CHAPTER 7

INFLUENCE OF DUST ON THE PRIMARY PRODUCTIVITY OVER THE ARABIAN SEA

7.1. Influence of dust during winter monsoon

The relation between atmospheric dust aerosols and Chl $a$ concentrations over the AS during the NEM period using satellite data and modeling is examined in this section. On an average, NEM has low dust levels in the atmosphere compared to SWM [Li and Ramanathan, 2002]. However, episodic dust storms often occur in association with the Shamal weather system [Perrone, 1979; Hubert et al., 1983] in the surrounding arid landmass. Whether any Chl $a$ response can be attributed to these episodic dust storms is explored here. The approach used here is to analyze if the oceanic supply of nutrients is adequate to support the observed levels of Chl $a$ in a region influenced by dust deposition and to provide an estimation of possible nutrients fluxes due to dust depositions. The period taken for study is NEM of 2002-2003 to 2010-2011 (total 9 NEMs).

7.1.1. Correlations between dust and chlorophyll

Over the AS, a large gradient is seen in dust and Chl $a$ concentrations (refer to Figure 2.2). Therefore, in order to study how Chl $a$ responds to dust depositions it is important to delineate a suitable region where this signature of dust depositions on Chl $a$ can be readily captured. To this end, a correlation map between $\tau_{du}$ and Chl $a$ concentration has been generated. Figure 7.1a shows the distribution of correlation between $\tau_{du}$ and Chl $a$ concentration (along with FLH) in the AS during the NEM.
Figure 7.1 (a) Spatial distribution of correlation coefficient between $\tau_{du}$ and (b) climatological mean chlorophyll $a$ (Chl $a$) concentration (mg m$^{-3}$) for the NEM of 2002-2003 to 2010-2011 over the AS. In (a) the thick white contours indicate the region having coefficient of correlation between $\tau_{du}$ and Chl $a$ greater than 0.5. The black contours show the distribution of the correlation coefficient between $\tau_{du}$ and Fluorescence Line Height (FLH). The green box outlines the region central Arabian Sea (CAS), which is considered for studying the effect of episodic dust storms on phytoplankton biomass. The dashed black box demarcates north AS (NAS) (see the text). In (b) the contours indicate the climatological distribution of $\tau_{du}$ and the vectors represent the current (in m s$^{-1}$) during the same period.
The $\tau_{du}$ showed high positive correlation with both Chl $a$ (mean value 0.45) and FLH (mean value 0.40) in the central AS (CAS) during NEM period, while the patch of high correlation between $\tau_{du}$ and Chl $a$ extended further north. However, in the north the correlation between $\tau_{du}$ and FLH was not very high leading to the conclusion that suspended particulate matters probably led to a pseudo correlation. Rest of the AS had little or negative correlation. Though the coastal regions of the AS also showed high positive correlation, for the present study only the open ocean region is considered. This is because: coastal waters usually have high concentrations of nutrients and hence difficult to delineate the signature of atmospheric input and also because retrieval of Chl $a$ in coastal waters is a challenge because of the presence of organic matters and suspended particulate matters. Thus, CAS is identified as the open ocean region (having average depth ~4km) where dust has the greatest potential of triggering Chl $a$ enhancements. However, CAS had comparatively lower value of $\tau_{du}$ which was about 0.02 (SD 0.01) (see the contours in Figure 7.1b). In contrast, northern, northeastern and western AS had higher values of $\tau_{du}$ but very low or negative correlation coefficient with both Chl $a$ and FLH. For instance, the northern AS (NAS, defined as 61-66°E, 20-24°N) had mean $\tau_{du}$ of 0.04 (SD 0.01) and correlation coefficient of -0.17. The climatological NEM average Chl $a$ values in NAS and CAS are about 2.0 mg m$^{-3}$ (SD 0.55) and 0.3 mg m$^{-3}$ (SD 0.08) respectively (Figure 7.1b). The maximum Chl $a$ values attained at the peak of the bloom based on 3-day mean climatology during NEM are ~5.0 mg m$^{-3}$ and ~0.4 mg m$^{-3}$ respectively. Such a north-south gradient in Chl $a$ concentrations can be elucidated by the behaviour of the mixed layer (see Figure 7.2), which is a proxy for the intensity of winter convection. The magnitude of the deepest mixed layer attained in NAS at the peak of NEM (end of January to beginning of February) is more than 100m (deepest MLD from Argo was ~122m). However, the influence of winter mixing, although present, somewhat dwindles
towards the south. The deepest Argo-derived MLDs in CAS usually cluster around 80 m. Average MLD from Argo during January is 89 m in NAS against 67 m in CAS. Clearly, the deeper penetration of mixing which leads to injection of more nutrients from the subsurface supports the high value of Chl a in NAS. The reported NO₃ concentration at the surface is more than 3.0 µM in the NAS in contrast to ~ 2.0 µM NO₃ in CAS [Madhupratap et al., 1996; Morrison et al., 1998. This is further corroborated by Figure 7.3. The SST increases from 24.5°C in NAS to 26.6°C in CAS, while NO₃ obtained from WOA09, decreases from 2.4 µM in NAS to 0.7 µM in CAS. Note that the NO₃ values from WOA09 are climatological mean for the NEM, while the values of Madhupratap et al. [1996] and Morrison et al., [1998] are spot measurements at the peak of NEM of 1995.

