

**Dispersal and sink pathways of suspended particulate matter from orographically enhanced SW monsoon regime of the SE Arabian Sea**

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Precipitation magnitude plays an important role on yield and supply of terrigenous matter into sea through fluvial supply. Influence of climate on suspended particulate matter (TSM) influx into the continental margin of the SE Arabian Sea has been evaluated from sub-weekly, synoptic variations in TSM, their advection rates, currents and winds during South West Monsoon (SWM) and post monsoon season. Our study endorses high influx of TSM during SWM ( $> 82 \text{ mg l}^{-1}$ ; advection  $110 - 26 \text{ mg m}^{-2} \text{ sec}^{-1}$ ), albeit most of it sequesters into the shallow coastal region. Over the mid-outer shelf, there occurs uniformly low TSM ( $12-24 \text{ mg l}^{-1}$ ) and a weak TSM advection ( $9-4 \text{ mg m}^{-2} \text{ sec}^{-1}$ ) round the year. This trend is persistent also in the areas having upwelling induced high marine productivity. We, therefore, surmise that higher fluvial influx and primary production during SWM do not necessarily enhance supply of particulate matter into the deeper offshore regions of the SE Arabian Sea. We ascribe a vital role to the prevailing morphodynamic processes.

Key words: SW monsoon, suspended particulate matter, SE Arabian Sea, morphodynamics

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## 1. Introduction

The sediment flux is vital for several biogeochemical processes in the marine environment, and regulates carbon production and sink processes. Besides, for coastal zone management strategies estimation of particulate flux dynamics is crucial for management of siltation of channels, shoreline changes and estimation of diffusion of light. It is widely believed that climate plays an important role for yield, influx and dispersal pathways of particulate matter (TSM) into marine environment (Weaver 1989; Chauhan *et al.* 2005; Naqvi *et al.* 2009; Rixen *et al.* 2009 and references therein). Even though there are several sources of particulate matter into the sea including authigenic production due to biological activities, land flux into the ocean supplied through rivers - which in turn is found related with magnitude of precipitation, has been deemed the most significant. This implies that during the seasons of high precipitation and fluvial discharge, particulate matter flux into ocean is expected to be optimum. An endorsement to such a hypothesis is derived from magnitude of particulate matter influx in three trap moorings at the central, the eastern and the western region of the Arabian Sea (Nair *et al.* 1989; Haake *et al.* 1993; 1996; Rixen *et al.* 2009). Prevalence of intense rainfall, augmented fluvial flux, vigorous winds, and upwelling coupled biogeochemical processes were found to enhance the flux of particulate matter into the deeper regions of the Arabian Sea with dominant control of SWM (Nair *et al.* 1989; Haake *et al.* 1993; 1996; Nair *et al.* 1999).

Over the northern Indian Ocean, there are two dominant points of fluvial discharge fed by orographically augmented precipitation. The first one lies at the northern boundary of the Bay of Bengal, while the SW continental margin of India (in which due to existence of a topographic high, the Western Ghats, the SW monsoon winds upon their entry into the land have excessive condensation of moisture) is an other site. Being crucial for the supply of nutrients, fluvial input plays a significant role over the marine biogeochemistry and surface hydrography. The rainfall in the Indian Subcontinent is synonymous with SW and NE monsoons, and mostly occurs during June through September. In order to evaluate a specific role of seasonality in precipitation on magnitude of particulate matter flux, and their residence time or mechanism of dispersal and sequestering, close grid studies from the marginal areas are *sine qua non* from these regions. Operational limitations to carry out recurrent and synchronous regional in situ measurements over these areas have so far eluded such an evaluation. The Indian Remote Sensing Satellite (IRS) is equipped with Ocean Color Monitor (OCM) with a recurrent period of 2 days. It is designed to obtain a synoptic view of phytoplankton pigments, colored dissolved organic

matter and suspended particulate matter, and is found useful for obtaining sub-weekly synoptic patterns of TSM. For the present study, the continental margin of the SE Arabian Sea is chosen because, besides having an intense SWM precipitation regime it has (i) upwelling regimes; (ii) seasonality in wind and hydrography; and (iii) it lies in a tropical humid climate zone with a network of high gradient rivers (Chauhan and Gujar 1996), which inhibit possibility of a large scale sequestering of particulate matter in the delta, as found in the large rivers debouching into the Bay of Bengal. Derived from the monthly TSM patterns, and the seasonal variations in current and wind regimes, the present study attempts to decipher processes that regulate dispersal and sequestering pathways of TSM over the SW continental margin of India. It evaluates specific role of SWM climate (an intense precipitation and upwelling) on yield and supply of particulate matter, their dispersal and sink pathways. It elucidates also if the fluvial flux from this intense SWM regime has any role on climate induced enhancement in particulate matter flux observed in the time series traps (Nair *et al.* 1989; Haake *et al.* 1993; Nair *et al.* 1999). The results of the present study will be useful also for paleoclimate reconstruction in which aridity is deciphered from reduction in mass accumulation rates or reduced fluvial supply (von Rad *et al.* 1999).

## **2. Study area**

As indicated earlier, associated with the orographic influence of a topographic high “the Western Ghats” (Chauhan *et al.* 2010), the SW continental margin of India receives about 2700 mm rainfall during SWM (June through September). There is a marked seasonality in the regional hydrography (see Figure 1). During SWM, the Indian Monsoon Current (also known as West Indian Current) carries high salinity the Arabian Sea Water into the Bay of Bengal through equatorwards hydrography (Vinayachandran *et al.* 1999). Upon cessation of SWM, associated with a change in climatology during the northeast monsoon, the polewards hydrography advects low salinity the Bay of Bengal Waters into the southeast Arabian Sea through the East India Coastal Current (Kumar *et al.* 2004 and references therein). During SWM, there are reports of regional upwelling coupled with higher marine productivity, and the deeper subsurfaces are hypoxic due to consumption of O<sub>2</sub> by a large supply of organic matter (Naqvi *et al.* 2009 and references therein).

## **3. Methodology**

We have obtained averaged monthly variations in TSM from IRS OCM-P4 data for path-09 row-13 (spectral channel central wavelength (bandwidth): 412(20), 443(20), 490(20), 510(20), 555(20),

670(20), 780(40), 860(40) nm; spatial resolution: 0.36 km; payload altitude: 760 km; satellite overpass: 1200±0020 hrs local standard time). After atmospheric and geometric corrections (Prasad *et al.* 2002), the algorithm of Tassan (1994) and SeaWiFS Data Analysis Software (SAC Report 2004) were utilized to obtain TSM concentration from the following relations:

$$\text{Log}(S) = 1.83 + 1.26 \text{Log}(\chi S) \quad \forall 0.0 \leq S \leq 40.0$$

where S is particulate sediment concentration (mg l<sup>-1</sup>) and  $\chi S$  is a variable defined as:

$$\chi S = [\text{Rrs}(555) + \text{Rrs}(670)] \times [\text{Rrs}(555) / \text{Rrs}(490)]^{0.5}$$

where Rrs( $\lambda$ ) is remote sensing reflectance in respective wavelengths ( $\lambda$ ).

