Evaluation of the influence of monsoon climatology on dispersal and sequestration of continental flux over the southeastern Arabian Sea

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Abstract

Associated with the coupled land-ocean heating-cooling, seasonal reversal of monsoon winds regulates hydrography, precipitation, upwelling, fluvial influx and a host of biogeochemical processes. We evaluate the role of the monsoon winds, fluvial discharge and currents on continental flux dynamics from advection magnitude of clays over an anomalous high precipitation regime of the southeastern Arabian Sea. Coupled with the intense rains and a high fluvial discharge, we archived an elevated content of detrital clays (> 41 mg l\(^{-1}\)) during the southwest monsoon over the <40 m water depth. The deeper waters (> 40 m), however, had much reduced detrital clays (<6 mg l\(^{-1}\)) year round. Therefore, two distinct environments (high and low detrital clays) prevailed over the shelf. Derived from the variations in the clays in the local riverine discharge and in the seawater loads, we found a dominant role of the southwest monsoon winds and that of the winter and the southwest monsoon (summer) coastal currents over the dispersal and sequestration processes. Over the inner shelf, an alongshore (equatorward) advection and merging of several, small, fluvial plumes by the southwest monsoon winds had sequestered most of the local fluvial discharge over the shallow region only. The outer-shelf received detritus mostly as a result of (a) the high salinity Arabian Sea water during the southwest monsoon, (b) through the Bay of Bengal Water and (c) by way of aeolian supply from the Arabia and the Somalia.

Key words: Clay minerals, detrital suspended matter, southeastern Arabian Sea, hydrography, wind regime, fluvial influx.
1. Introduction

Regulated by the coupled ocean-land heating-cooling, there is a seasonal reversal in the winds over the northern Indian Ocean that is termed as monsoon (Prell and Kutzbach, 1992). Being a regulator of the magnitude of weathering, fluvial supply, ocean circulation and winds, the monsoon plays a vital role upon yield, supply, dispersal and sequestration of continental fluxes (Chauhan et al., 2006; Naqvi et al., 2009; Rixen et al., 2009). Conventionally, the Arabian Sea has been considered to have a strong evaporation over precipitation regime (E>>P), and it is therefore deemed that it receives a low amount of fluvial discharge (Vörösmarty et al., 1996; Yu and McCreary, 2004). The River Indus is the only large river that debouches into the northern region of the Arabian Sea (Fig. 1). However, because of the orographic influence by an elevated regional topographic high (the “Western Ghats”), a narrow belt of the entire southwestern continental margin of India has been found to receive incessant seasonal rains (2700-4800 mm) during the southwest monsoon (SWM; Chauhan et al., 2010, 2011). Aided by such a high precipitation and the existence of hilly terrain all along the coast (average elevation ~ 2000 m), this rainfall is expected to sustain a large fluvial discharge that carries anthropogenic load of untreated sewage, fertilizers and insecticides from the littoral states by way of fluvial route into the sea. Studies found elevated marine productivity in the coastal region during the prevalence of the fluvial supply (Chauhan et al., 2011; Raghavan and Chauhan 2012). Study of Lückge et al. (2012) also found that marine productivity and carbon sequestration were linked with the magnitude of detritus supply into the Arabian Sea. There are, however, several climate regulated processes that may supply detritus and nutrients into the Arabian Sea.

During the SWM, strong onshore winds are known to induce upwelling over the shelf and it sustains high marine productivity (Naqvi et al., 2009). The winter cooling is known also to supply a large amount of nutrients (Madupratap et al., 1996; Kumar et al., 2001). Aided by the SWM climate, there is an intrusion of high salinity from the Arabian Sea Water (ASW) into the Bay of Bengal by way of the West India Coastal Current (equatorward summer coastal current; Kumar et al., 2004). Upon the termination of the SWM, there is a reversal of winds and current regime, and that leads to an advection of nutrient rich, low salinity Bay of Bengal Water (BBW) into the southeastern Arabian sea by way of a poleward coastal current (known also as the East India Coastal Current; Kumar et al., 2004). The winter coastal currents were found to be a carrier of nitrate and phosphate, and these have enhanced marine productivity along the southeastern Arabian Sea (Kumar et al., 2004). The southwestern continental margin of India is known to have anoxia (Naqvi et al., 2000; 2009; Chauhan et al., 2011 and references therein). There is a widespread use of fertilizers and insecticides in the hinterland, and that may enhance their import into the sea by way of the fluvial route. Any
further augmentation in nutrient input from a distal or a local source may therefore be a further cause of anoxia, and that may lead to environmental degradation or fish mortality along the southeastern Arabian Sea. It remains pertinent, therefore, to determine detritus contribution from each of the aforesaid sources to get an insight into the processes that regulate marine biogeochemical cycle in the Arabian Sea.