**Figure 7.2** Climatological (2002-3003 to 2010-2011) mixed layer depth (MLD) during the NEM time for NAS (upper panel) and CAS (lower panel). The blue squares are the MLD calculated from Argo data to which a third order polynomial curve was fitted for NAS and a second order polynomial curve was fitted for CAS as indicated by the blue curves. Daily climatology of modeled MLD is shown by the black lines.
7.1.2. Simulated episodic dust depositions

Episodic dust storms during NEM which might influence the region marked from the correlation map (in Figure 7.1a) were identified from NASA Natural Hazards website (http://earthobservatory.nasa.gov/NaturalHazards/) for the study period. Further, the near real time MODIS imageries (http://rapidfire.sci.gsfc.nasa.gov/realtim) were examined to see the signature of any dust haze over the AS. There were in total 45 dust storms with about 2 to 9 dust storms every year between the NEMs of 2002-2003 to 2010-2011 that had the potential of influencing the Chl $a$ in the region. These dust storms either sent off plumes over the AS or much less obvious haze (which is more difficult to identify). The total (wet+dry) dust depositions following each of the episodic dust storms were examined using the results from RegCM4 dust storm simulations. Results are shown in Figure 7.4 for some specific dust storms. High values of dust depositions near the dust sources (similar to that of the distribution of $\tau_{dl}$)
was seen which was common for all other dust storms. The magnitudes, however, showed a large variation from event to event (see also Table 7.1). For example, dust deposition within CAS varied by about an order of magnitude ranging from ~10 mg m$^{-2}$ to more than 150 mg m$^{-2}$. Spatially the dust deposition decreased significantly from northwest AS towards CAS. Total dust depositions is about one order of magnitude higher over NAS (more than 1000 mg m$^{-2}$) compared to CAS (less than 100 mg/m$^{2}$). Comparing the values with those derived from sediment trap, dust depositions ranges from 33 mg m$^{-2}$ day$^{-1}$ at around 17° N to 4 mg m$^{-2}$ day$^{-1}$ at 10° N [Clemens, 1998]. The predominant (more than 90%) size fraction of the deposited dust in CAS were between 0.01 and 1 µm (fine mode fraction). Most of the medium to small-sized events were responsible for wet depositions, which varied between 0.1 to 72 %. This has important implications for the bio-availability of Fe as cloud processing of the Fe during wet processes increases the solubility of Fe [see example Duce and Tindale, 1991]. Table 7.1 lists the dust depositions following some of the dust storms.

A comparison of the model simulated $\tau_{du}$ with that of remotely sensed data from MODIS/Aqua showed that while the model could successfully reproduce the spatial and temporal pattern of $\tau_{du}$, there is general underestimation with respect to dust storms, which have values of $\tau_{du}$ that are well above 1(Figure 7.4). The extent of underestimation becomes larger towards the southern part of AS. However, in the immediate vicinity of the dust sources the model overestimates. It is important to note that satellite measured $\tau_{du}$ captures a snapshot of aerosol each day, while the model is forced by 6-hourly wind. Nonetheless, the underestimations in $\tau_{du}$ for some of the highest dust storms are expected to reflect in the dust depositions and the calculations of the possible amount of nutrients that can be derived from dust.
Figure 7.4 Simulated dust depositions (mg m$^{-2}$) for the episodic dust storms using RegCM4 model. The black contours indicate the difference between $\tau_{du}$ sensed from MODIS/Aqua and model simulation. The value of the thick contour is 0. All contour intervals are 0.1. Continuous contours indicate positive difference and dashed contours indicate negative difference. The white square indicates the study region CAS.
Table 7.1 Estimated dust deposition in the CAS following dust storms and the possible amount of nutrients that can be derived from dust.

<table>
<thead>
<tr>
<th>Episode number</th>
<th>* Dust storm detected by satellite</th>
<th>Total dust deposition (mg/m²)</th>
<th>Wet deposition (%)</th>
<th>MLD during dust storm (m)</th>
<th>NO₃ supplied (nM)</th>
<th>PO₄ supplied (pM)</th>
<th>‡DFe supplied (1%)</th>
<th>‡DFe supplied (10%)</th>
<th>‡DFe supplied (50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>12-14 Dec 2003</td>
<td>50</td>
<td>38.0</td>
<td>49</td>
<td>0.32</td>
<td>3.2</td>
<td>0.01</td>
<td>0.10</td>
<td>0.34</td>
</tr>
<tr>
<td>E2</td>
<td>09 Feb 2004</td>
<td>5</td>
<td>10.0</td>
<td>59</td>
<td>0.03</td>
<td>0.3</td>
<td>0.001</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>E3</td>
<td>04 Jan 2007</td>
<td>23</td>
<td>72.0</td>
<td>58</td>
<td>0.13</td>
<td>1.3</td>
<td>0.003</td>
<td>0.03</td>
<td>0.13</td>
</tr>
<tr>
<td>E4</td>
<td>01-03 Dec 2007</td>
<td>9</td>
<td>30.0</td>
<td>35</td>
<td>0.08</td>
<td>0.8</td>
<td>0.001</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td>E5</td>
<td>06-07 Jan 2008</td>
<td>5</td>
<td>8.0</td>
<td>50</td>
<td>0.03</td>
<td>0.3</td>
<td>0.001</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>E6</td>
<td>02-05 Feb 2008</td>
<td>161</td>
<td>25.0</td>
<td>56</td>
<td>0.91</td>
<td>9.1</td>
<td>0.02</td>
<td>0.20</td>
<td>1.0</td>
</tr>
<tr>
<td>E7</td>
<td>22-23 Feb 2008</td>
<td>12</td>
<td>0.4</td>
<td>45</td>
<td>0.08</td>
<td>0.8</td>
<td>0.002</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>E8</td>
<td>14-15 Mar 2008</td>
<td>12</td>
<td>0.1</td>
<td>22</td>
<td>0.17</td>
<td>1.7</td>
<td>0.003</td>
<td>0.04</td>
<td>0.18</td>
</tr>
</tbody>
</table>

* The episode dates are given based on satellite detection of the dust storms. It may take few days for the plume to reach CAS. ‡ Unit of DFe is in nM obtained after considering the dust deposition normalized within the mixed layer. DFe (1%), (10%) and (50%) refers to the fraction of Fe in the dust that is soluble.