The reported retrieval accuracy of TSM from OCM data is ±15% (SAC Report 2004). An intense cloud cover had persisted during June through September. An evaluation of rain gauge data between 2001 and 2005 from two meteorological stations (Karwar, 14° N 74° E; Mangalore 12° N: 74° E; Chauhan OS and KV Singh 2010, unpublished data) reveals the occurrence of ~ 20 rainy days month<sup>-1</sup> during SWM. Such a climate has curtailed availability of cloud free images, and has precluded us from maintaining crucial, sub-weekly resolution during SWM. We have prepared, therefore, bi-monthly TSM distribution for June – July and August – September. Because there is a prevalence of high number of rainy days, we speculate that TSM flux had rather small, short-span anomalies during SWM, and these composite patterns provide the generalized synoptic distribution trend of TSM during SWM.

Weekly imageries were validated with the pass synchronous measurements (see Figure 2) by routinely taking 6-10 samples every week by local crafts for TSM measurements during 2004. Besides, dedicated mid-tide synchronous, multiplatform measurements (65 stations; see Figure 1) were carried out during August and November of 2004 (SWM and post monsoon seasons respectively) as per the protocol of JGOFS (matter retained on <0.45  $\mu\text{m}$  optipure fiber filter paper; UNESCO 1994). Currents were measured synchronously using CONtrol current meter (accuracy ± 5%) at 2m water depth. Monthly wind data have been obtained from QuikSCAT (data source: <ftp://ftp.ifremer.fr/pub/ifremer/cersat/products/gridded/mwf-quickscat/data/monthly/>). TSM advection vectors may be a good tool to quantify variability of advection magnitude over different regions of the

continental margin. These had been estimated (65 stations) during SWM and the post monsoon season of 2004 from the following relation:

$$\text{Advection Rate (AD)} = \text{TSM} \times \text{Cur} \times \text{dir}$$

where TSM is suspended load ( $\text{g l}^{-1}$ ),

Cur = measured current ( $\text{m sec}^{-1}$ );

Dir = direction of surface flow with respect to north

$$\text{AD} = \text{mg m}^{-2} \text{ sec}^{-1}$$

#### 4. Results

Temporal and spatial variations in TSM are presented in Figures 2-5. We found a good correlation between the imagery derived and the ship borne data ( $r = 0.89$ ,  $p=0.001$ ;  $n=130$ ; see Figure 6). However, the imagery derived values were found underestimated over the inner shelf (restricted to optimum detection limit of the algorithm), and this has a bearing on the regression equation (see Figure 6). However, the distribution patterns of TSM were found similar in the measured and imageries derived maps during SWM (see Figures 3-4). We have deciphered two regional patterns. Associated with the existence of a network of the rivers, the entire inner shelf was highly and uniformly turbid ( $\sim 40 \text{ mg l}^{-1}$  in imageries; measured 182- 89  $\text{mg l}^{-1}$ ; see Figures 3-5) for about 25 km (boundary at  $\sim 35\text{-}40 \text{ m}$  isobaths) during SWM. Without any seasonality, the deeper region ( $> 40 \text{ m}$ ), in contrast, had low TSM ( $12\text{-}24 \text{ mg l}^{-1}$  during SWM;  $12\text{-}18 \text{ mg l}^{-1}$  during the rest of the year; see Figures 3-5).

Current vectors during SWM and the post monsoon season are presented in Figure 7(a). Current magnitude does not show any seasonality. Round the year, currents were generally moderate – strong ( $22\text{-}72 \text{ cm sec}^{-1}$ ) in the shallow waters ( $< 20 \text{ m}$ ). Their magnitude was marginally reduced in the deeper waters ( $21\text{-}52 \text{ cm sec}^{-1}$ ). The direction of currents was alongshore (equatorwards) during SWM and reversed to polewards during the post monsoon. Such a trend is in conformity with the reported hydrography (Vinayachandran *et al.* 1999; Kumar *et al.* 2004 and references therein). TSM advection vectors are presented in Figure 7(b). The study area had along-shelf advection round the year (equatorwards during SWM; polewards during post monsoon season). During SWM, the advection rates were many folds higher over the inner shelf (see Figure 7(b)).

## 5. Discussion

Our study area receives  $\sim 2700$  mm of rains and has  $\sim 20$  rainy days month<sup>-1</sup> during SWM. There are several small rivers debouching into the study area (see Figure 1). These rivers originate in the Western Ghats (elevation  $\sim 1900$  m above mean sea level), are short (60-153 km in length), and are sustained from the SWM precipitation. Although these rivers are small, persistent precipitation in the mountainous hinterland is expected to yield considerable fluvial discharge. The short-length and the high-gradient of these rivers appear to aid in a rapid transfer of their TSM load into the sea. We, therefore, link higher TSM in the coastal waters to a large fluvial influx into the sea. In order to reinforce our inference, we have obtained and evaluated also sea surface salinity (SSS) in the study area during SWM (June – September) and post monsoon (January – April; data source Levitus *et al.* 1994). Vinayachandran *et al.* (1999) have reported intrusion of high salinity the Arabian Sea Water along the SE Arabian Sea during SWM. As is the case in the deeper regions, such an intrusion is expected to enhance SSS in the study area (Naqvi *et al.* 2009 and references therein). The entire study area, however, has reduced SSS during SWM (33.8-34.6 practical salinity units; see Figure 8). Observed regional salinity reduction, despite an intrusion of the high salinity the Arabian Sea Water, endorses a large fluvial input. An elevated supply of TSM into the sea during SWM is endorsed further from its manifold reduction in the shallow coastal waters upon the cessation of SWM (see Figures 2-5). However, beyond  $\sim 25$  km, despite optimum precipitation, fluvial yield and upwelling, the seawaters were persistently TSM poor all year round (see Figures 3-5). We infer therefore that regardless of the prevalence of upwelling, substantial fluvial discharge and supply of TSM, the quantity of TSM in the deeper regions of the Arabian Sea does not show any seasonality.

Besides land supply, water column biogeochemical processes sustaining marine productivity were linked also with the augmentation of flux of particulate matter (Haake *et al.* 1993 and references therein). In order to estimate regional supply from the subsurface flux through water column processes, we have evaluated the characteristics of seabed sediments in the study area. Hashimi and Nair (1981; 1986) have found the inner shelf ( $< 40$  m) veneered with modern silty –clays. In our data, this region has high TSM (see Figures 2-5). We therefore infer substantial subsurface flux through water column processes over the inner shelf. The seabed, however, has exposed, relict, coarse, carbonate detritus over the entire mid - outer shelf (age 8.0-9.1 ka BP; Hashimi and Nair 1981; 1986; Vora *et al.* 1996; Chauhan and Gujar 1996). Clays and fine-silt size detritus are conspicuous by their absence at the sea-bed.

