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Upwelling in the southeastern Arabian Sea as evidenced by Ekman mass transport using wind observations from OCEANSAT–II Scatterometer

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Monthly Ekman mass transport in the southeastern Arabian Sea using scatterometer data from Oceansat-II satellite were estimated in the present study. Seasonal variability of Ekman mass transport has been analyzed to study the occurrence of coastal upwelling in this region. Prominent region of upwelling along the southwest coast of India is between 8° and 14°N. Strong offshore Ekman mass transport of about -2000 kg/m/s was observed during August due to the favorable wind conditions. Very weak offshore Ekman transport was observed during the pre-monsoon months when the wind is weak and variable. Moderate offshore transport was observed along the southwest coast between December 2009 and February 2010.

[**Keywords**: Upwelling, Southwest coast of India, Ekman mass transport, Biological productivity]

Introduction

Upwelling is an oceanographic phenomenon that involves wind-driven motion of dense, cooler, and usually nutrient-rich water towards the ocean surface, replacing the warmer, usually nutrient-deplete surface water. Arabian Sea is one of the highly productive seas in the Indian Ocean region due to its boundaries and the open ocean processes which manifest as upwelling during summer monsoon (June–September) and cooling during winter in the northern Arabian Sea. Coastal areas of the Arabian Sea are major zones of upwelling during the southwest (SW) monsoon. Phytoplankton blooms are observed in the coastal waters of India under favourable conditions of sea surface temperature (SST) and nutrients. Off the SW coast of India, upwelling starts even before the onset of the summer monsoon and continues till it ends in September. Major features of the upwelling are the upward displacement of the 20°C isotherm by nearly 100 m, the invasion of the shelf off the west coast by nutrient-rich waters and the reduction of SST by 4-5°C with the development of rich plankton blooms[1,2,3,4].

This Oceanic phenomenon was studied by many a marine scientists using in-situ measurements, mathematical modelling and satellite observations[5,6,7]. From these studies, it was established that upwelling along SW coast of India formed by February/March; however, the chlorophyll concentration and the intensity of upwelling in this region strengthened with the onset of SW monsoon emphasising the importance of wind in the entrainment of subsurface nutrients towards the surface. As the west coast of India is oriented along the meridional axis with an angle of 24° with north[8], it is imperative to estimate the meridional Ekman transport for coastal upwelling. Also wind direction during the SW monsoon is north-northwesterly along the coast line to the south of 15°N. Wind stress parallel to the coast line is the driving factor for upwelling during the monsoon, as conceptually understood.The objective of this study is to monitor and understand the seasonal variability of coastal upwelling as revealed by Ekman mass transport in southeastern Arabian Sea using the recently launched OCEANSAT–II Scatterometer data.

Materials and Methods

Level 3 daily wind data from Oceansat-II Scatterometer were obtained for the period November 2009 to October 2010 from the Oceansat-II portal of the National Remote Sensing Centre, Hyderabad http://www.nrsc.gov.in. Oceansat-II is a polar orbiting satellite at an altitude of 720km launched in September 2009. It has a respectivity cycle of 2 days. Oceansat-II carry three sensors onboard, viz., Ocean Colour Monitor (OCM-2), Ku-band pencil beam Scatterometer and an Italian payload called Radio Occultation Sounder for the Atmosphere (ROSA). Scatterometer operates at a frequency of 13.5 GHz. It measures the wind speed in the range of 4-24 m/s with an accuracy of 2 m/s (rms) and wind direction with an accuracy of 20^o (rms). Level 3 wind data consists of wind speed, direction and quality flag for both ascending and descending passes on a global grid at 50 km x 50 km resolution. In order to compute the Ekman mass transport, the pass with best coverage over the study region has been selected from both the ascending and descending passes for each day. Ekman mass transport has been computed after calculating the monthly mean wind and a distance-weighted average remapping is applied to reduce the gap in the spatial data.