7.1.3. Enhancements of chlorophyll a following episodic dust storms in the central Arabian Sea

Time-series of 3-day composite Chl a concentrations were examined within CAS for significant increases in Chl a above the background values as well as for the construction of 3-day climatology. The 3-day windows coinciding with the dust storms were discarded to avoid satellite overestimation of Chl a concentrations immediately following the dust storms. During the time period under study, 8 episodes of Chl a enhancements following the passage of dust storms were discerned (Figure 7.5) when the average Chl a enhanced 2 to 4 times the background values in CAS. The criterion chosen to identify the Chl a enhancements was that it should be more than 2 SD of the climatological values. These 8 cases were further segregated according to different phases of the mixed layer evolution (Figure 7.6 and Table 7.2). The Chl a enhancements during E1 (episode 1) was associated with mature phase of winter convection. E4
and E5 were in the early part of winter convection when the mixed layer was in the deepening phase as inferred from the PWP model. Conversely, the Chl $a$ enhancements during E1, E3, E6 and E7 were associated with the shallowing phase of the winter convection. The high Chl $a$ episode during E8 took place following the cessation of winter convection when MLD was around 22 m.

Figure 7.5 Time-series of 3-day averaged chlorophyll $a$ (Chl $a$) concentration (mg m$^{-3}$) and mixed layer depth (MLD) in central Arabian Sea (CAS) region for the winter monsoon of 2002-2003 to 2010-2011. The green dashed line shows the 3-day Chl $a$ climatology and the vertical lines represent their 2 standard deviations; the red squares are the Chl $a$ concentrations for each corresponding year; the blue line is the MLD; the black squares indicate the windows when dust storms were observed by satellite around CAS and the hollow black rectangles indicate the cases of Chl $a$ enhancement when Chl $a$ exceeded 2 SD level. The numbers on the top of the rectangles indicate the episode numbers which are referred in the text as E1, E2 and so on.
Figure 7.6 Schematic representation of the time evolution of mixed layer in the Arabian Sea during the northeast monsoon and its association with the episodic chlorophyll enhancements. E1 to E8 indicates the numbers of the episodes of chlorophyll enhancements.

Table 7.2 Nutrient requirements for the observed surface Chl a enhancements in CAS.

<table>
<thead>
<tr>
<th>Episode Number</th>
<th>Period of the bloom</th>
<th>Maximum Chl a during bloom (mg/m³)</th>
<th>MLD during bloom (m)</th>
<th>Total N (C:N:P=106:16:1)</th>
<th>PO₄ (Fe:C=7.5)</th>
<th>DFe (Fe:C=12.8)</th>
<th>DFe (Fe:C=33.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>28 Dec 2003-07 Feb 2004</td>
<td>1.40</td>
<td>56 (MP)</td>
<td>3.29</td>
<td>0.20</td>
<td>0.28</td>
<td>0.74</td>
</tr>
<tr>
<td>E2</td>
<td>17 Feb -08 Mar 2004</td>
<td>1.57</td>
<td>36 (SP)</td>
<td>3.69</td>
<td>0.23</td>
<td>0.18</td>
<td>0.31</td>
</tr>
<tr>
<td>E3</td>
<td>30 Jan -04 Feb 2007</td>
<td>0.92</td>
<td>42 (SP)</td>
<td>2.16</td>
<td>0.13</td>
<td>0.11</td>
<td>0.18</td>
</tr>
<tr>
<td>E4</td>
<td>10-24 Dec 2007</td>
<td>1.20</td>
<td>38 (DP)</td>
<td>2.82</td>
<td>0.18</td>
<td>0.14</td>
<td>0.23</td>
</tr>
<tr>
<td>E5</td>
<td>15-17 Jan 2008</td>
<td>0.72</td>
<td>52 (DP)</td>
<td>1.69</td>
<td>0.11</td>
<td>0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>E6</td>
<td>20-22 Feb 2008</td>
<td>1.70</td>
<td>32 (SP)</td>
<td>3.99</td>
<td>0.25</td>
<td>0.20</td>
<td>0.34</td>
</tr>
<tr>
<td>E7</td>
<td>29 Feb-11 Mar 2008</td>
<td>2.14</td>
<td>28 (SP)</td>
<td>5.03</td>
<td>0.31</td>
<td>0.25</td>
<td>0.42</td>
</tr>
<tr>
<td>E8</td>
<td>17-19 Mar 2008</td>
<td>0.79</td>
<td>22 (NC)</td>
<td>1.85</td>
<td>0.12</td>
<td>0.09</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Units: N and PO₄ are expressed in µM; Fe/C, (µmol/mol) and DFe in nM. Note the calculated DFe value in CAS is ~0.2 nM. The cell Fe/ C quota in the phytoplankton increases with the increase in external DFe availability. MP refers to mature phase of convection-driven mixed layer deepening, SP= shallowing phase, DP=Deepening phase, NC=No convection.
7.1.4. Possible mechanisms leading to phytoplankton blooms in the central Arabian Sea

The pattern of nutrients supply to the AS is primarily governed by the physical processes that control the degree of mixing in the upper layer of the ocean. A deeper mixed layer, as encountered in the NAS, is conducive for supplying higher subsurface nutrients and therefore higher Chl $a$ concentrations. A comparatively shallow mixed layer towards the south leads to decreased nutrients supply which is responsible for the lower levels of Chl $a$. It is this set-up which makes CAS a suitable region for detecting the dust induced Chl $a$ enhancements. Although dust depositions are expected to have effect on the nutrient stocks within NAS, its effects are largely masked by the huge water column turn-over of nutrients. Dust is more efficient in feeding the phytoplankton stocks in the regions experiencing limited oceanic supply of nutrients. Thus, a low dust flux can have its imprint on the CAS phytoplankton biomass. The region south of CAS has too little oceanic nutrient inventories and/or is too remote from dust sources to have appreciable Chl $a$ levels during NEM. So, it is the crucial location of CAS, which hinges on the balance between oceanic nutrients supply and atmospheric depositions, that resulted in the positive correlation between $\tau_{du}$ and Chl $a$.