Considering the age of these sediments (age 8.0- 9.1 ka BP; Vora *et al.* 1996), it is inferred also that this relict facies has poor contribution of carbonate shells from water column. Such a sediment distribution pattern leads us to infer a poor subsurface flux over the entire deeper regions of the mid-outer shelf (characterized by intense upwelling and high marine productivity; Naqvi *et al.* 2009). Besides suspended load, bed-load carried under traction may be a major source of sediments over seabed. The occurrence of relict carbonate facies over the mid-outer shelf, however, implies that this region does not receive any modern detritus through bed – load either. The conspicuous absence of fine detritus matches well with low TSM in the seawaters over these regions. The patterns of TSM in the shallow and the deeper waters, and the characteristics of the sea bed sediments, therefore, suggest that dispersal and sink mechanism regulate the surface or the subsurface TSM flux. We have therefore evaluated the role of morphodynamic processes.

The study area is meso-tidal (tidal range < 1.6 m; Varkey *et al.* 1982). The shallow coastal region has marginal spatial variability in the weekly and the seasonal TSM patterns, which implies that re-suspension by tidal forcing is not vigorous over the inner shelf. No specific extension of any across-shelf plume is distinct also during SWM or during the non monsoon (see Figures 2-4). If across-shelf advection is present, and fluvial supply has a role on the magnitude of flux in the deeper regions of the Arabian Sea, a distinct plume similar to one reported off the mouth of the River Dhamara (in the Bay of Bengal; Rajawat *et al.* 2005) should have been observed. We have found no such across-shelf plume in our weekly or monthly data (see Figures 2-4). It is inferred therefore that across-shelf advection is rather weak to sustain higher flux of particulate matter into the deeper regions of the Arabian Sea.

Although their direction shows seasonality, strong alongshore currents prevail all year round (equatorwards during SWM and polewards during the post monsoon season; see Figure 7(a)). This hydrography is favorable for alongshore advection of TSM. In order to substantiate this inference further, we have evaluated the spatial and the temporal variations in the advection rate. During SWM, advection rate over the inner shelf is  $110 - 26 \text{ mg m}^{-2} \text{ sec}^{-1}$  (equatorwards), which reduces to  $9 - 4 \text{ mg m}^{-2} \text{ sec}^{-1}$  over the outer shelf. Upon cessation of SWM, the magnitude of advection had reduced ( $26 \text{ mg m}^{-2} \text{ sec}^{-1}$  over a narrow band of the inner shelf region), albeit the deeper regions had marginal reduction in advection magnitude ( $8.5-3.4 \text{ mg m}^{-2} \text{ sec}^{-1}$ ; see Figure 7(b)). We therefore infer that despite considerable supply of particulate matter into the sea during SWM, the prevalent hydrography curtailed its influx into the deeper regions.

Wind regime influences dispersal – sink pathways through upwelling, deepening of mix- layer and advection of coastal waters (Gopalakrishna *et al.* 2008 and references therein). Strong onshore winds prevailed during SWM ( $\sim 0.7 \text{ dyne sec}^{-1}$ ), though their magnitude reduced after cessation of SWM (see Figure 9). These winds with equatorwards wind stress component during SWM are known to aid in sequestering of particulate matter over the inner shelf (Shenoi *et al.* 2005; Sardessai *et al.* 2007; Gopalakrishna *et al.* 2008). Unfavorable for the offshoreward advection of TSM, there is a persistent upwelling over the outer shelf during SWM (Naqvi *et al.* 2009). The prevalent morphodynamic regime along the SE Arabian Sea, therefore, inhibits advection of TSM into the deeper regions. We surmise therefore that sustained by orographic precipitation in the mountainous terrain of the Western Ghats, an augmented supply of TSM into the SE Arabian Sea during SWM sequestered most of these flux over the inner shelf and appears not to be a major contributing factor for the supply of these into the deeper regions of shelf and slope. The occurrence of poor surface and subsurface flux of TSM all year round over the mid - outer shelf (the region having prevalence of upwelling coupled with high marine productivity), implies control of morphodynamic regime. Our data, therefore, do not endorse that higher flux of particulate matter in trap or marine cores has any link with higher production in the water column (upwelling region), or its large supply due to prevalence of high precipitation regime from the SW continental margin of India. We underscore the significance of the morphodynamic processes, and propose that most of the particulate suspended matter yielded from the intense SWM regime of the Peninsular India is dispersed and sequestered into the shallow coastal region. This finding has implication for: (i) large sink of land derived anthropogenic insecticides and pesticides into the shallow coastal region leading to coastal eutrophication, and (ii) for paleoclimatic reconstruction of fluvial flux derived from marine cores.

**Acknowledgment:** Authors acknowledge Director NIO for providing the facility. They thank Indian Coast Guard for valuable support during collection of sea truth data. We thank Pratima Jauhari for the English correction in the manuscript. The work is supported by funding from the Space Application Center, and IGBP- ISRO, Ahmedabad. NIO Contribution no XXXX.



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## Figure Captions

Figure 1. Location of sampling stations and three transects used for estimation of monthly variations in TSM. Regional hydrography is shown also.

Figure 2. Validated, sub-weekly remote sensing data during pre and post monsoon seasons (used for obtaining monthly synoptic patterns).

Figure 3. Imagery derived monthly averaged synoptic patterns of TSM for March (pre- monsoon), August (SWM) and November (post-monsoon) of 2003-2004.

Figure 4. Measured TSM patterns during SWM and post monsoon.

Figure 5. Monthly variations in the TSM along three transects during 2003-2004. Refer Figure 1 for the location of transects. Note poor TSM in the regions deeper than 40 m (~ 25 km offshore) uniformly on all the profiles round the year.

Figure 6. X-Y plots of measured and imagery derived TSM.

Figure 7. Measured current vectors (*a*), and TSM advection vectors (*b*) in the study area during SWM and the post monsoon season.

Figure 8. Regional sea surface salinity variations in the study area during the SW monsoon and the post monsoon seasons (modified from Levitus *et al.* 1994).

Figure 9. Averaged monthly wind vectors during 2003 (data source:

<ftp://ftp.ifremer.fr/pub/ifremer/cersat/products/gridded/mwf-quikscat/data/monthly/>).