Upwelling intensity can be estimated from Ekman mass transport which is perpendicular to the direction of the wind in the region. Ekman mass transport along the coast has been computed from the bulk aerodynamic formula as used for satellite derived wind stresses by Koracin *et al.*[9] and Petit *et al.*[10] and the references therein:

$$\tau_y = \rho_a C_d w_{mag} v \qquad \text{... (1)}$$

where τ_y is the meridional wind stress (N/m^2), ρ_a is density of air which is 1.25 kg/m^3, C_d is wind dependent drag coefficient calculated using Large and Pond[11] method, w_{mag} is the magnitude of wind speed (m/s) and v is the meridional wind speed (m/s).

$$M_e = \tau_y / f \qquad \text{... (2)}$$

where M_e is the Ekman mass transport (kg/m/s), *f* is the Coriolis parameter (2 Ω sin φ) (s^{-1}), Ω is the angular frequency of the earth (rad/s) and φ is the latitude.

As the wind is equator-ward, the negative sign for M_e is taken as offshore transport (upwelling) and vice–versa[12]. In order to support the upwelling phenomena identified through Ekman mass transport, corresponding maps of monthly surface chlorophyll-a (chl-a) concentration and SST at 9 km x 9 km spatial resolution from AQUA Moderate Resolution Imaging Spectroradiometer (MODIS) has been obtained from the website, http://reason.gsfc.nasa.gov/Giovanni.

The study region (Fig.1) is between 5-18^{o}N and 65-78^{o}E in the southeastern Arabian Sea. Over the North Indian Ocean (NIO), winds generally blow from SW during summer monsoon and from northeast during winter monsoon. March-April and October are months of transition between the monsoons, and winds are weakest at these times[13]. Winds are much stronger during the summer monsoon than during the winter monsoon. These seasonally reversing monsoon winds over the NIO force a seasonally reversing circulation in the upper ocean. The Indian subcontinent divides the NIO into two basins, the Arabian Sea and the Bay of Bengal. Though located in the same latitudinal belt, they exhibit distinct oceanographic features. Arabian Sea receives highly saline waters from the Persian Gulf and the Red Sea, and experiences more evaporation than precipitation (except along the west coast of India during the SW monsoon) for most of the time in a year, resulting in an upper layer of rather high saline waters.

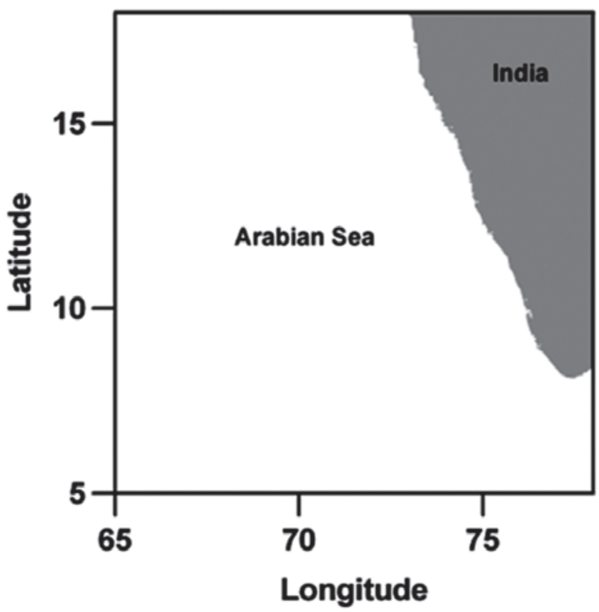

Fig. 1—Location map of the study region (southeastern Arabian Sea)

Results and Discussion

Figure 2a and Figure 2b shows the mean wind vector with wind speed and Ekman mass transport in the southeastern Arabian Sea from November 2009 to February 2010. During November 2009, the mean wind was northerly above 12°N and northwesterly below. Offshore Ekman mass transport was observed along the SW coast during this time with the strongest transport near 14°N and off the southern tip of India. By December 2009, the wind became northeasterly and a slight decrease in the offshore mass transport was observed near the coast while it increased further west and off the southern tip of India. No much variation was observed during January 2010. In February an overall decrease of wind speed occurred together with a decrease in the offshore transport off the southern tip of India.

During March and April 2010 the wind was weak, and hence the Ekman mass transport was minimum in the southeastern Arabian Sea. By May the wind gets organised to northwesterly above 9°N latitude while in the south it was westerly. An increase of offshore mass transport was observed between 7°N and 11°N during this time.