There were in total 8 cases of episodic Chl $a$ enhancements following passage of dust storms within CAS. However, whether the enhancements can indeed be attributed to atmospheric depositions has to be determined with caution. In general, three factors could lead to the Chl $a$ enhancements in the CAS during NEM: (1) advection of nutrients and/or Chl $a$ from a region of high production, (2) wind-mixing and/or winter convection and subsequent entrainment of nutrients to the upper ocean and (3) atmospheric deposition of nutrients. Over the CAS, the prevailing ocean surface current at this time of the year is weak (~0.1 m s$^{-1}$) and the general direction is from south to north as inferred from Figure 7.1b, which is not congenial for the
advection of nutrients into this region. The same direction was maintained during each of these studied episodes with some changes in magnitudes. Since the region south of CAS is low in Chl $a$ and nutrients, advection as a mechanism to support the observed high Chl $a$ in CAS can be discounted.

Next, the case of wind-mixing and/or winter convection as potential source of nutrients to the upper ocean is considered by examining the modeled MLD (Figure 7.5 and Table 7.1). Dust storms are generally associated with high wind speed (often exceeding 10 m s$^{-1}$) that can lead to greater mixing of the upper water column. Indeed, 3 out of the 8 dust storms (E1, E3 and E6) had wind speed greater than 10 m s$^{-1}$. Also the deepening of the mixed layer associated with winter convection leads to gradual build up of nutrients within this layer (see also Figure 7.3), which can potentially support the observed Chl $a$ levels. An important observation in this regard is that under dust-storm free conditions MLD has been seen to deepen (due to winter convection or high winds) without any appreciable enhancement (not presented) of Chl $a$ indicating that MLD deepening alone cannot mitigate the nutrient(s) limitation in CAS. In view of the above discussion, the requirements of different nutrients (total inorganic N, PO$_4$ and dissolved Fe) for the observed enhancements of Chl $a$ concentrations have been estimated and compared with the supply of these nutrients.

7.1.5. Requirements versus supply of nutrients

Requirements versus supply of nitrate and phosphate

Table 7.2 shows the requirements of total inorganic N, PO$_4$ and dissolved Fe for the observed levels of Chl $a$ enhancements following dust storms. For calculating requirements of N and PO$_4$, carbon: nitrogen: phosphorus (C: N: P) ratio of 106:16:1 [Redfield et al., 1963] has been
assumed and C/Chl \( a \) (µg carbon/µg Chl \( a \)) ratio of 186 obtained from in situ measurements in the AS [Takeda et al., 1995] has been considered. Comparing the values obtained in Table 7.2 with the available nutrients data during JGOFS, it is seen that at the peak of NEM the surface NO\(_3\) values within CAS ranges between ~1.0 to 3.0 µM with an average of ~2.0 µM while the total inorganic Nitrogen (NO\(_3^+\)NO\(_2^-\)+NH\(_4^+\)) can be well above 3.5 µM [Morrison et al., 1998]. Madhupratap et al. [1996] found surface NO\(_3\) less than 2.0 µM. Similarly during JGOFS PO\(_4\) has been seen to vary between 0.3 and 0.5 µM within CAS [Morrison et al., 1998]. It is seen that requirements versus the oceanic supply of inorganic N and PO\(_4\) are in the same order of magnitude given the uncertainties involved and hence can be concluded that inorganic N and PO\(_4\) were likely not limiting at the time of the dust storms. Although levels of nutrients residing in the mixed layer can vary from year to year, several studies [example Prasanna Kumar et al., 2001] have shown that it is the depth of mixing dictated by the intensity of winter convection that exerts the first order influence on the replenishment of nutrients. The MLD and SST during the times when inorganic N and PO\(_4\) data were retrieved have been compared with the present episodes leading to the conclusion that there is broad similarity in the intensity of winter convection between these years.

An examination of the dust sample collected on 10\(^{th}\) April 2013 using high volume sampler at a station in Goa, along the west coast of India, during a dust storm event yielded a NO\(_3\) concentration of ~20 mg g\(^{-1}\) of dust (V. Ramaswamy personal communications, 2014). Note that Milli-Q water was used to extract NO\(_3\) from dust. This when compared to the dust depositions and the depth of mixing within the water column gives an insignificant increase in NO\(_3\). This is in agreement with the conclusion drawn by Singh et al. [2012] regarding dust aerosol being a limited source of nitrogen and contributing to just 1.2 % of the new production in the AS during

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NEM. However, in the case of E7, the requirement of N (~5 µM) at the peak of the bloom significantly exceeds that of the estimated instantaneous oceanic supply, indicating that the requirement was likely met from N build up during initial stage of the bloom when the phytoplankton biomass was comparatively low. Similarly, PO$_4$ concentration was about 0.2 mg g$^{-1}$ of dust, which also results in negligible contribution to the water column. Thus, based on the climatological concentrations of inorganic N (including NO$_3$) and PO$_4$ in the water column and the amount of new nutrients that can be derived from dust, it can be concluded that the main source of N and PO$_4$ for these episodes of phytoplankton blooms is the water column. In fact, the climatological concentrations of inorganic N and PO$_4$ at the peak of NEM should be able to support Chl $a$ levels of ~1.0 mg m$^{-3}$. However, the climatological Chl $a$ concentration is about 0.4 mg m$^{-3}$. JGOFS, Landry et al. [1998] noted that without any nutrient addition, average phytoplankton growth rate ($0.5$ day$^{-1}$) balances the average grazing mortality rate ($0.6$ day$^{-1}$) in CAS. However, in case of addition of nutrients, the average growth rate becomes $1.2$ day$^{-1}$. Also, Goericke [2002] proposed that high grazing rate in the AS likely led to accumulation of excess nutrients in the surface waters. During Here, the possibility of any other nutrient likely limiting Chl $a$ concentrations in the AS is explored.