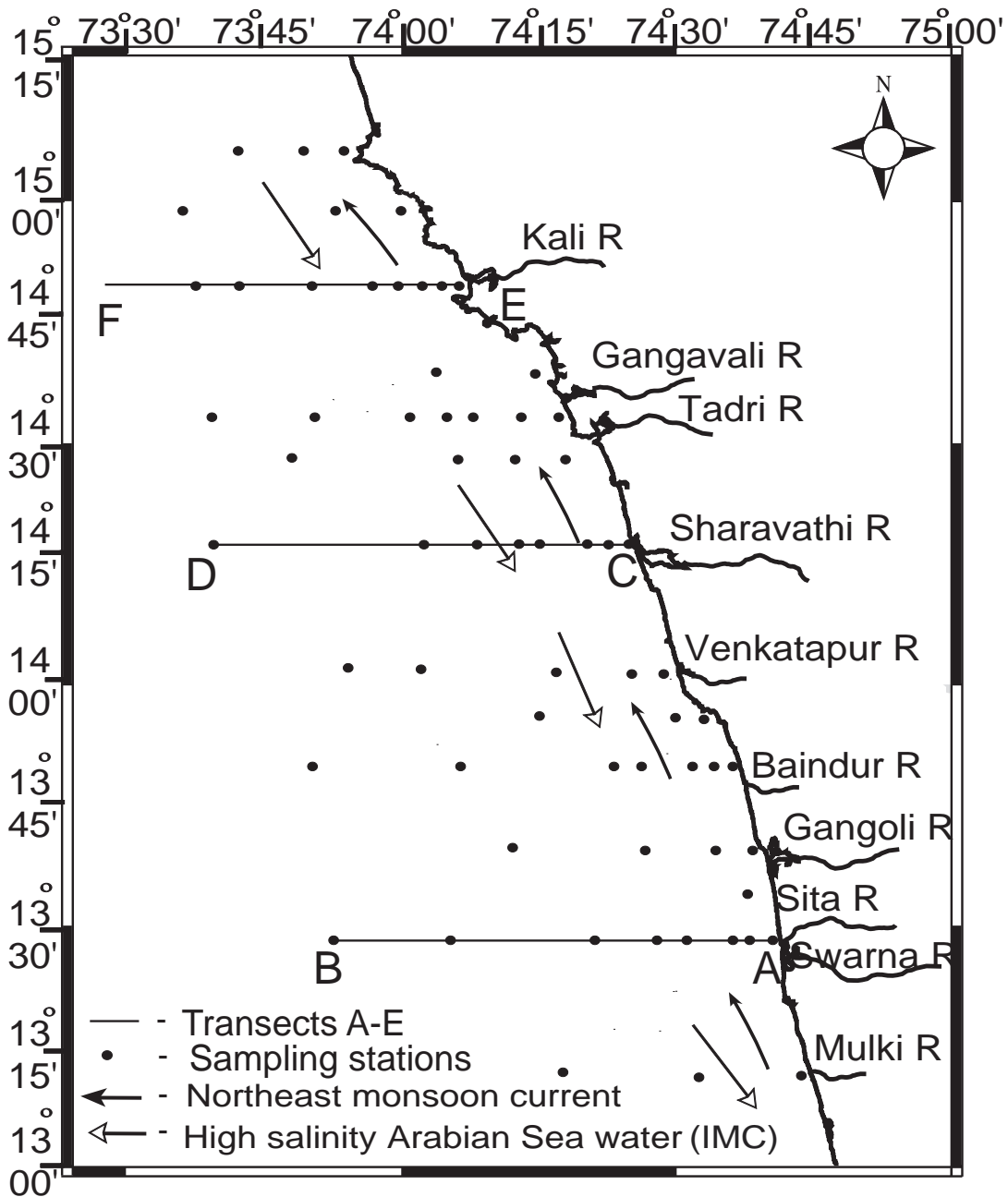


Figure 1. Location of sampling stations and three transects used for estimation of monthly variations in TSM. Regional hydrography is shown also.

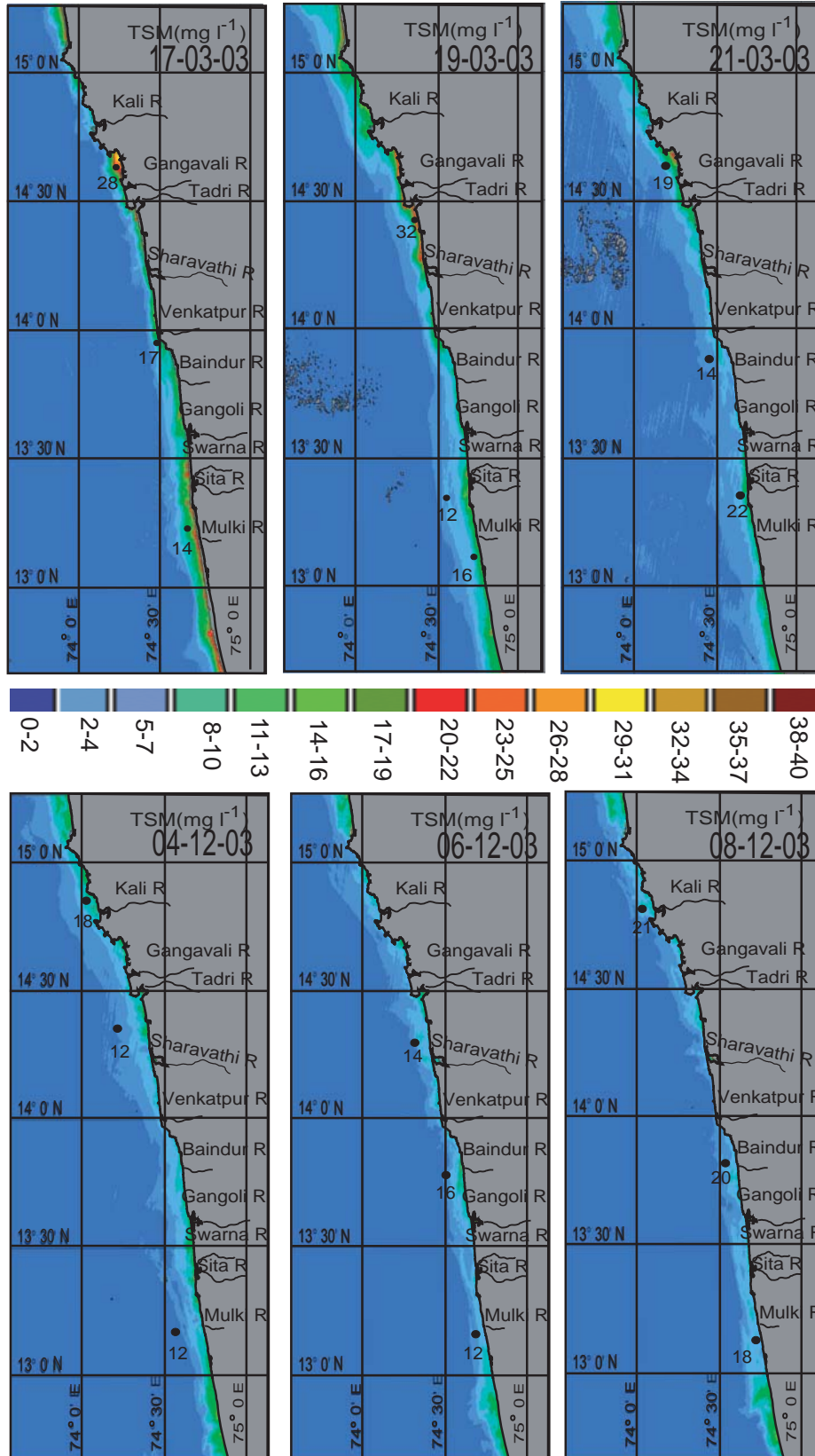


Figure 2. Validated, sub weekly remote sensing data during pre and post monsoon seasons used for obtaining monthly synoptic patterns.