Source and dispersal pathways of continental fluxes over the Arabian Sea have been investigated rather inadequately. The time series trap data were the only archive that had estimated the role of climate on detrital flux dynamics over the Arabian Sea (Nair et al., 1989; Haake et al., 1993; Rixen et al., 2009). These studies speculated that because of high fluvial fluxes of the River Indus (aided by the seasonal rains in the hinterland) and seasonal upwelling, the magnitude of terrigenous flux into the deeper regions of the Arabian Sea (> 2000 m water depth) enhanced many fold during the SWM. However, being point observations (three traps), it is not known if the inferences drawn in these studies remain valid for the shallow region of the continental shelf. Nor had these studies elucidated the specific source, dispersal and sequestration mechanism of the detritus. Unlike the deeper regions of the Arabian Sea, however, the continental shelf has: (a) several, closely-spaced, fluvial discharge points, each with variable intensity; and (b) seasonal currents, upwelling, down-welling, etc. (Kumar et al., 2004 and reference therein; Raghavan and Chauhan, 2012). Winds are known also to transport aerosol dust into the Arabian Sea (Sirocko et al., 1991; Chauhan, 1996). No insight, however, has been acquired over the comprehensive role of the monsoon specific morphodynamic agents such as rainfall, fluvial influx, winds, and seasonal currents over dispersal or sequestration pathway of detritus that may carry micronutrients such as iron and zinc into the shelf of the southeastern Arabian Sea.

The spatiotemporal variations in suspended particulate matter (SPM) has been used as a proxy to estimate dispersal and sink pathways of fluvial fluxes in the northern Indian Ocean (Chauhan et al., 2005, 2006, 2010, 2011; Raghavan and Chauhan, 2012). However, the application of this tool has limitation in case I waters because these have a very little spatiotemporal variability in the amount of turbidity. Besides, SPM is comprised of detrital and biogenic components. The biogenic component is contributed through biological processes. The detrital component is allogetic, and it is contributed mostly from continental sources. In earlier studies (Chauhan et al., 2005, 2006, 2010, 2011; Raghavan and Chauhan, 2012) the synoptic distribution of SPM has been obtained and it had been used to estimate the magnitude of fluvial supply from the hinterland. Because of upwelling and fluvial influx, high marine productivity has been reported from our study area (Chauhan et al., 2011). This may contribute a sizable amount of biogenic component into SPM. The spatiotemporal
variability in SPM therefore may not be unequivocally used to estimate quantum of allogenic continental flux. We have therefore used the detrital components of SPM as a geo-tracer. Clay minerals are a weathering residue. The formation of these had been linked with geological characteristics, drainage and climate of a region (Weaver, 1989; Chauhan and Gujar, 1996). Their occurrence in each of the fluvial or in the hydrographic sources is therefore expected to be a source specific. Because of their smaller size (≤ 2 µm) and a low density, these have an ability to remain in suspension in atmosphere, river, and in sea. Taking advantage of these properties, we have used clay minerals as a proxy to decipher possible sources and dispersal of the terrigenous flux over the southeastern Arabian Sea. A two fold approach had been adopted. First, clays carried in the potential contributors were identified by a source specific sampling (rivers, and that in the summer and in the winter hydrography). Then, we obtained the spatiotemporal variability in total detrital matter (TSM) and that in its clay size detritus (≤ 2µm fraction; DC) through multi-platform, mid-tide synchronous, seasonal measurements over the shelf. The spatiotemporal variations in TSM and DC, the advection direction of the clays, and prevalent currents and winds climatologies have been used to decipher sources, dispersal and sequestration of detritus in this anomalous, high-precipitation region of the southeastern Arabian Sea. Our study is an attempt to decipher the role of monsoon climatology on dispersal and sequestration processes of the terrigenous flux from local as well as distal sources. The results of our study have application for the better understanding of the processes that regulate supply of detritus and nutrients, and influence biogeochemical cycle of the southeastern Arabian Sea.