**Requirements versus supply of dissolved iron**

It is clear from the previous section that the supply of a nutrient other than N and PO$_4$ must have played an important role in episodically enhancing the phytoplankton stocks. Because dust is an important source of Fe it brings forth an interesting possibility that the region might be experiencing some Fe limitation and Fe from episodic dust storms might be leading to the observed episodic Chl $a$ enhancements. The main function of iron in the phytoplankton is its role as a catalyst in photosynthesis [Geider and La Roche, 1994]. In Fe limited environments, an
increase in the external supply of dissolved Fe (DFe) will lead to enhanced DFe uptake and specific growth rate. For example, for the oceanic diatom *Thalassiosira oceanica*, an increase in external DFe from 10.6 to 760 pM increases Fe/C ratio (µmol mol\(^{-1}\)) from 4.9 to 33.9 [Sunda and Huntsman, 1995]. A range of cell Fe/C ratios have been considered to study the DFe requirements under different conditions of availability of DFe and the implied sensitivities: (1) A mean value of 7.5 over the AS based on modelling by Moore *et al.*[2002], (2) based on apparent oxygen utilization, Sunda [1997] arrived at a Fe/C ratio of 12.8 for North Atlantic Ocean during the spring bloom time when primary productivity ranges from 71.3 to 91.1 mmol C m\(^{-2}\) day\(^{-1}\) [Martin *et al.*, 1993] and (3) a ratio of 33.9 indicator of the highest possible DFe requirements based on laboratory experiments [Sunda and Huntsman, 1995]. Based on the above 3 cell Fe/C ratios (namely 7.5, 12.8 and 33.9) the results for the calculation of DFe requirements are shown in Table7. 2.

Much care is needed in order to ascertain the supply side of DFe. Few sets of *in situ* DFe (defined as Fe that can pass through 0.2 µm filter) measurements exist in the AS during the NEM: (1) surface sampling along 65°E meridional transect and a profile at 15°N by Takeda *et al.* [1995] during end of December, 1992 to beginning of January, 1993 (2) along US JGOFS track by Measures and Vink [1999] during January-February, 1995 as a part of US JGOFS Arabian Sea Process Studies and (3) recently, as a part of the GEOTRACES program, DFe was measured roughly along 69°E, to the east of the present study region during the NEM of 2009 [Nishioka *et al.*, 2013; Vu and Sohrin, 2013]. Two important observations emerge from these studies: (1) a general increase in the DFe concentrations from south to north and (2) within CAS, the ferricline lies at a depth deeper than the nitracline with the difference between the two about 25m. So while the MLD attained at the peak of the NEM can erode the top of the nitracline, it may not be
able to erode the top of the ferricline within CAS. However, within NAS, both nitracline and ferricline can be eroded by the deep mixing under winter convection. This mismatch between the depth of nitracline and ferricline probably has the potential of turning CAS into a Fe-limited region. Being surrounded by dust sources AS receives mineral dust flux throughout the year. Hence, it is first needed to ascertain just the oceanic supply of DFe to see whether the episodic Chl $a$ enhancements in CAS can be supported by DFe supplied from the water column alone. For this, the entrainment of DFe with the progress of NEM has been calculated using the profile of Takeda et al. [1995] with the assumption that the values reflect the ambient concentrations. This enables to account for the entrainment of DFe with the deepening of mixed layer. The rationale for this assumption is that the DFe values of Takeda et al. [1995] is measured earlier in the NEM period compared to Measures and Vink [1999] and the values are significantly lower (mean DFe $\sim 0.3$ nM) compared to those collected by the latter ($\sim 1$ nM). While there are several uncertainties associated with this method, in the absence of more in situ DFe measurements, it might be a convenient starting point to understand how oceanic DFe supply is regulated.

The surface DFe values measured by Takeda et al. [1995] ranges between 0.15 nM (at $12^\circ30'N$ lying within CAS) to 0.47 nM (at $17^\circ30'N$) and at $15^\circN$ it is 0.23 nM. The MLD during the study by Takeda et al. [1995] at $15^\circN$ was around 50m. With the progress of NEM, the deepening of MLD to about 80m within CAS entrains DFe to the surface waters. For an 80m deep MLD, it is estimated that the winter entrainment process results in the mixed layer DFe concentration of about 0.33 nM. This value matches with those from GEOTRACES cruise data collected to the east of the study region with reported value of DFe of 0.35 nM and MLD of around 70m. The available DFe within CAS can be expected to be lower than the above calculated value since the region is situated more south of the location where the DFe profile was collected. The surface
DFe value within CAS is almost 1.5 times less than the surface DFe value at 15°N where the DFe profile has been taken. Accordingly, scaling the DFe value obtained due to winter entrainment at 15°N, the DFe within CAS due to winter entrainment comes to ~0.2 nM. On comparing this value with the DFe requirements estimated from the Fe/C ratios (Table 7.2), it is seen that at Fe/C ratio of 7.5 the entire requirements can be met from the water column for all the cases of Chl \( a \) enhancements except E7. However, as the Fe/C ratio shifts to higher values, the water column DFe supply becomes increasingly insufficient. For Fe/C ratio of 12.8, episodes E1, E2, E4, E6 and E7 would require an external source of DFe. At Fe/C ratio 33.9, all of the episodic phytoplankton blooms would require external DFe. However, the ratio of 33.9 (mainly applicable for diatoms) is only a theoretical assumption in this case and is highly unlikely as CAS is primarily dominated by Picoplankton.