Figure 4.

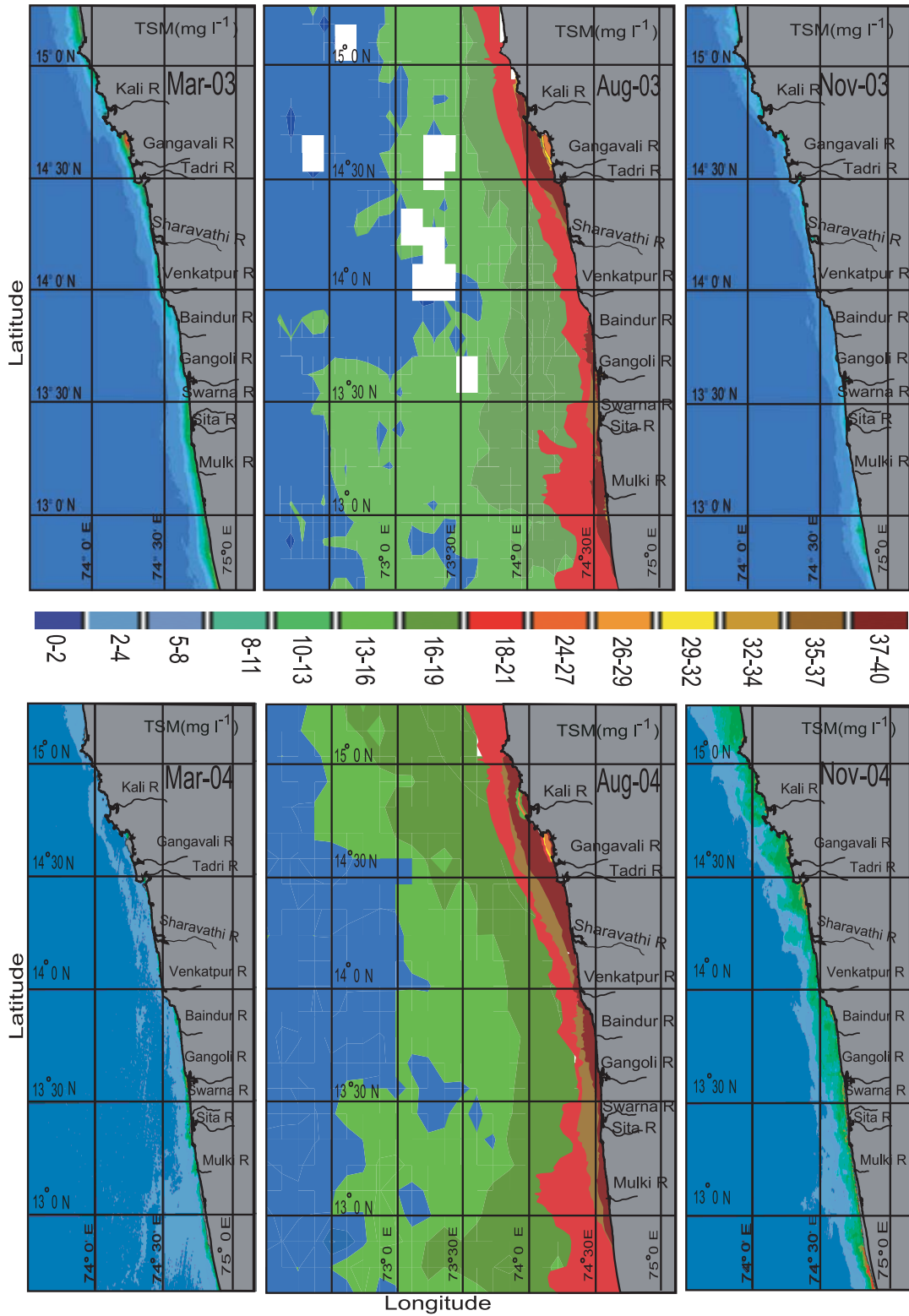


Figure 3. Imagery derived monthly averaged synoptic patterns of TSM for March (pre-monsoon), August (SWM) and November (post-monsoon) of 2003-2004.