2. Methodology

For estimation of the seasonal and the temporal variation in TSM and DC, mid-tide synchronous measurements (77 stations) were carried out during the SWM (July-August) and the post monsoon (November-December) season during 2007 (Fig. 1). In order to decipher the clay mineral flux from the hinterland, six rivers were sampled at an inland location (about 25-35 km away from their mouths) to avoid any influence of flocculation due to fresh-sea water interaction in the estuarine region. For an estimation of clay minerals carried in the ASW and that in the BBW, seawater samples were collected from the northern Arabian Sea (during the SWM) and from the Bay of Bengal (during post monsoon) from the locations that lie in their known paths of advection (Fig. 1; Kumar et al., 2004 and references therein). SPM estimation is carried out as per the protocol of JGOFS (matter retained on <0.45 µm optipure fiber filter paper; United Nations Educational, Scientific, and Cultural Organization (UNESCO), 1994). In addition, we used a 6 foot Prep/Scale TFF regenerated cellulose cartridge (No CDUF 006 Lm) on a tangential flow filtration system of Millipore, which had been designed to separate out ~ 0.02 µm size particulate matter directly from
seawater. About 100 l of seawater was filtered for each station for acquiring SPM. To avoid any possible contamination, about 10 l of ultrapure water had been filtered between two successive filtrations. The SPM contains biogenic and detrital components. Pre-weighted samples were treated with 10% acetic acid and 30% hydrogen peroxide and TSM was estimated from the weight loss method. Synchronous current measurement at each station was carried out using CONtrol current meter (accuracy ± 5%) at surface (2m water depth). Synchronously, a Hydrosonde DS-5 system of Hach Inc. was used to measure temperature and salinity at 54 stations. A recalibration of the measurements against conductivity standards (0.1, 0.5, 12.85 and 47.6 mS/cm of Hach Inc.) suggested that the precision was better than 5% for salinity.

Clay mineral analysis was performed on an aliquot of the acquired sample. A pre-weighted quantity of each of the samples was filtered through micro-plated sieves of 15 and 5 μm openings. Subsequently, the filtrate was passed through a membrane filter paper of 2 μm size. The clay fraction retained on the filter paper was transferred into a dish and it was treated with mild acetic acid and hydrogen peroxide to remove carbonate and organic matter. After removal of these reagents, it was dispersed on a glass slide and air-dried to obtain an oriented sample. The samples were analyzed on an X-ray diffractometer using Ni filtered Cu Kα radiation (λ= 1.5481A°). Normally, for the identification of smectite, glycolation is carried out at 60° C for one hour (Carroll, 1970). Because identification of smectite is crucial for our study, we have glycolated our samples for 6 h at 100° C to aid an optimum expansion of smectite. Smectite and kaolinite show disintegration at 300 and 550° C respectively (Carroll, 1970). In order to affirm identification of these clays, 22 samples were heated at 550° C for one hour to affirm the identification of these clays. Clay minerals were identified and quantified using the methods of Biscaye (1965) and Carroll (1970). The accuracy, derived from replicate analysis, was found to be better than ±8% for smectite and ±5% for rest of the clays.

The clay mineral abundance derived from the weighted peak area is routinely interpreted as a relative, semi-quantitative abundance of clays in a sample (Sirocko and Lange, 1991 and references therein). However, being not normalized to the weight of clay size detritus in a sample, such data may not give a quantitative estimation of clays in the suspended load in sensu stricto. We have, therefore, adopted the following methodology; a predetermined portion of collected SPM was treated with mild acetic acid and hydrogen per- oxide to remove carbonates and organic matter. After repeated washing to remove these reagents, the aliquot was passed through the micro-plated sieves of 15 and 5 μm opening. The separated fraction was then filtered through a pre-weighted 2 μm optipure filter paper, and matter retained on it has been estimated and termed as DC fraction. We had carried out synchronous current measurement during collection of SPM. These measured flows had been
deemed to be surface flow. Advection rate of each of the clays was derived using the following relation:

\[ AD = Cl \times S \times \text{dir} \]

where \( AD \) = Advection vector of an individual clay (mg m\(^{-2}\) sec\(^{-1}\) dir); \( Cl = ((\text{wt}\% \text{ of an individual clay} /100) \times \text{detrital clay fraction; g l}^{-1}) \); \( S \) = measured surface flow (cm sec\(^{-1}\)); \( \text{dir} \) = current dir 0 - 359\(^{0}\)

Advection rate of TSM had been estimated from the following relation:

\[ ADS = TSM \times S \times \text{dir} \]

where \( ADS \) = Advection vector of TSM (mg m\(^{-2}\) sec\(^{-1}\) dir); \( TSM = (\text{TSM g l}^{-1}) \); \( S \) = measured surface flow (cm sec\(^{-1}\)); \( \text{dir} \) = current dir 0 - 359\(^{0}\)

