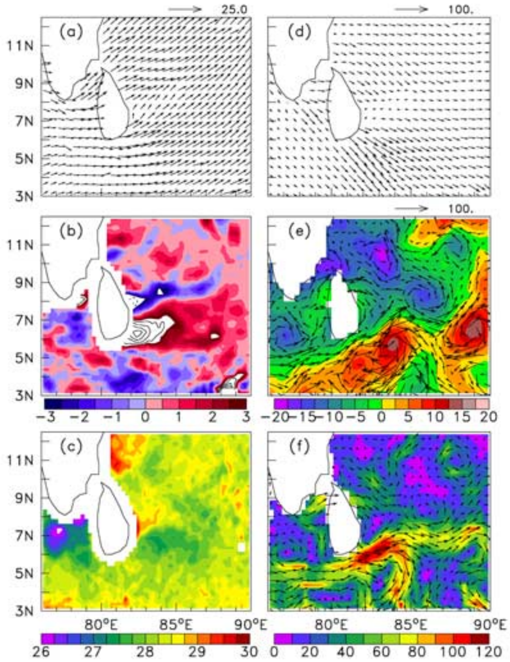

Figure 4. (a) Wind vectors (m s^{-1}) from QSCAT for 20 July 1999. (b) Ekman pumping (m day^{-1}) for the winds in Figure 4a. Values from −3 to 3 are shaded. Positive values above 3 and negative values below −3 are contoured at an interval of 2 m day^{-1} by continuous and dashed lines respectively. (c) SST from TMI for 19 July 1999. (d) Ekman drift for the winds shown in Figure 4a. (d) SLA (shaded, in cm) for 18 July 1999 and corresponding geostrophic currents (vectors in m s^{-1}). (e) Sum of geostrophic and Ekman currents; speed is shaded.

narrow band of high chl *a* exists along the southern coast of Sri Lanka (Figures 3a–3c) which extends from south of Sri Lanka upto about 88°E. The chl *a* within this band decreases offshore and there are also indications of its bifurcation towards south as well as north (Figure 3b). In the open ocean east of Sri Lanka, high chl *a* is seen to the north of this band upto about 12°N as isolated patches. One such patch is located around 8°N, 86°E and another around 10°N, 83°E which has chl *a* around 0.5 mg m^{-3}.

4. Physical Processes

[8] The chl *a* in the upper layer of tropical oceans is, in general, limited by the availability of nutrients. Therefore, oceanic processes that can bring nutrients into the euphotic zone are of prime importance. Nutrients can be brought in by coastal upwelling driven by alongshore winds, open ocean upwelling driven by Ekman pumping, entrainment due to wind stirring at the base of the mixed layer and by horizontal advection due to ocean currents. In order to identify the physical process that could cause the high chl *a* blooms described above, we have examined the relevant physical oceanographic data and the results corresponding to 19 July 1999 are shown in Figure 4.

[9] We find that local generation of blooms is possible along the southern coast of Sri Lanka. The winds have a large alongshore component (Figure 4a) and strong offshore Ekman transport which can drive coastal upwelling. Since there is no previous report of upwelling along this coast we have examined other data set for evidences. Vertical sections of temperature along approximately 6°N measured using XBTs [*WOCE Data Products Committee*, 2002] during June, 1999 and by a CTD [*Diggs et al.*, 2002] along 80.5°N during July 1993 (Figure 5) clearly shows evidences for upwelling in a band of width of about 70 km. The upwelled water has a temperature in the range of 24–25°C and originate from a depth of about 100 m. The winds blow towards the coast on the western side of Sri Lanka and away from the coast on the eastern side and thus do not favor upwelling and local generation of blooms along these coasts.