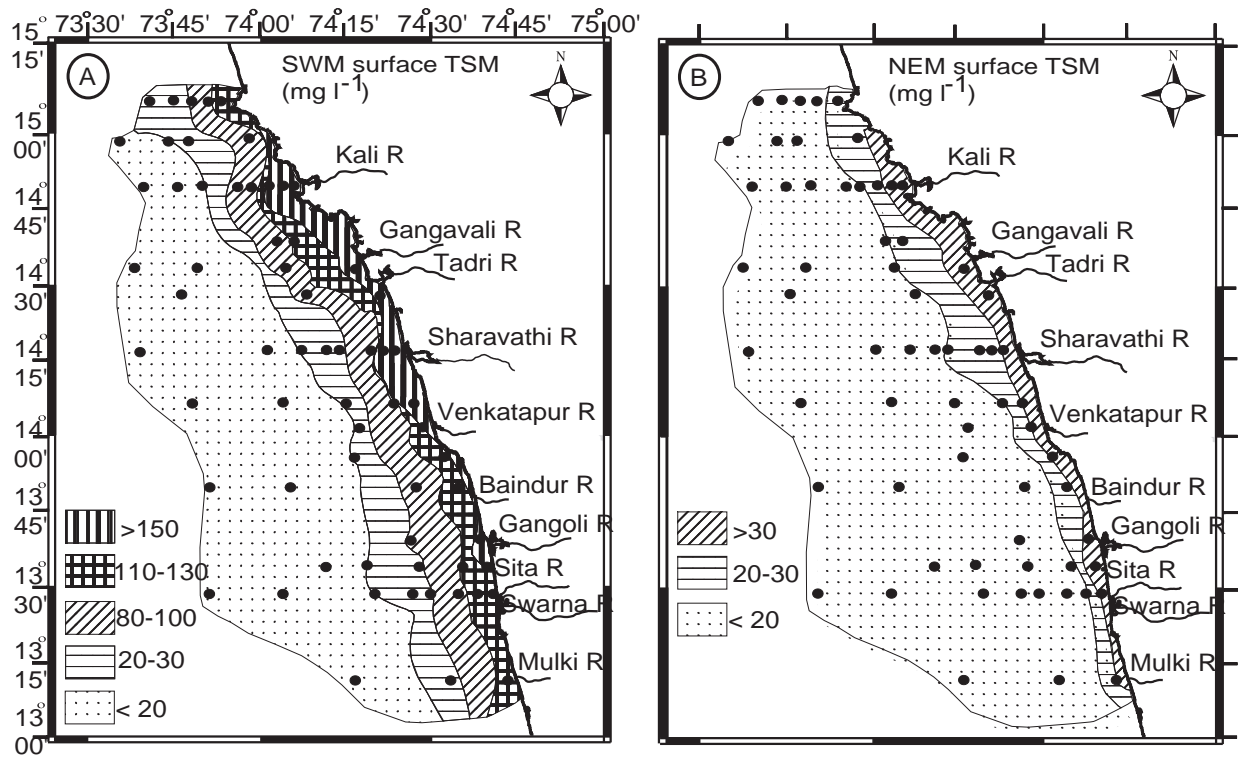


Figure 4. Measured TSM patterns during SWM and post monsoon.



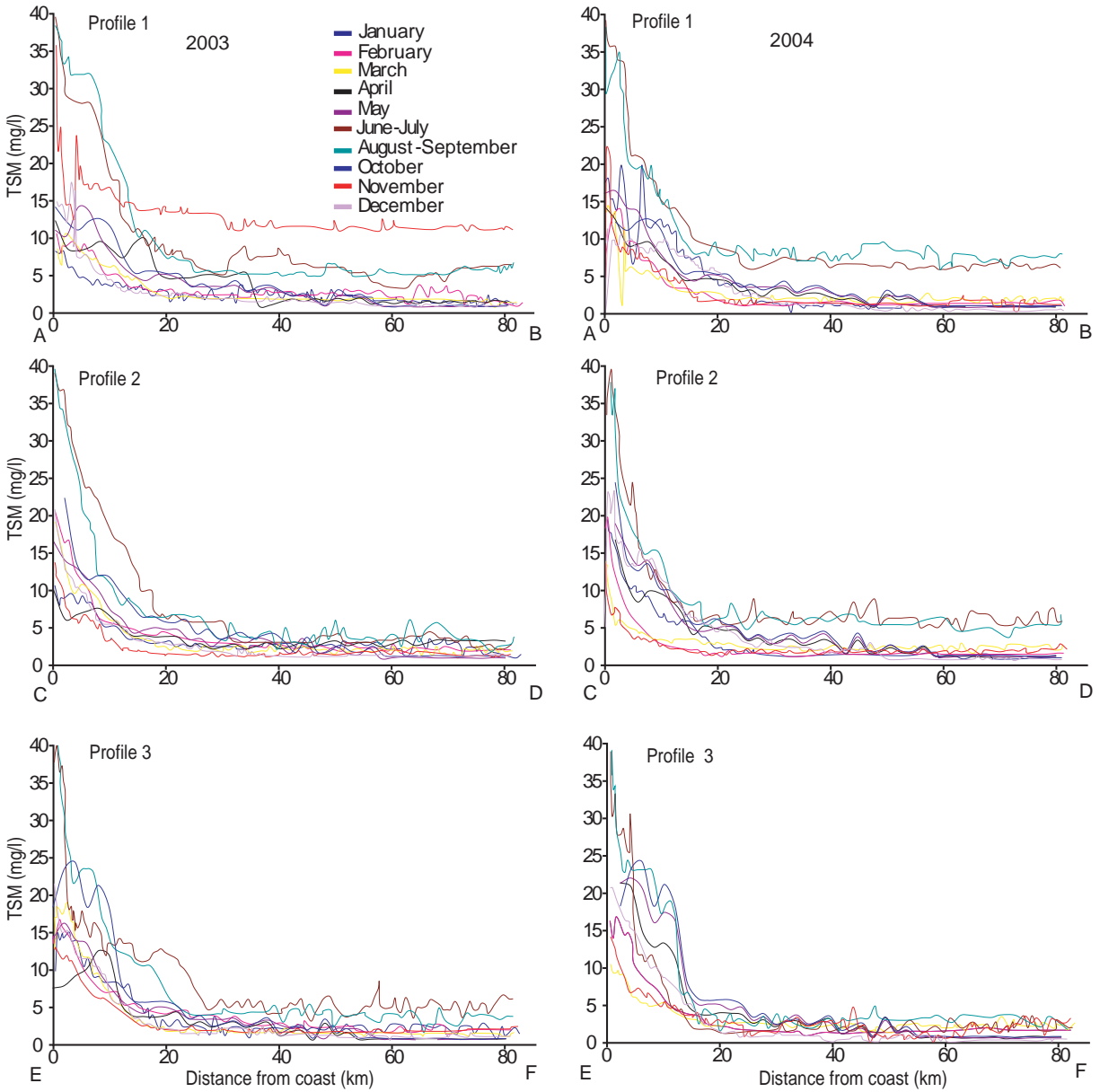


Figure 5. Monthly variations in the TSM along three transects during 2003-2004. Refer Figure 1 for the location of transects. Note poor TSM in the regions deeper than 40 m (~ 25 km offshore) uniformly on all the profiles round the year.