Next, an aeolian source of DFe is considered. About 3.5% Fe content in the soil dust [Taylor and McLennan, 1985] have been assumed. As mentioned earlier, dust deposition within CAS is primarily dominated by fine mode fraction. Upon being deposited on the ocean surface a certain fraction of Fe in the dust is instantaneously dissolved followed by a much longer time dissolution of Fe (ranging from hours to weeks) [Mackie et al., 2006; Boyd et al., 2010]. It has been reported that during May when air masses over the AS comes mainly from the Middle East, thereby enriched with crustal materials, the fraction of labile Fe (II) to total Fe in the fine mode fraction of the aerosol (< 3.0 µm) varies from less than 1% to around 8% [Seifert et al., 1999]. This includes both the instantaneous and the long term soluble Fe fraction. It has also been seen that with increasing distance from land the fraction of labile Fe (II) in the total aerosol can be ~50% [example Zhuang et al., 1992]. By considering DFe constituting 1% (DFe\(_{1\%}\)), 10% (DFe\(_{10\%}\)) and 50% (DFe\(_{50\%}\)) of the total Fe in dust we have calculated the probable ranges of atmospheric
supply of DFe during these episodic events. Based on this, Table 7.1 shows the total amounts of DFe that can be extracted following dust depositions. Note, at this point it has been noticed that considerable underestimation of $\tau_{\text{du}}$ for episodes E1, E6 and E7 (where the $\tau_{\text{du}}$ value exceed 1) which will impact the dust deposited and the amount of DFe that can be possibly derived. A comparison of the possible scenarios when total DFe (dust-derived + oceanic supply) can meet the Chl $a$ requirements is depicted in the form of a matrix in Figure 7.7. Maximum cases of Chl $a$ enhancements are supported at Fe/C ratio of 12.8 along with DFe$_{10\%}$ and DFe$_{50\%}$ (a scenario that is not quite likely). At Fe/C ratio of 7.5, demand for DFe is entirely met from the water column inventory, while at the extreme Fe/C ratio of 33.9 the demand for DFe is too high even at DFe$_{50\%}$ (an extreme that is also highly unlikely). It is quite possible that Chl $a$ during E7 and E8 are likely to draw DFe not only from the immediate dust storm event, but also from previous events as there were continuous pulses of dust depositions during this year (that is NEM of 2007-2008) which would lead to slow build up of DFe within the surface mixed layer. In case of the dust deposition events which are accompanied by significant wet depositions (E1, E3, E4 and E6), the likelihood of bio-availability of Fe increases even for small deposition fluxes. Based on the above calculations in the matrix that highlight the different requirement versus supply scenarios, it can be concluded that the phytoplankton blooms related to episodes E1, E4, E6 and E7 are likely fuelled by dust derived DFe when the Fe/C ratio is 12.8 and about 10% of Fe in dust is dissolved (DFe$_{10\%}$). For episode E2, although the requirement of DFe cannot be met by the water column, the calculation implies that dust can support the bloom provided the fraction of Fe that is soluble in dust is much greater than 10%. This in its entirety is conceptualized in Figure 7.8, which shows how the degree of oceanic mixing sets the stage for atmospheric deposition to alter
the biogeochemistry of the region. Following addition of DFe during dust storms there can be multiplication of large sized phytoplankton leading to a bloom condition.

**Figure 7.7** Matrix showing the possible scenarios when observed phytoplankton bloom can be ascribed to be driven by dust depositions and oceanic supply of DFe under varying Fe dissolution threshold and Fe/C ratio. The episodes listed in black are entirely supported by oceanic DFe. The episodes listed in red need an atmospheric source of DFe. The episodes that have not been listed are the ones which cannot be supported even with the atmospheric and oceanic sources of DFe taken together.
Figure 7.8 Schematic diagram showing the mechanism leading to chlorophyll $a$ enhancement in the central Arabian Sea following dust storms during the northeast monsoons (see text for explanation).

The episodic Chl $a$ enhancements took place after a time lag, which varied from 1 to 10 days following the passage of the dust storms (see Table 7.1 and 7.2) and 20 days in case of E3. It is important to note that once a dust-storm is detected by a satellite it may take a day or two or at time up to five days for the storm to travel to CAS. Time lags of 1-2 days [Singh et al., 2008] to 5-6 days [Bishop et al., 2002] have been reported elsewhere. The observed magnitude and timing of Chl $a$ enhancements following the dust storms should match with the time required for Fe dissolution plus the time required for phytoplankton growth to take place. The time scale for dissolution of Fe ranges from hours to weeks depending on the mechanism involved [see Boyd et al., 2010 and references therein]. For example, dissolution of Fe by photolysis of colloidal
ferrihydrite takes hours [Barbeau and Moffett, 2000]; while flagellate mediated phagotrophy can solubilize Fe within a time period of 2 to 10 days [Nodwell and Price, 2001].