3. Results

The spatiotemporal variations in TSM have been presented in Fig. 2. During the SWM, we found: (a) turbid coastal waters all along the shallow region of the study area, (b) high contents of TSM (48-102.5 mg l\(^{-1}\)) between 10-40 m isobath, and (c) a zone of depleted TSM (<7 mg l\(^{-1}\)) beyond 40 m isobath extending along the entire mid and the outer shelf (Fig. 2). The boundary between the waters of the inner shelf and that of the deeper region was rather sharp during the SWM, and it shrunk closer to the coast upon the cessation of the SWM (Fig. 2). The magnitude of surface currents in the study area are shown in Fig. 3. The direction of currents was equatorward during the SWM, and it reversed to poleward during the post monsoon season.

Clay mineral distribution in the fluvial load and from the selected locations of the Bay of Bengal and that of the Arabian Sea (ref to Fig. 1 for location) are presented in Tables 1-2. In local riverine load, we found kaolinite > illite > gibbsite (Table 1). The assemblage of clays over the shelf was different from that found in the load of the local rivers, and these had a large seasonal variability (Figs. 4-6). During the SWM, kaolinite, smectite, illite and gibbsite were found over the inner shelf. The outer shelf had smectite, kaolinite, illite and palygorskite. The clay mineral assemblage altered after the termination of the SWM. The waters of the inner shelf were devoid of smectite, and these had kaolinite, illite and gibbsite (Figs 4-6). The clays found over the outer shelf were illite, kaolinite, smectite and chlorite. There was a progressive northward reduction in the content of chlorite, and it was not found over the northern part of the shelf (Fig. 6). The advection rate of the clays showed marked seasonality. During the SWM, the advection of DC was equatorward (410-5590 \( \mu \)g m\(^{-2}\) sec\(^{-1}\)), and over the outer shelf it reduced many fold (40-290 \( \mu \)g m\(^{-2}\) sec\(^{-1}\)). Upon the termination of the
SWM, except in the isolated shallow areas (water depth < 10 m), advection reduced many fold over the entire shelf (inner shelf 28-430; outer shelf 15-99 µg m⁻² sec⁻¹), and it was found to be poleward.

4 Discussions

4.1 Southwest Monsoon

Because of the existence of the small rivers, it had been perceived that the magnitude of fluvial fluxes into the eastern Arabian Sea is insignificant (Vörösmarty et al., 1996; Yu and McCreary, 2004). Associated with the operational limitation, the shallow region had been poorly sampled during the SWM (< 20 m water depth), and perhaps the inferences derived in the earlier studies were based upon such a data set. Our study sampled these shallow waters as well (Fig. 1). All along the southwestern section of the Western Ghats, we found high amount of TSM and DC (TSM >48 mg l⁻¹; DC > 41 mg l⁻¹) during the SWM, albeit these were restricted to the inner shelf only (water depth <40 m). The amount of TSM and DC in sea waters reduced after the termination of the SWM all along the study area (< 7 and <6 mg l⁻¹ respectively). Chauhan et al. (2011) also found the high (low) amount of SPM over the inner (outer) shelf during the SWM. However, the amount of SPM compared to that of TSM was higher, and that may be attributed to the prevalence of a high marine productivity during the SWM. The rivers of the study area have short length (66-153 km), high gradient (1:94 - 1:255), and these have originated in the Western Ghats at an altitude of 500-2010m (Table 1). We have found high TSM (131-172 mg l⁻¹) in the fluvial load during the SWM only. Because of the gradient and the length of the rivers, high precipitation in the Western Ghats appeared to be carried near instantaneously into the sea. The absence of any gauge on the local rivers had eluded our efforts to determine quantitatively the magnitude of fluvial discharge from this section of the Western Ghats. In order to get an approximation, we had relied upon the measured fluvial discharge (gauge data) of 16 major coastal rivers in the adjacent southern region of the Western Ghats (with similar geomorphology and precipitation regime; Chandaramohan and Balchand, 2007). The cumulative fluvial discharge of these 16 rivers was found to be 77,900 MCM (CWRDM 1995; Chandaramohan and Balchand, 2007). We presumed equitable fluvial discharge from our study area, and it carried a high amount of TSM (Table 1) into the sea. The elevated amount of suspended matter in the shallow coastal waters, therefore, emulated the magnitude of fluvial supply into the inner shelf. Such an inference was endorsed further by the uniform and reduced salinity during the SWM over the entire inner shelf region (27.6-33 practical salinity unit; Fig. 7). A uniform, low salinity in the coastal area suggested also the absence of any plume off the mouth of the rivers (Fig. 7). Such a trend had led us to infer further that the fluvial discharge dispersed rapidly along the shelf. Chauhan et al. (2011) had also found a reduced salinity over the entire inner shelf, and their data endorsed our
inference. Upon the termination of the SWM, TSM and DC in the sea reduced considerably (Fig. 2). Despite a high amount of fluvial influx during the SWM, the amount of TSM and DC over the mid-outer shelf had not shown any spatiotemporal variability (Fig. 2). This implied that unlike the shallow region of the shelf (< 40 m) the amount of TSM over the deeper region had no coupling with that of the seasonal magnitude of the local fluvial flux.