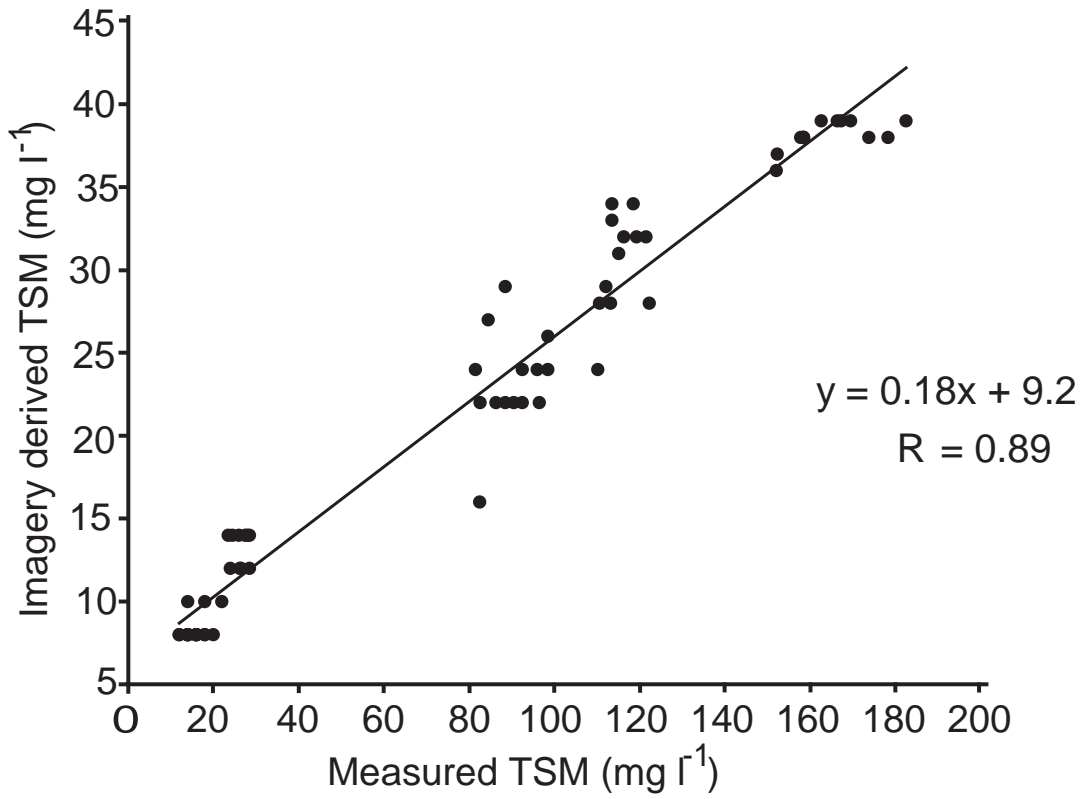


Figure 6. X-Y plots of measured and imagery derived TSM.

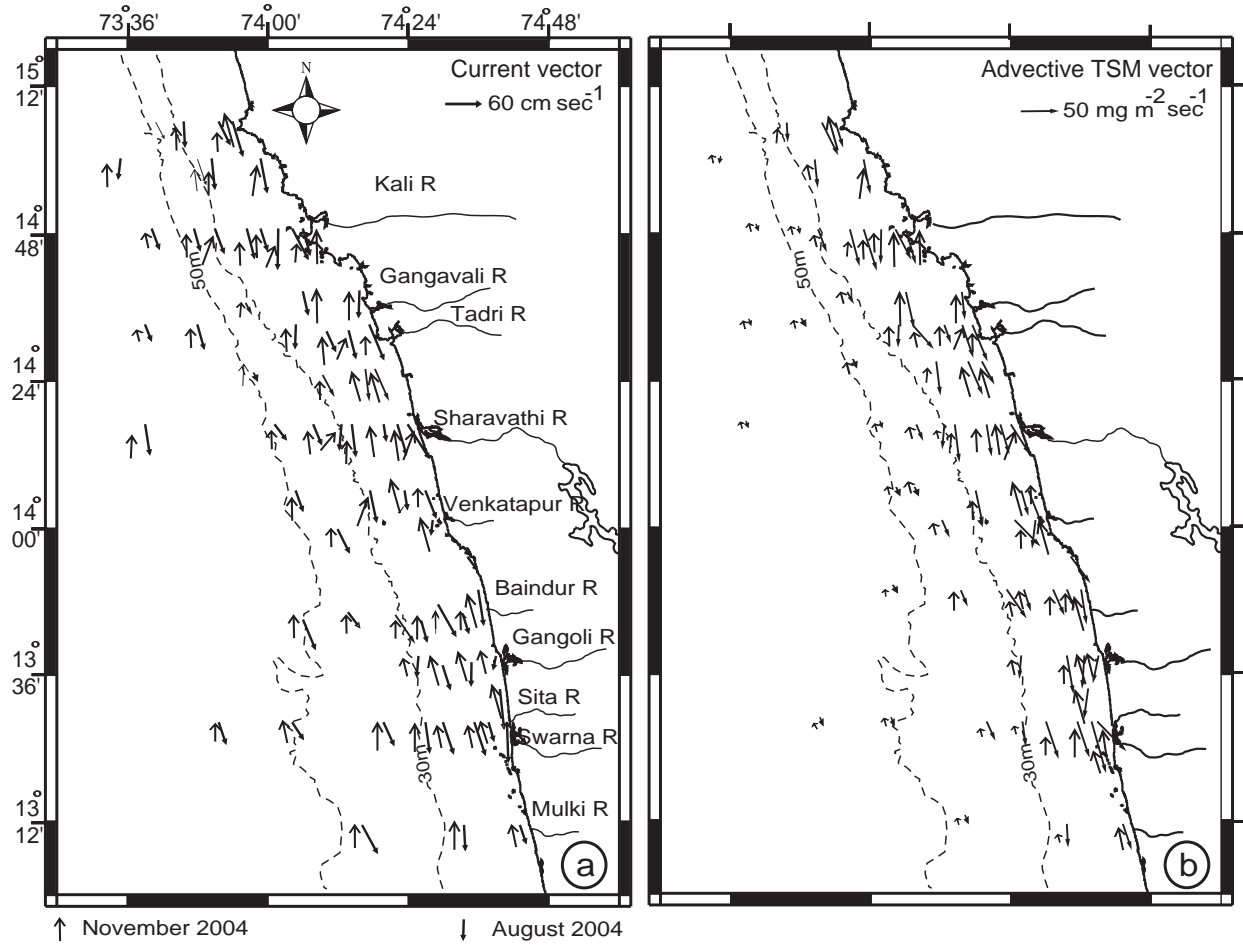


Figure 7. Measured current vectors (a), and TSM advection vectors (b) in the study area during SWM and the post monsoon season.

