CHAPTER 6

Factors Regulating DMSP and DMS in Seawater
Maximal concentrations of DMS and DMSP occur closer to sea surface (Chapter 4). Such occurrence facilitates higher emission of DMS to atmosphere than otherwise. Interestingly, even though these compounds are biogenic in origin their maximal concentrations do not always coincide with those of chlorophyll $a$ (Chapter 4). Therefore, it is important to understand what factors control the abundance of these compounds in the water column with particular reference to their maximal abundance near the surface. This chapter examines the roles of salinity, chlorophyll, nitrate, mixed layer depth (MLD) and Ultra-Violet radiation (UVR) as factors responsible for regulation of DMS and DMSP levels in Indian Ocean.

6.1 Salinity as a controlling factor

Salinity of seawater plays a very important role in the physiological functions of marine organisms. The changes in salt contents in the body fluid and ambient seawater medium can result in osmotic pressure imbalance. The imbalance is likely to put the cell under stress. In order to maintain the required osmotic pressure, for the cell to remain in equilibrium with the surrounding seawater, the plankton said to produce DMSP [Reed, 1983; Kirst et al., 1991], although the DMSP may also serve other functions as well [Kiene et al., 2000]. Therefore, salinity could be one of the factors responsible for the extent of production of DMSP by phytoplankton. The DMS in seawater
results from the degradation of this DMSP and hence we examine their relations with salinity to understand its role in controlling their abundances.

The Arabian Sea region is the source of high salinity waters in the North Indian Ocean. Water masses such as the Arabian Sea High Saline Watermass (ASHSW), Persian Gulf water (PGW) and Red Sea Water (RSW) masses are important in the top 1000 m. Fig. 6.1 shows the typical vertical distributions of salinity, DMS and DMSP in the upper 100 m of the water column of the southern Arabian Sea. Profiles show general high salinity near the surface that decreases below. Salinity variation was between 34.560 and 36.570. DMS and DMSP were higher closer to the surface and decreased with depth. Weak positive relations for salinity with DMS and DMSP can be seen in Fig. 6.1. Thus an attempt was made to check if these relations are influenced by similarities in behaviours of the properties considered. Fig. 6.2a depicts the relations between vertical gradients in salinity (differences in property between any two depths at each station, \( d \) Salinity) with those in DMS (\( d \) DMS) and DMSP (\( d \) DMSP). Both DMSP and DMS gradients show somewhat positive relations with changes in salinity despite considerable scatter. It is possible, however, that these relations might be influenced by vertical behaviors of these properties. Therefore, horizontal gradients were evaluated (based on differences between properties at similar depths of two neighboring stations) and the consequent relations are shown in 6.2b. Here changes in DMSP and DMS showed unclear relations with that in salinity.
Fig. 6.1 Vertical variations in salinity, DMS and DMSP, and relations for salinity with DMS and DMSP in the Arabian Sea.
Fig. 6.2a. Relations between vertical gradients in salinity (based on differences between any two depths at each station) with those in DMS and DMSP in the Arabian Sea.
Fig. 6.2b. Relations between horizontal gradients in salinity (based on differences at a specific depth between two neighbouring stations) with those in DMS and DMSP in the Arabian Sea.
From this it is not clear whether changes in salinity influence the concentrations or production of DMSP and DMS in the Arabian Sea.