The major supply of SPM into the sea is deemed to be through: (a) fluvial supply, (b) aeolian supply, and that through (c) in situ production. In addition, supply from non-local sources by way of inter basin hydrographic processes is also known to contribute detritus over shelf (Chauhan and Gujar, 1996; Chauhan et al., 2010 and references therein). As indicated earlier, a spatiotemporal variability in the SPM has been used to estimate dispersal and sequestration pathways of detrital flux (Chauhan et al., 2005, 2006, 2010, 2011; Raghavan and Chauhan, 2012). However, in the region of high marine productivity, the biogenic component may be an important constituent of SPM. Therefore, its synoptic distribution may not be a true representation of continental fluxes. Moreover, because of a lack of spatiotemporal variability of SPM in Case I waters of the outer-shelf, it was not possible to determine the specific source or the dispersal pattern of detritus from these data (Raghavan and Chauhan, 2012). We had therefore relied upon the clay mineral data to resolve the source of detritus. In all the rivers of the study area, kaolinite > illite > gibbsite were found (Table 1).

The southwestern continental margin of India has a high precipitation (> 2700 mm y⁻¹) and a tropical climate (Chauhan et al., 2011). Such an environment has an ability to sustain intense chemical weathering of the granitic rocks found in the hinterland, and it is favorable for the formation of kaolinite, illite and gibbsite. However, such a geologic setting is unfavorable for the formation of smectite because this clay is produced mostly in basaltic terrain (Weaver, 1989; Ramaswamy and Nair, 1989). Deepthy and Balakrishnan (2002) had found kaolinite, illite and gibbsite assemblage in the soil profiles of the southwestern continental margin. It is inferred therefore that smectite may not have been contributed through local fluvial flux.

During the SWM, winds were strong, and these prevailed mostly from the northwest over the study area (Fig. 8). Such onshore winds with an equatorward component of wind stress appeared to have churned out an alongshore (equatorward) displacement, and these had induced coastal upwelling in this region. Other studies (Naqvi et al., 2009 and references therein) also found strong upwelling along the southeastern region of the Arabian Sea. The observed equatorward currents (26-68 cm sec⁻¹) during the SWM (Fig. 3) were therefore a manifestation of the SWM winds. The prevalence of such a climatology appeared to have induced and sustained a rapid alongshore distribution of local fluvial discharge over the inner shelf, and that had stimulated an alongshore advection and merging
of the several, small, fluvial plumes over the inner shelf. We derived support to our inference from the salinity and the TSM data. A uniform, low salinity had been observed along the inner shelf (Fig. 7). Coupled with this low salinity, the inner shelf had a high amount of TSM and DC (Fig. 2). This implied that strong onshore winds induced an alongshore dispersal of the fluvial plumes. In satellite imageries of the southwestern continental margin of India, similar to our data, Raghavan and Chauhan (2012) found also uniform turbidity. Salinity data (Fig. 7) further affirm absence of any plume off the mouth of the rivers. Studies had also found an alongshore expansion of the fluvial plume of the Columbia River due to wind induced coastal currents (Liu and Weisberg, 2005; 2007; Liu et al., 2009). It is inferred, therefore, that a rapid, alongshore (equatorward) redistribution of detritus by the SWM alongshore currents had led to a large-scale sequestration of the local fluvial fluxes over the shallow region of the shelf. Our inference is in line with that of Liu et al. (2009) and it underscores a significant role of wind induced hydrography for a stronger coastal sequestration of fluvial flux over the shallower shelf. Apparently, such a process was unfavorable for the across-shelf advection of suspended particulate matter debouched by the local rivers, and therefore the deeper region of the shelf received an insignificant amount of TSM during the peak fluvial discharge period of the SWM (Fig. 2). This inference, therefore, does not endorse a coupling between fluvial discharge and detritus supply into the deeper region (Nair et al., 1989; Haake et al., 1993; Rixen et al., 2009).