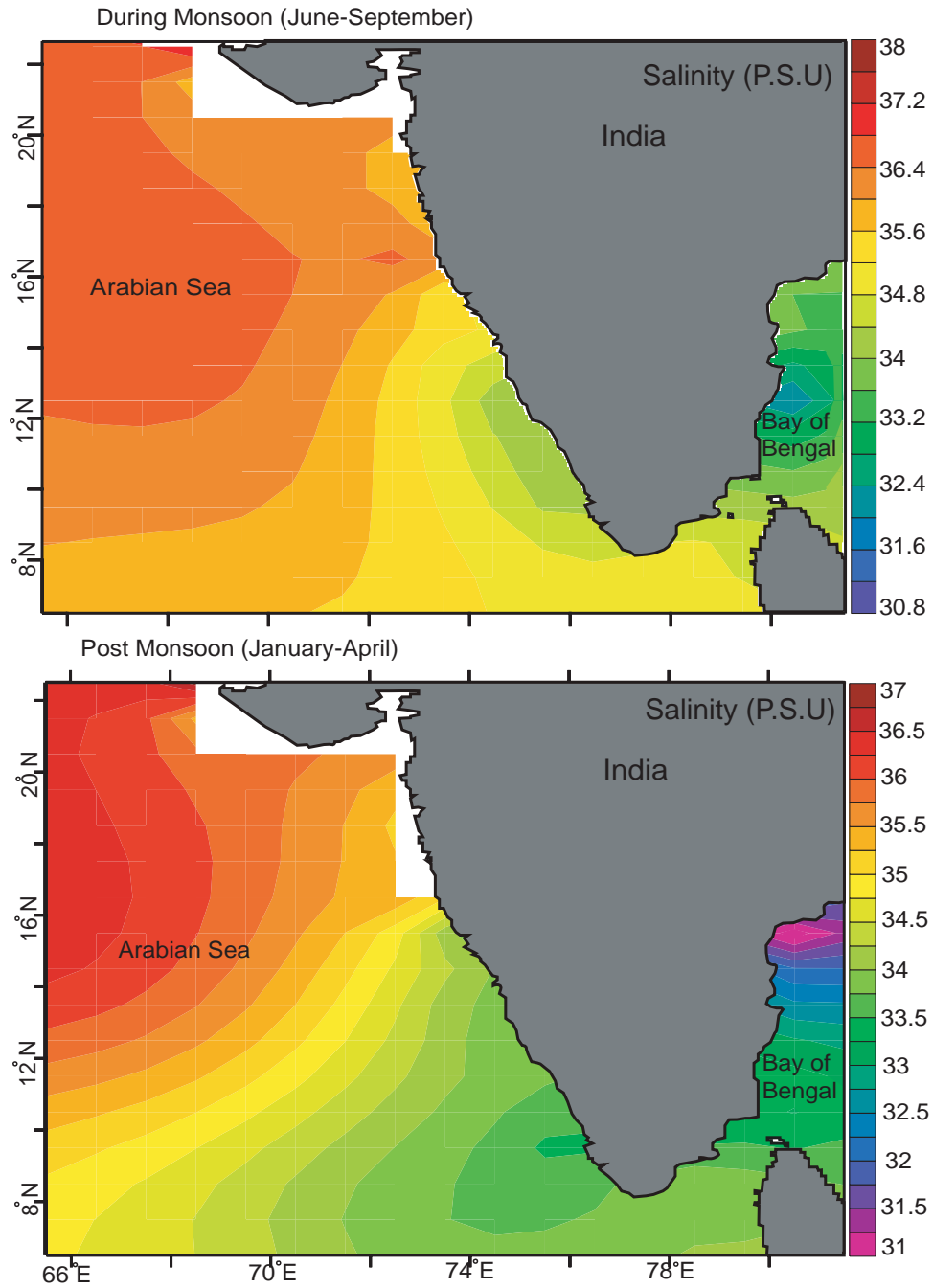


Figure 8. Regional sea surface salinity variations in the study area during the SW monsoon and the post monsoon seasons (modified from Levitus et al. 1994).

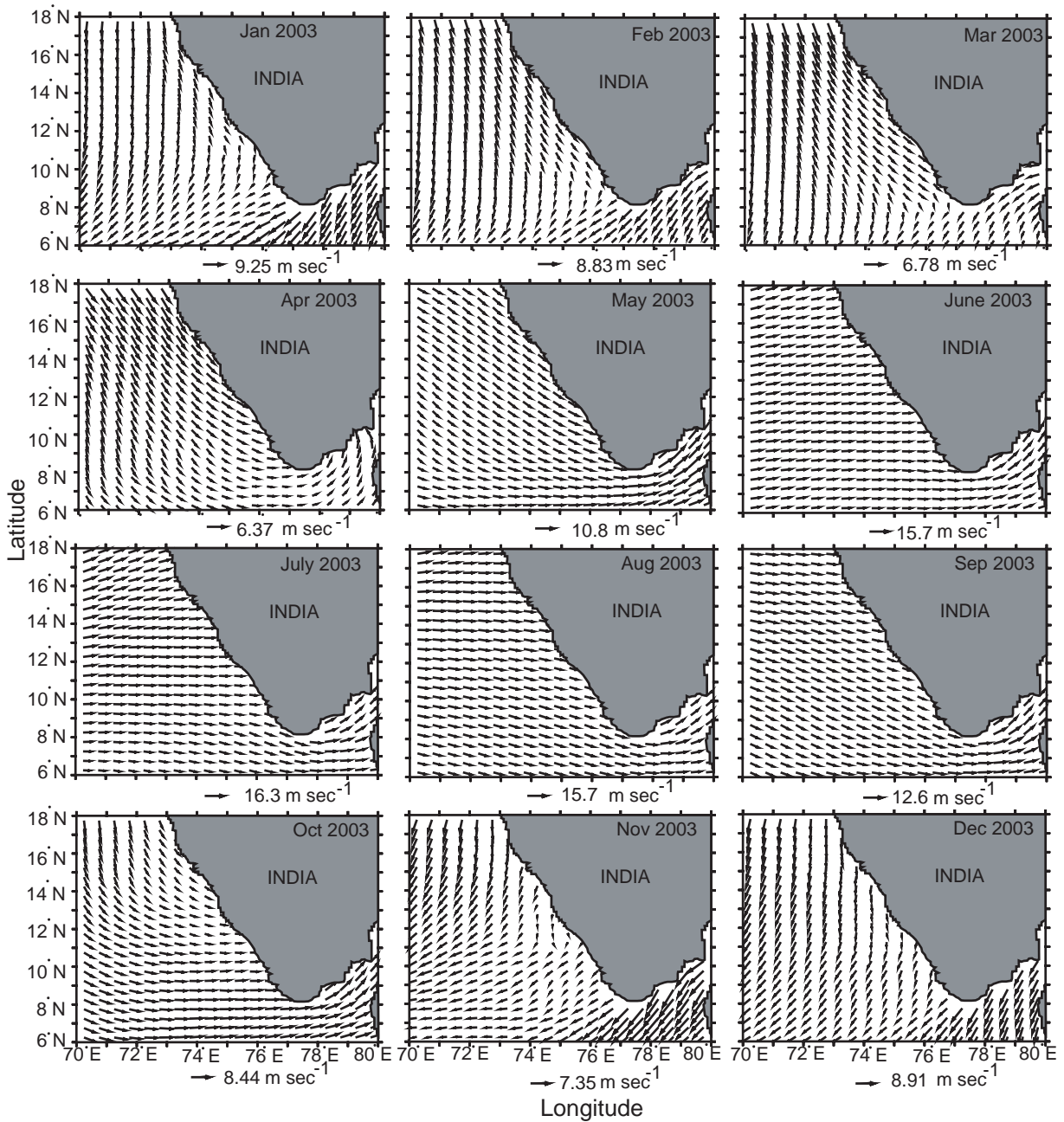


Figure 9. Averaged monthly wind vectors during 2003  
 (data source: <ftp://ftp.ifremer.fr/pub/ifremer/cersat/products/gridded/mwf-quikscat/data/monthly/>).