The Bay of Bengal is a region of positive water balance with strong salinity gradients. In contrast to that in the Arabian Sea, salinity in the Bay of Bengal (Fig. 6.3) shows an increase with depth. The Bay receives enormous amounts of fresh water from a few of the world's largest rivers. This together with monsoonal rain forms a low saline cap at the surface. During a time series study (SK 147A, see Fig. 3.8a,b) the salinity varied between 26.630 and 35.020 in the upper 100 m with higher values in the deep. The DMS and DMSP exhibited decreases in abundance with increasing depth with maximal values occurring in the upper 20 m. A few higher values were found around 40 m. The relations for DMSP and DMS with salinity were negative. This behaviour is in apparent contrast with the relations found in 6.1 for the Arabian Sea. The differences between 6.1 and 6.3 could be a result of contrasting vertical behaviour of salinity between the two regions. Relations between vertical gradients in salinity and that of DMSP and DMS revealed that enhanced DMSP and DMS levels are favoured where salinity decreased (Fig. 6.4a). As this relation may also be a biased result from vertical behaviors we considered horizontal gradients again (Fig. 6.4b). The obvious negative relations in Fig. 6.4b have important implications since horizontal gradients in this case were deduce from the variations at the same location but with changes in properties with time. Fig. 3.8a clearly indicates the incursion of low salinity waters into the study area. Although the negative relation appears not
Fig. 6.3. Vertical variations in salinity, DMS and DMSP; and relations for salinity with DMS and DMSP in the Bay of Bengal.
Fig. 6.4a. Relations between vertical gradients in salinity (based on differences between any two depths at each station) with those in DMS and DMSP in the Bay of Bengal.
Fig. 6.4b. Relations between horizontal gradients in salinity (based on differences at a specific depth between two neighbouring stations) with those in DMS and DMSP in the Bay of Bengal.
well resolved it indicates to the possibility that a decrease in salinity can lead to an increase in DMS. This is clear from the dense number of points. In the case of DMSP the negative relation is more obvious. These relationships (Fig. 6.4b), in fact, prompted us conduct laboratory experiments (see chapter 5 and Fig. 5.1) in which our experiments unequivocally confirmed that plankton (diatoms) produce more DMSP when subjected to sudden changes in salinity.

Fig. 6.5 depicts the vertical distributions of salinity, DMSP and DMS and also the relations for salinity with DMSP and DMS in the central Indian Ocean. Vertical distributions of the properties in question are nearly similar to that in the Bay of Bengal (Fig. 6.3) but with changes in trends between relations. Detectable levels of DMS and DMSP occurred even below 100 m that differ with the vertical behaviours both in the Arabian Sea and the Bay of Bengal. Salinity varied between 34.620 and 36.440 in the upper 150 m of the Central Indian Ocean. Vertical gradients in salinity and DMS are clearly related negatively but not that involving DMSP (Fig. 6.6a). The relations are not clear also with respect to horizontal gradients (Fig. 6.6b).

Iverson et al. [1989], in a study on DMSP and DMS production in estuarine and coastal waters, found positive correlations between concentrations of these biogenic sulphur species and salinity. On the other hand, experiments performed on axenic cultures of Phaeocystis sp., revealed that production of DMSP and its cleavage by DMSP lyase are not related to short-term regulation of the osmotic potential based on salinity changes [Stefels and Dijkhujzen, 1996]. Nianzhi et al. [1999] found no correlation
Fig. 6.5. Vertical variations in salinity, DMS and DMSP; and relations for salinity with DMS and DMSP in the Central Indian Ocean.
Fig. 6.6a. Relations between vertical gradients in salinity (based on differences between any two depths at each station) with those in DMS and DMSP in the central Indian Ocean.
Fig. 6.6b. Relations between horizontal gradients in salinity (based on differences at a specific depth between two neighbouring stations) with those in DMS and DMSP in the Central Indian Ocean.
between DMSP and salinity in the East Chine Sea. Stefels [2000] opined that due to very slow plankton adaptation while changing its intracellular DMSP concentration in relation to ambient salinity changes DMSP need not be considered as an osmolyte, but rather as a constitutive compatible solute. Nevertheless, our field, particularly from the Bay of Bengal (Figs. 6.3 and 6.4) and experimental results (detailed in chapter 5) clearly establish the following: (i) salinity shocks (spontaneous dilution in salinity) do increase the DMSP\textsubscript{t} content in phytoplankton, (ii) extent of DMSP production depends on age of the plankton and (iii) the laboratory results appear to be of limited applicability in the field because of the fact that the expected sudden changes in salinity (as those in the diatom salinity shock experiment) may not occur in natural conditions. Thus salinity may not have a direct control over DMSP and DMS production in the Indian Ocean except to some extent in the Bay of Bengal due to intense vertical and horizontal salinity gradients aided by sudden changes in circulation driven by extreme climatic events.