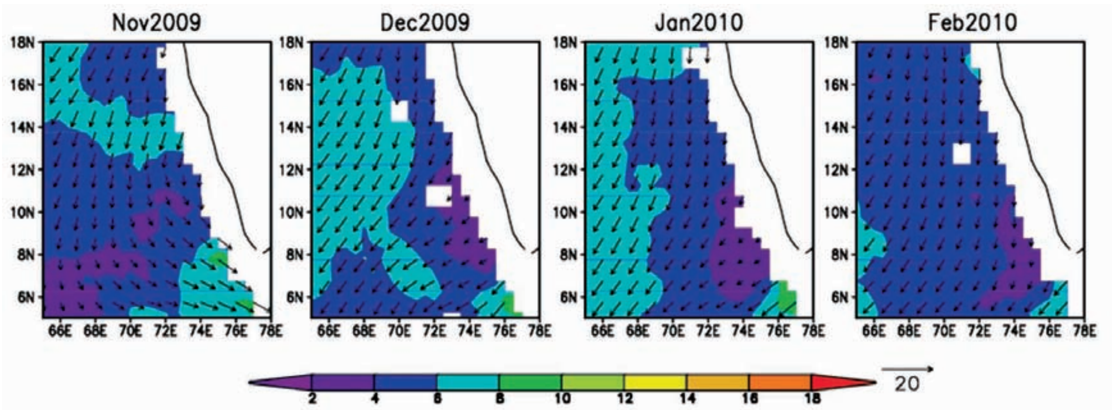

Fig. 2a—Mean monthly wind vector and wind speed (m/s) over the southeastern Arabian Sea during November 2009 to February 2010 from scatterometer on board Oceansat II

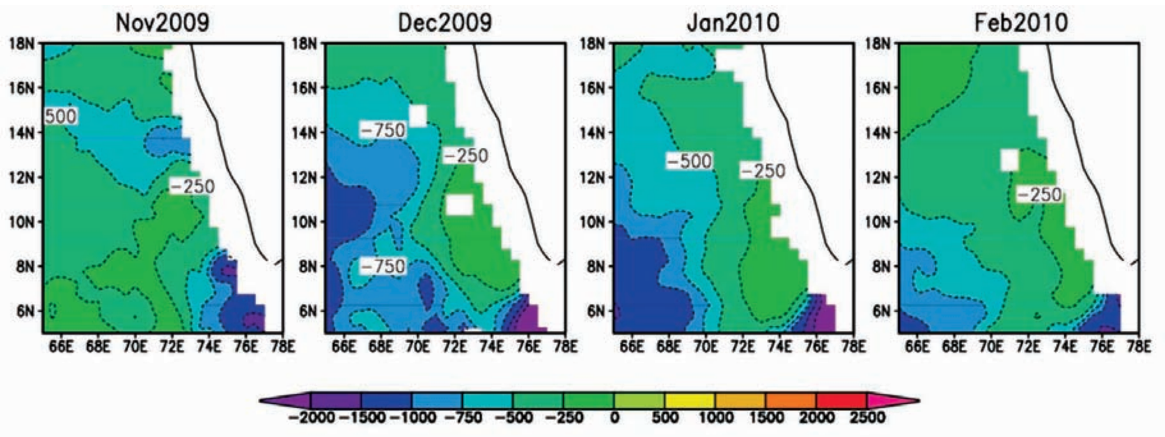

Fig. 2b–Monthly Ekman mass transport (kg/m/s) in the southeastern Arabian Sea during November 2009 to February 2010

During June 2010 when the wind was west-northwesterly below 12°N (Fig.3a), offshore Ekman mass transport (Fig. 3b) reached upto -750 kg/m/s between 8-10°N inducing upwelling. By July 2010 when the wind became westerly, offshore mass transport decreased and shifted southward. During August 2010 the wind direction changed to northwesterly favouring strong offshore Ekman mass transport and upwelling that extend upto 14°N. Offshore mass transport of about -2000kg/m/s was located near the SW coast. In September 2010 the wind became westerly in the south while it remained northwesterly in the north. The offshore Ekman mass transport decreased in the southern part while north