Because of the prevailing onshore winds and the alongshore current regime during the SWM, illite and kaolinite found in the load of local rivers had not been carried into the outer shelf. Smectite had not been found in the load of the local rivers (Table 1), but it occurred over the outer shelf. It is therefore inferred that the source of the clays over the outer shelf is non-local. Because smectite had an equatorward advection during the SWM (Fig. 9), the source of this clay shall be located poleward to our study area. Poleward to our study area, there exists a massive volcanic formation known as Deccan Traps (area 1.5 million km²; www.wikipedia.org/wiki/Deccan_Traps). In order to affirm the supply of smectite from this source, we sampled three rivers that had catchment area in the Deccan Traps (Table 2). We found occurrence of smectite in the load of all these rivers. We estimated clays at few offshore locations off the Deccan Traps that were located also in the pathways of the ASW (Fig. 1; Table 2). Smectite was found at all these locations (Table 2). Besides, illite and kaolinite were found also at these stations. This implied that a clay assemblage of smectite, illite and kaolinite-similar to one found over the outer shelf, was carried in the ASW. The currents during the SWM were equatorward (Fig. 3). These coastal currents were known to carry high salinity in the ASW along the southwestern continental margin of India (Vinaychandran et al., 1999). Derived from the
similarity in clay assemblage and that from their advection direction, it is construed that the ASW contributed smectite, illite and kaolinite into the outer shelf during the SWM.

Over the outer shelf, the advection magnitude of smectite, illite, kaolinite and palygorskite was found to be much reduced compared to that found over the inner shelf (Figs. 6, 9). A low advection magnitude may be attributed to the prevailing alongshore currents. Such currents aided a large-scale sequestration of TSM over the inner shelf and these curtailed supply of local clays into the deeper region of the sea. We therefore surmised that the outer shelf had not been a preferred depo-center of local fluvial flux due to a lack of across-shelf advection, and it received detritus carried by the summer coastal currents. The contribution from the non-local source was evident further from the occurrence of palygorskite, a clay not carried in the fluvial load nor was it present in the soil samples of India because it forms under semi-arid, hot, climate with changing ground water level (Sirocko and Lange, 1991; Sirocko et al., 1991). Such a climate with changing ground water level, however, does prevail in the Sebka and the Wadi regions of the Arabia. Besides, Mesozoic rocks in the Somalia have this clay, and these regions are deemed to be the major source of palygorskite (Chauhan, 1996 and references therein). Between the Red Sea and the Persian Gulf, the Arabian northwesterly winds prevail throughout the year, and these have very high aerosol content (3000 µg m⁻³; Sirocko et al., 1991). The clay minerals found in the aerosol dust were illite, smectite and palygorskite (Tomadin et al., 1989). The deposition of a significant amount of such aerosol over the northern Arabian Sea had been archived by way of these winds (Sirocko et al., 1991; Banerjee and Kumar, 2014). The specific occurrence of this clay over our study area had therefore been linked with the aeolian supply from the eastern Arabian Sea. Further support to our inferences had been found in the satellite imageries that had archived the advection of the Arabian dust into the southwestern continental margin of India by the northwesterly winds (Chauhan, 1996 and references therein).

4.2 Post southwest monsoon

Upon the termination of the SWM, the front of the turbid waters shrunk closer to the coast (Fig. 2). Such a trend led us to infer that the fluvial supply into the sea dwindled rather rapidly upon the cessation of the SWM precipitation in the hinterland. This appeared plausible considering the hilly terrain, the high gradient and the short length of the rivers of the Western Ghats (Table 1). As explained earlier, these characteristics had sustained a vigorous riverine flow and that had carried the meteoritic water from the hinterland into the sea rather rapidly. It implied that the meteoritic water stayed for a very short time in the hinterland. The clay mineral data sustained this inference. After the termination of the SWM, the clays found in the sea-water over the shallower region of the inner
shelf were kaolinite, illite and gibbsite - similar to the clay assemblage found in the load of the local rivers. In conjunction with TSM distribution, such data further endorsed a strong coupling between the magnitudes of local supply of terrigenous matter by way of the fluvial route with that of the SWM rains in the hinterland. Over the outer-shelf, in contrast, illite and smectite were predominant clays though gibbsite was not found in any sample (Figs. 4-6). In addition, chlorite was found also on the southern region of the study area. From the conspicuous absence of gibbsite, it may be deduced that across-shelf advection was absent year round. Upon the termination of the SWM, the winds and the hydrographic currents reversed (Figs. 3, 8). Although the winds were milder during the post SWM, moderate to strong poleward currents prevailed in the study area (Fig. 3). A reduced influx of detritus into the shelf together with an alongshore hydrography appeared to have remained unfavorable for any across-shelf advection of the local terrigenous flux.