[10] The open ocean blooms seen east of Sri Lanka appears to be caused by open ocean Ekman pumping (Figure 4b). The Ekman pumping east of Sri Lanka is in general upward interspersed with downwelling, the latter being most prominent in a narrow band east of Sri Lanka. This downwelling band coincides with warmer (>29°C) SSTs (Figure 4c) and low chl *a* (Figure 3). Upwelling is maximum near the southeast corner of Sri Lanka and is coincident with high chl *a* (Figure 3) and cool (<28°C) SSTs (Figure 4c). The high chl *a* band extending eastward from the southeastern tip of Sri Lanka is located within this region of upward Ekman pumping. The SLD, which is forced by Ekman pumping (VY98), consists of two cyclonic eddies east of Sri Lanka (Figure 4e) embedded within a larger cyclonic gyre. The centers of these eddies are approximately at 10°N, 83°E and 8°N, 86°E. Theses eddies lie under upward Ekman pumping in the range of 1–1.5 m/day. The geostrophic circulation around the low in sea level is (Figure 4e) modified considerably by the Ekman drift (Figure 4d) but the signature of these eddies on the surface can be seen in both SST (Figure 4d) and in ocean color (Figure 3b).

[11] The chl *a* distribution around Sri Lanka is closely connected to the path of the SMC. The most striking example for this is the advection of high chl *a* east of Sri Lanka along the path of the SMC and the bifurcation thereafter. The chl *a* band is located along the northern edge of the SMC and not along its core, suggesting that source region is the southern coast of Sri Lanka. Part of the SMC flows southward between 84–86°E (Figure 4e) which

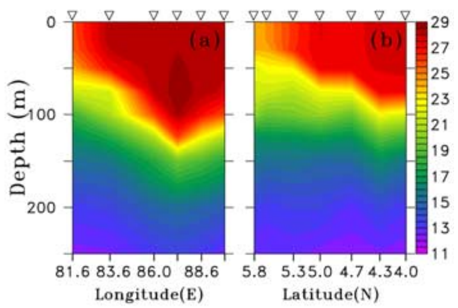

Figure 5. (a) Vertical section of temperature (°C) (a) along approximately 6°N measured using XBT during 13–17, June, 1999 and (b) along 80.5°E measured using CTD during 28–30, July, 1993. The station locations are marked in Figure 1.

is associated with a large vortex south of Sri Lanka [VY98]. There are indications in OCM images (Figure 3b) that the chl *a* patches are being carried along this branch of the SMC. The influence of the SMC is also seen between India and Sri Lanka. The southeastward flow of chl *a* rich water from the Indian tip towards Sri Lanka is caused by Ekman drift (Figure 4d). Offshore meandering of the chl *a*-band is also seen in OCM images along the northeast coast of Sri Lanka (Figures 3b and 3c) under the influence of the prevailing currents (Figure 4f) in that region.

5. Summary and Conclusions

[12] In a previous paper, we [*Vinayachandran and Mathew*, 2003] showed that chl *a* blooms occur in the southwestern Bay of Bengal during northeast monsoon. In this study, we have shown that high chl *a* occurs around Sri Lanka during summer monsoon. Nutrient introduction into the upper layer caused by coastal upwelling driven by alongshore winds lead to high chl *a* along the southern coast of Sri Lanka and we have presented the first evidences for coastal upwelling in this region. The coastal winds do not favor upwelling along the western and eastern coasts of Sri Lanka. Open ocean Ekman pumping also appears to contribute to the chl *a* concentration east of Sri Lanka. The SMC advects chl *a* rich water from the Indian coast towards Sri Lanka and from the Sri Lankan coast into the open ocean towards east upto 88°E. Although the spatial coverage of the blooms are smaller compared to the summer blooms in the Arabian Sea, the blooms around Sri Lanka last for more than four months and should be of consequence to the biogeochemistry of this region. Models such as those employed in the Arabian Sea [*McCreary et al.*, 1996] will be useful to isolate the dynamics and assess the relative contribution of various processes. Although our study is qualitative, the physical processes are robust features of this region and their quantification will be a major challenge for future observational as well as modeling studies.

[13] **Acknowledgments.** Thanks to the SeaWiFS Project and the GESDISC/DAAC at the GSFC, Greenbelt, MD 20771, for the production and distribution of these data, respectively. These activities are sponsored by NASA's Earth Science Enterprise. The altimeter products have been produced by the CLS Space Oceanography Division as part of the European Union's Environment and Climate project AGORA and DUACS with financial support from the Centre for Earth Observation programme and Midi-Pyrinies regional council. TMI data and images are produced by Remote Sensing Systems and sponsored by NASA's ESIP: a federation of information sites for Earth Science; and by NASA's TRMM Science Team. This study was funded by the IRS-P4 utilization project.

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