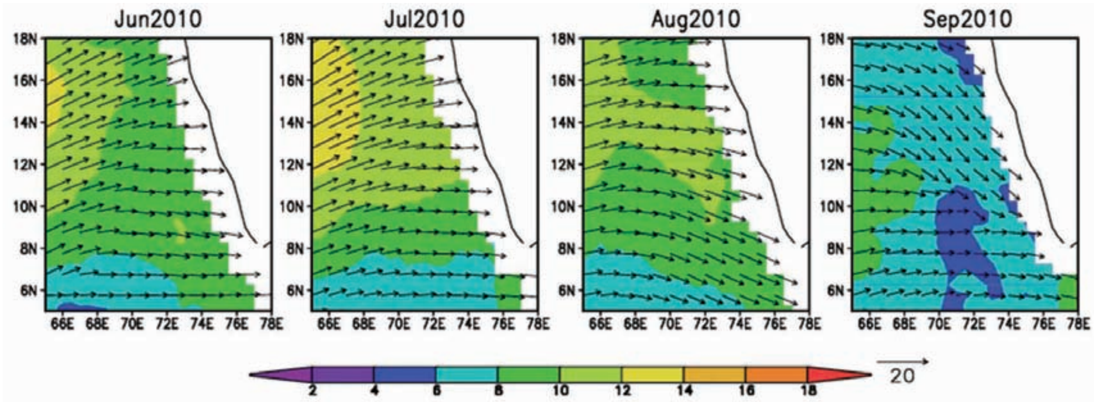

Fig. 3a–Mean monthly wind vector and wind speed (m/s) over the southeastern Arabian Sea during June to September 2010 from scatterometeron board Oceansat II

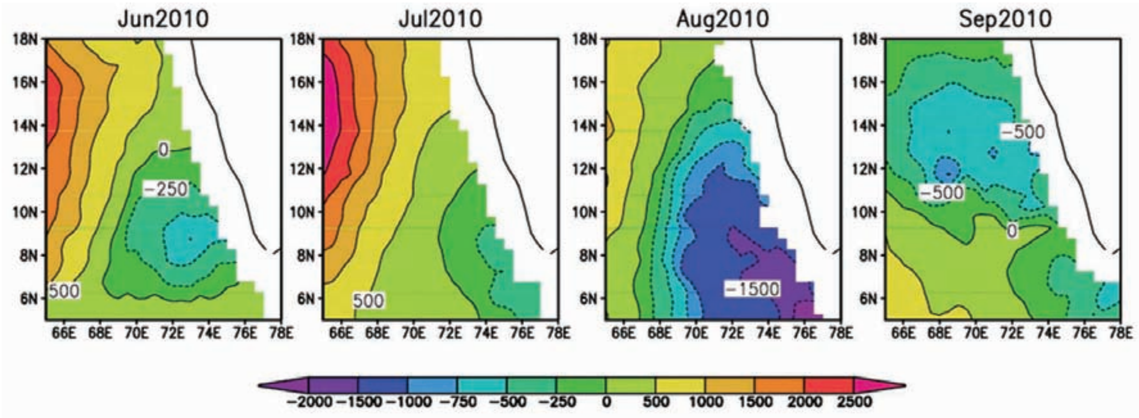

Fig. 3b–Monthly Ekman mass transport (kg/m/s) in the southeastern Arabian Sea during June to September 2010

of 11°N it was strong, with the maximum of ~-1500 kg/m/s located at 12°N and 68°E. By October wind speed decreased except near the SW coast while the direction was generally north-northwesterly. Below 10°N offshore Ekman mass transport increased with the maximum of about -2500 kg/m/s located off the southern tip of India.

Fig. 4 shows the monthly chl-a in mg/m^3 in the southeastern Arabian sea during January and August 2010. During January chl-a concentration near the SW coast below 12°N was low when the offshore mass transport is weak. Chl-a was high in this region during August, due to the strong upwelling at that time.