Advection direction of smectite was found to be poleward during the post SWM (Fig. 9). Because of its equatorward advection during the SWM (Fig. 9), we had mooted that the main source of this clay was from the Deccan Traps. However, upon the cessation of the SWM, the regional currents had reversed (Fig. 3). Our study area is located south of the Deccan Traps and the poleward current flowed toward this source. Smectite had therefore not been contributed from the Deccan Traps after the termination of the SWM. Smectite and illite had been found in aerosol dust emanating from the Arabia-Somalia, and these winds were known to prevail round the year (Tomadin et al., 1989). However, a sizable contribution from this source alone over the entire outer-shelf appears not plausible, specifically when the palygorskite is a minor clay in our study area, and it is conspicuous by its absence during the post monsoon season (Fig. 6). As described earlier, the supply of smectite from the hinterland appeared unlikely because of the geological setting of the Western Ghats. Besides, it was not found over the entire inner shelf. This had led us to look for some other non-local source. We had relied upon the distribution trend of other non-local clay. Chlorite had not been found during the SWM over the entire shelf (Fig. 6). It was not found in the load of the ASW also. Therefore, it had not been supplied through the equatorward coastal currents carrying the ASW. Nor had it occurred in the soil and that in the load of any river along the southwestern continental margin (Chauhan and Gujar, 1996; Deepthy and Balakrishnan, 2002; Chauhan et al., 2010 and reference therein). Chlorite forms under arid, cold climate. The absence of chlorite in the local fluvial load (Table 1) may be linked with prevalent tropical, humid climate of the region, which is not suitable for the formation of this clay (Weaver, 1989). In the northern Indian Ocean, the source of this clay lies mostly in the rivers that have major catchment area in the Himalayas (Konta, 1985; Chauhan et al., 2005). The River Indus has a major catchment area in the Himalayas, but the contribution of
chlorite from this source appears implausible because of the prevalent poleward circulation. The other source of this clay lies in the Ganga-Brahmaputra Rivers that have major catchment in the Himalayas. These rivers discharge a large amount of detritus (about 2000 m tones) annually into the Bay of Bengal (Chauhan et al., 2005). Studies had reported advection of low salinity in the BBW along the southern region of the southwestern continental margin of India by way of the winter hydrographic currents prevalent during November through January (Chauhan and Gujar, 1996; Kumar et al., 2004 and reference therein). In order to affirm a contribution from this source, an estimation of the clay load of the BBW at different locations over the Bay of Bengal and that over the Arabian Sea (which lies in the advection path of BBW) was made (Table 2). We found illite, smectite and chlorite (with minor kaolinite) in the load of the BBW over all the stations of the Bay of Bengal (Table 2). Our study area had similar clay assemblage during the post monsoon season, and these clays had a poleward advection (Figs.6, 9). Derived from the similarity in the clay mineral assemblage and that from the advection direction of these clays, it is construed that the supply of illite, smectite and chlorite is through the winter poleward currents (Fig. 3) that carried the low salinity BBW along the southeastern Arabian Sea (Kumar et al., 2004).

We concluded that: (a) barring the shallow regions of the shelf, this study did not find any coupling between the magnitude of fluvial influx and that of the TSM flux into the deeper regions of the southeastern Arabian Sea; (b) the strong alongshore currents induced by the SWM winds had sustained the merging and the expansion of the fluvial plumes, and that had led to sequestration of the local fluvial flux over the shallow region; (c) beside the aeolian supply, the deeper region of the shelf received detritus carried mostly in the ASW and that in the BBW; (d) the nutrient rich BBW is known to have enhanced productivity in its pathways, and its advection along the southwestern continental margin may have implication for sustaining productivity after the termination of the nutrient supply from the upwelling upon the cessation of the SWM.