Thus, from the above discussion it is evident that the possibility of an atmospheric supply driving the episodic blooms depends on the amount of DFe that can be extracted from the dust depositions and the assumed Fe/C ratios. Although CAS shows a positive correlation between $\tau_{du}$ and Chl $a$, dust depositions actually leading to phytoplankton blooms has to be dealt with caution as several factors like amount of dust deposition, DFe that can actually be extracted, the MLD and availability of other nutrients come into play. However, the important point remains that although all dust storms are not followed by phytoplankton blooms, these blooms are detected only following dust storms. In the absence of dust storms, even high winds do not lead to blooms indicating nutrient deficiency in the system. This probably arises because the top of the nitracline is shallower than the ferricline. The estimates of dust-derived DFe given by here are only indicative. With the availability of more DFe data from this region, the ranges of DFe that can be supplied by dust can be narrowed down.

7.1.6. Significance of dust deposition related to community structure of the Arabian Sea

The AS as a whole undergoes a steady transition from a stratified oligotrophic system to a highly productive system characterized by deep mixing with the onset of NEM. Such transition is usually accompanied by community succession: from Picoautotrophs to larger size Microautotrophs, especially Diatoms and Dinoflagellates [Garrison et al., 2000]. However, southwards, within the nutrient-depleted CAS the autotrophic biomass is mainly dominated by Picoplankton followed by Nanoplankton [Garrison et al., 2000]. This north-south distinction in the autotrophic community is also reflected in the grazers consisting of mainly heterotrophic
bacteria indicative of microbial food web within CAS. In contrast, Mesozooplankton makes up much of the food web in the productive parts of AS [Smith and Madhupratap, 2005]. Without any nutrient addition the growth rate (~0.4 d\(^{-1}\)) of the autotrophs within CAS matches the grazing rate (~0.5 d\(^{-1}\)) [Landry et al., 1998]. It has been estimated that grazing accounts for consumption of 29% of the Chl \(\text{a}\) [Caron and Dennett, 1999] within the CAS region. If this amount is added to the levels of Chl \(\text{a}\) sensed by satellites, then the actual requirement for nutrients become even larger. Takeda et al. [1995] has demonstrated that phytoplankton in AS achieved a mean growth rate (d\(^{-1}\)) of 0.6 following addition of NO\(_3\) and Fe, in spite of not screening out the grazers. The increase in phytoplankton biomass in their experiment was accompanied by predominance of diatoms leading to the conclusion that phytoplankton growth is co-limited by NO\(_3\) and Fe, at least in the initial stage of winter monsoon. However, as the winter convection intensifies with time, the nitrate builds up within the mixed layer. Eventually, the phytoplankton growth may be limited by Fe and an adequate atmospheric deposition of DFe can possibly relieve them of Fe stress. It is worth mentioning that the contribution of new Fe to total Fe supply varies from 10% in high-nutrient-low-chlorophyll (HNLC) waters to 50% in Fe-replete waters [see Boyd and Ellwood, 2010 and references therein]. As the NO\(_3\) + Fe addition leads to increased Chl \(\text{a}\), other nutrients like P and Si becomes limiting. Such a shift in the community with the addition of NO\(_3\) + Fe has important implications for carbon export as this seemingly expands the domain of winter convection much more southwards.

### 7.1.7. Contribution of dust to interannual variability in the chlorophyll

The incidences of Chl \(\text{a}\) enhancements following the passage of dust storms leads to the question: how far are the episodic events important in defining the interannual variability of Chl \(\text{a}\) over CAS during NEM? Figure 7.9a clearly depicts the difference between phytoplankton
biomass during the NEMs of the 3 years having highest $\tau_{du}$ (2003-2004, 2006-2007 and 2007-2008) and rest of the 6 years with low $\tau_{du}$ (Figure 7.9b). The NEMs of these 3 years together contributed to 46.6% of the total Chl $a$ concentration within CAS when all the 9 years of the study period are considered. The NEMs of 2003-2004 and 2007-2008 alone contributed to 38.5% of Chl $a$ within CAS. The 2 years with the highest values of $\tau_{du}$ were the NEMs of 2003-2004 ($\tau_{du}$ of 0.04) and 2007-2008 (~0.05). These 2 years had average Chl $a$ of 0.83 mg m$^{-3}$ and 0.57 mg m$^{-3}$ respectively. In contrast, the years with lower levels of dustiness had average Chl $a$ of 0.31 mg m$^{-3}$. For the 3 years with the highest $\tau_{du}$ (2003-2004, 2006-2007 and 2007-2008), CAS accounted for about 43.0% of the total Chl $a$ of the AS (60-67°E, 5-25°N) during NEM period. For the rest of the 6 years CAS accounted for only 24.3% of the total Chl $a$ of the entire AS for the NEMs. It is therefore evident that, although, CAS supports low levels of Chl $a$ biomass during the NEM time, the influence of episodic events like dust depositions supplying DFe can turn CAS into a productive system and account for a large part of the interannual variability within this region.

**Figure 7.9** Mean northeast monsoon time chlorophyll $a$ concentration (mg m$^{-3}$) for (a) heavy dust years (2003-2004, 2006-2007 and 2007-2008) and (b) less dust years (2002-2003, 2004-2005, 2005-2006, 2008-2009, 2009-2010 and 2010-2011) within central Arabian Sea.
7.2. Influence of dust during rest of the year

The probable influence of dust depositions on the Chl a concentrations of the AS during the NEM period is clear from the previous section. In order to investigate if Chl a concentrations show some response to dust depositions during other seasons, maps showing correlations between $\tau_{du}$ and Chl a concentrations for other seasons have also been constructed. These maps are shown in Figure 7.10 for SIM period, Figure 7.11 for SWM period and Figure 7.12 for FIM period.