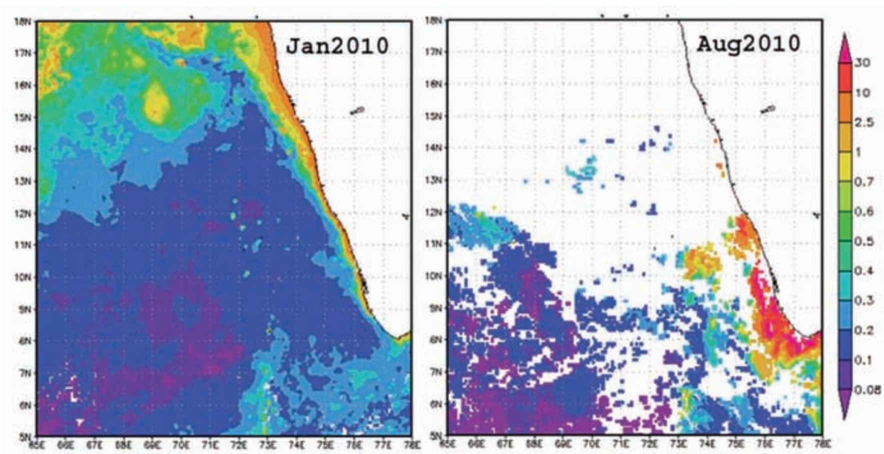

Fig. 4–Surface chlorophyll-a concentration (mg/m^3) during January and August 2010 from AQUA MODIS.

SST during the months January and August 2010 are given in Fig. 5. SST near the SW coast was more than 30°C during January indicating weak or no upwelling. Lowering of SST (~26°C) was observed during August near the coast caused by strong upwelling in this region.

From the study with the available scatterometer data it was observed that the SW monsoon from June to September is the major upwelling season in the southeastern Arabian Sea below 14°N. The strongest offshore Ekman mass transport occurred during August 2010 due to the favourable wind conditions. Offshore Ekman transport was weak during the pre-monsoon months of March and April 2010 when the wind is weak and variable. In November 2009 considerable offshore transport was observed. Moderate offshore transport occurred along the SW coast between December 2009 to February 2010 and October 2010. Also strong offshore mass transport was observed south of 8°N during this period. Monthly maps of chl-a and SST support the upwelling phenomena that occur near the SW coast of India during summer monsoon.

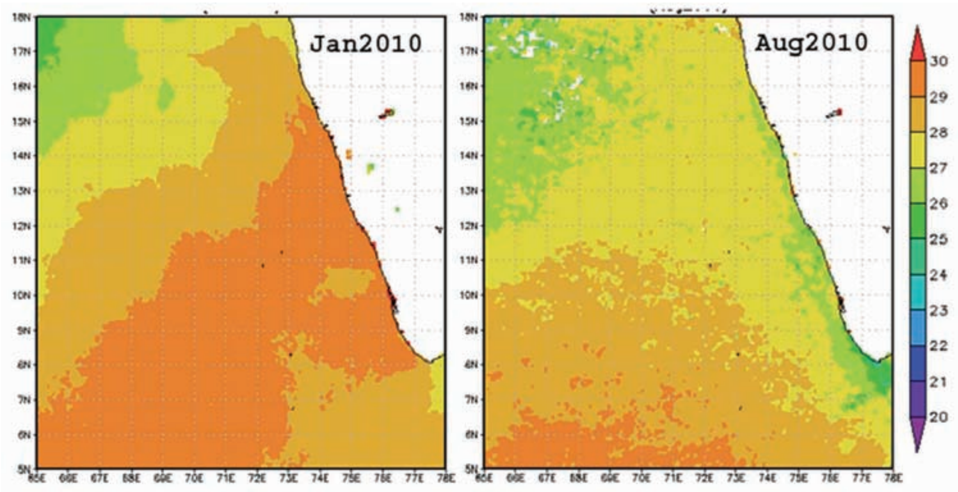

Fig. 5–SST in °C during January and August 2010 from AQUA MODIS

Conclusion

Based on Ekman mass transport, prominent region of upwelling along the SW coast of India is identified between 8°N and 14°N. SW monsoon is the important upwelling season near the SW coast of India. Pre monsoon period is found to be a weak upwelling season when the offshore Ekman mass transport is weak. Between October and February upwelling is moderate near the SW coast but it is strong off the southern tip of India accompanied by strong offshore mass transport.

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Accommodation at hotels is available and the tariff for various hotels ranges from Rs. 1500/- to Rs. 8000/- per day. Participants are advised to take care of their travel and stay well in advance as Nainital is exceptionally expensive tourist place. Nainital remains cold during March and woollen dress is needed. Nainital is well connected by Road and Rail (Kathgodam Railway Terminus) from Delhi, Dehradun and Lucknow.

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