Our study contributes towards a better understanding of the role of monsoon climatology on biogeochemical cycle and for the reconstruction of monsoon. Studies (Schulz et al., 1996; von Rad et al., 1999) have derived precipitation intensity vis-a-vis fluvial discharge from the magnitude of detritus supply. We propose that sequestration of detritus is not linearly related with that of the magnitude of supply from a single source. Our inferences are in agreement with that of Kumar et al. (2002). Our data advocate much stronger control of the SWM winds and the hydrographic processes over the sequestration of detritus. However, similar to the inference of Lukage et al. (2012), we endorse a strong coupling between marine productivity and the supply of nutrients from continental fluxes.
Acknowledgement.

We thank Director NIO for providing facilities. We are grateful to Indian coast guard for their help during the collection of samples. We thank G. Prabhu for help in the clay mineral analysis. We acknowledge funding from ISRO–SAC, and ISRO-IGBP for TSM and clay mineral data collection and their analysis. We thank Dr. John T. Well and an anonymous referee for their critical and constructive review that brought improvement to the science in the manuscript. This is contribution no xxxx.

References


Fig. 1. Study area with sample location of the Bay of Bengal and the Arabian Sea. The mouths of the River Indus and the River Ganga-Brahmaputra are shown. BBW in the inset figure denotes the Low salinity the Bay of Bengal water (winter hydrographic coastal current), and ASW denotes the high salinity the Arabian Sea Water (summer hydrographic coastal current). A color version is available on the web.
Fig. 2. Total detrital suspended matter (TSM) and detrital clay (DC) distribution in the study area during the SWM and the post monsoon season. Note a conspicuous enrichment of the TSM and DC in the shallow region during the SWM. A color version is available on the web.
Fig. 3. Seasonal variations in the surface currents in the study area. A color version is available on the web.
Fig. 4. Spatiotemporal distribution in gibbsite and kaolinite in the study area. A color version is available on the web.
Fig. 5. Spatiotemporal distribution of illite and smectite in the study area. A color version is available on the web.
Fig. 6. Distribution and advection rates of chlorite and palygorskite in the study area. A color version is available on the web.
Fig. 7. Seasonal salinity and temperature variability in the study area. Note uniform and low salinity during the SWM in the shallow region. A color version is available on the web.
Fig. 8. Seasonal variations in the winds along the southeastern Arabian Sea.
Fig. 9. Seasonal variability of advection rates of (A) gibbsite (B) kaolinite (C) illite and (D) smectite. A colour version is available on web.
Table 1. Characteristics of the rivers and TSM abundance during the southwest monsoon and the post monsoon season. The clay minerals found in the river load during the southwest monsoon is also shown.

<table>
<thead>
<tr>
<th>River</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Catchment area (km²)</th>
<th>Gradient</th>
<th>Altitude of origin (m)</th>
<th>Length (km)</th>
<th>Clay Minerals (wt %)</th>
<th>TSM (mg/l) SW PM</th>
</tr>
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<tbody>
<tr>
<td>Kali</td>
<td>74 16 01 E</td>
<td>14 53 31 N</td>
<td>4188</td>
<td>1:255</td>
<td>600</td>
<td>153</td>
<td>65 22 13</td>
<td>138 04</td>
</tr>
<tr>
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<td>74 22 56 E</td>
<td>14 35 55 N</td>
<td>3574</td>
<td>1:217</td>
<td>700</td>
<td>152</td>
<td>61 20 19</td>
<td>145 06</td>
</tr>
<tr>
<td>Tadri</td>
<td>74 26 51 E</td>
<td>14 26 55 N</td>
<td>1330</td>
<td>1:168</td>
<td>500</td>
<td>84</td>
<td>59 24 17</td>
<td>151 07</td>
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<tr>
<td>Sharavathi</td>
<td>74 26 11 E</td>
<td>14 16 10 N</td>
<td>3592</td>
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<td>122</td>
<td>64 18 18</td>
<td>171 08</td>
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<td>Gangoli</td>
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<td>2010</td>
<td>103</td>
<td>59 19 22</td>
<td>131 04</td>
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Table 2. Clay minerals and TSM abundance data for the stations of the Bay of Bengal and in the Arabian Sea that lie in the pathways of the BBW and the ASW. Clays found in the fluvial loads of the rivers draining the Deccan Traps are also shown.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Depth</th>
<th>Clay Minerals (wt %)</th>
<th>TSM (mg/l)</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>G*</td>
<td>I*</td>
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<td></td>
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<tr>
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