7.2.1. Influence of dust during spring intermonsoon

SIM is the time of the year when the dust deposition into the AS starts increasing (as is shown in Table 5.2). It is seen from Figure 7.10 that there are several scattered patches throughout the AS that show high positive correlations between $\tau_{du}$ and Chl a concentrations without, however, showing much coherent pattern. This is also true for the correlations between $\tau_{du}$ and FLH. Moreover, the regions of positive correlations between $\tau_{du}$ and Chl a concentrations and that between $\tau_{du}$ and FLH do not coincide. This makes it difficult to come to any conclusions regarding the probable influence of dust on the Chl a levels. Also, the AS is oligotrophic during this time of the year [Morrison et al., 1998]. Therefore, NO$_3$ becomes a limiting nutrient. Since it is clear from Section 7.1 that dust is a poor supplier of NO$_3$ in the open ocean, phytoplankton growth will likely to be limited by the supply of macronutrients, even though sufficient amount of DFe is likely to be supplied by dust.
Figure 7.10 Distribution of correlation coefficient between dust optical depth and chlorophyll $a$ concentration over the AS (shading) for the spring intermonsoons of 2003-2011. The black contours enclose the regions where the correlation between dust optical depth and FLH exceeds a magnitude of 0.4: continuous contours for positive correlation and dashed contours for negative correlation.

7.2.2. Influence of dust during southwest monsoon

During the SWM time period a coherent region of high positive correlations between $\tau_{du}$ and Chl $a$ concentrations is seen in the northern AS (see Figure 7.11). This region also exhibits positive correlations between $\tau_{du}$ and FLH. This is the time of the year when AS experiences maximum dust depositions and also has high supply of macronutrients because of upwelling and horizontal advection. Thus, it is likely that dust might have some influence on the phytoplankton biomass of the AS by supplying DFe (although the same can be supplied by upwelling). However, this positive correlation between $\tau_{du}$ and Chl $a$ concentrations have to be regarded with caution. This is primarily because, during the SWM time, satellite retrieval of Chl $a$ is hampered by the presence of cloud over the AS. By examining the Chl $a$ images year by year, it is evident that the
region of high correlation between $\tau_{du}$ and Chl $a$ concentration has large number of Chl $a$ pixels missing. Therefore, although dust can influence Chl $a$ levels during this time of the year, any definite conclusion cannot be arrived at with the present data set.

![Spatial distribution of correlation coefficient between dust optical depth and chlorophyll $a$ concentration over the AS (shading) for the southwest monsoons of 2003-2011. The black contours enclose the regions where the correlation between dust optical depth and FLH exceeds a magnitude of 0.4: continuous contours for positive correlation and dashed contours for negative correlation.]

**Figure 7.11** Spatial distribution of correlation coefficient between dust optical depth and chlorophyll $a$ concentration over the AS (shading) for the southwest monsoons of 2003-2011. The black contours enclose the regions where the correlation between dust optical depth and FLH exceeds a magnitude of 0.4: continuous contours for positive correlation and dashed contours for negative correlation.

### 7.2.3. Influence of dust during fall intermonsoon

Figure 7.12 shows the correlations between $\tau_{du}$ and Chl $a$ concentrations for the FIM period. This is the time of lowest dust deposition over the AS. This is also an oligotrophic time of the year. However, some remnants of macronutrients from the SWM upwelling may still be present during the early part of the FIM. Like SIM, there are several scattered patches of positive correlations between correlations between $\tau_{du}$ and Chl $a$ concentrations over the AS during FIM.
Of particular interest is the one located off the Oman coast centred on 15°N latitude and 60°E longitude. The patch also shows positive correlation between $\tau_{du}$ and FLH. It has been proposed by the modeling study of Wiggert and Murtugudde, [2007] that there is a possibility of Fe limitation during the late SWM period in the western AS. A case of Fe-limitation was also reported by Naqvi et al. [2010] during the waning stage of the SWM period off Oman. They hypothesized that the upwelled water during the SWM came from above the depth of the oxygen-poor DFe-rich zone. Thus, within this upwelled water, the NO$_3$: DFe ratio is much above the value (~ taken as 15,000) at which Fe limitation can take place. However, relating Chl $a$ enhancements to dust depositions within this track proved inconclusive mainly because of the strong advection still present during the beginning of FIM.

**Figure 7.12** Spatial distribution of correlation coefficient between dust optical depth and chlorophyll $a$ concentration over the AS (shading) for the fall intermonsoons of 2003-2011. The black contours enclose the regions where the correlation between dust optical depth and FLH exceeds a magnitude of 0.4: continuous contours for positive correlation and dashed contours for negative correlation.
7.3. **Summary**

The chapter brings to light the mechanistic relationship between phytoplankton blooms and episodic dust depositions in the AS during the NEM period. Dust depositions can lead to Chl $a$ enhancements within CAS, which is located away from the realm of active winter convection. Overall, there were 45 dust storms over the AS during the NEMs of 2002-2003 to 2010-2011 of which only 8 were followed by Chl $a$ enhancements. For each of these 8 cases of Chl $a$ enhancements, a comparison was made to see how much is the demand for different nutrients (like N, PO$_4$ and DFe) to sustain the observed levels of Chl $a$ versus the supply of these nutrients. For the supply side, it was examined if the oceanic supply of nutrients were enough to support the observed levels of Chl $a$ and, if not, how much nutrients can be obtained from dust depositions. It is likely that the deepening of the mixed layer can incorporate enough N and PO$_4$, but not enough DFe from the subsurface waters leading to potential Fe limitation. Following episodic dust storms, the supply of DFe can alleviate the Fe limitation and result in phytoplankton blooms. Although, all the phytoplankton blooms within CAS were observed following episodic dust events, only four blooms can be attributed to dust depositions. It is seen that the years with high levels of dust can contribute 47% of the total Chl $a$ concentrations in the AS during the NEM period. Such conclusions cannot be arrived at for other seasons primarily because of the nature of the data used.