6.2 Chlorophyll and phytoplankton speciation

Chlorophyll represents the biomass of mainly the phytoplankton origin. Since plankton largely produces DMSP the concentrations of DMSP and DMS might depend on phytoplankton productivity. The chlorophyll $a$ is a measure of phytoplankton productivity even though the measured pigment is fresh or that accumulated over sometime. Although a fraction of that comprises the dead materials chlorophyll $a$ is a good indicator of primary production in the immediate past, and therefore, this section attempts to explore the possible
relations for DMSP and DMS with chlorophyll. Both DMSP and DMS did not appear to exhibit clear relations with chlorophyll as the most number of Arabian Sea data appear to cluster near the point of origin in a linear plot (left panels) in Fig. 6.7, except for DMSP at concentrations > 2 nM. It could be seen from the scales that the variations in these parameters ranged by three-four orders of magnitude. The Arabian Sea is the most productive region in the Indian Ocean and the data used in Fig. 6.7 represent coastal, including SW monsoonal upwelling regions along the west coast of India, and open ocean data. When these data are plotted on log-scales the linear relations are well resolved both for DMS and DMSP. Interestingly, linearity is consistently found in different seasons and cruises. Very high concentrations in Fig. 6.7 were found along the Indian coast during and after the SW monsoonal upwelling. Thus phytoplankton production seems to have a direct influence on the levels of DMSP and DMS in the Arabian Sea despite the fact that one to one correlation with chlorophyll is not seen in their vertical distributions. Although DMSP and DMS levels seem to depend on phytoplankton production in the Arabian Sea occurrence of their maximal concentrations very close to surface cannot be explained with these relations.

Fig. 6.8 shows the relations as in Fig. 6.7 for the Bay of Bengal. As in Fig. 6.7 the simple linear plots did not clearly indicate the relations but the log plots did show weak positive relations compared to those in the Arabian Sea. Significantly, despite the widely variable chlorophyll contents between cruises and seasons both DMSP and DMS levels are almost the same. Increased
Fig. 6.7. Relations for DM S and DMSP with chlorophyll in the Arabian Sea.
Fig. 6.8. Relations for DMS and DMSP with chlorophyll in the Bay of Bengal.
chlorophyll in the second phase of BOBMEX time series experiment (SK 147B) is striking. This has been a result of pumping of nutrients into the surface due to the turbulence created by storm in the first phase. On the other hand, chlorophyll does not show any specific trends in both linear and log plots with DMSP and DMS in the Central Indian Ocean (Fig. 6.9). The data distribution resulted in scattered diagrams although are well separated with respect to chlorophyll abundance. The eastern Central Indian Ocean (SK150) is found to have the least chlorophyll a levels (Fig. 6.9). Therefore, unlike in the Arabian Sea, DMSP and DMS do not show clear dependency on phytoplankton production in the Bay of Bengal and the Central Indian Ocean. One obvious reason, however, is the range of chlorophyll concentrations observed; 0-1 mg m\(^{-3}\) in the Central Indian Ocean, 0-10 mg m\(^{-3}\) in the Bay and 0-100 mg m\(^{-3}\) in the Arabian Sea. Nevertheless, DMSP and DMS levels are higher in the Central Indian Ocean than in the Bay of Bengal. Therefore, it is possible that factors other than phytoplankton production might be dominating in the regulation of DMSP and DMS abundances in the Bay of Bengal and Central Indian Ocean whereas biological dynamics seem to have a significant role in the Arabian Sea.

Presently attempts are being made to establish global relations between chlorophyll a and DMS so as to facilitate mapping of DMS through satellites imageries [Liss et al., 1993; Kettle et al., 1999]. Yang et al. [1999] and Yang [2000] have found positive correlations between DMS and chlorophyll for the South China Sea. Turner et al. [1988] found positive
Fig. 6.9. Relations for DMS and DMSP with chlorophyll in the Central Indian Ocean.
correlations after segregation based on independent taxonomic groups in coastal waters of the United Kingdom but not when the data have been considered in toto. Use of global data sets by Kettle et al. [1999] did not show any clear relations between DMS and Chlorophyll. Our results on chlorophyll relations with DMS and DMSP in the Arabian Sea agree with that of Yang et al. [1999]. On the other hand, our results for the Bay of Bengal and the Central Indian Ocean agree with most of the other observations [see Kettle et al., 1999; and references therein].

To study the species dependency of DMS and DMSP in this region time series measurements were made in the Dona Paula Bay (see Chapter 4). Blooms of diatoms occurred during SW monsoon season (see Fig. 4.9). In July a mixed bloom comprising mainly of diatoms and dinoflagellates was found. Even though dinoflagellates made up merely about 15% of the bloom biomass they appeared to significantly contribute to DMS and DMSP abundances since the highest levels of these compounds (DMSP of 419 nM and DMS of 12.8 nM) occurred in this month. Thus, DMSP and DMS abundances showed a very clear species dependency in coastal waters of India.

6.3 Nitrate

In the presence of nitrate production of DMSP by phytoplankton has been found to decrease [Turner et al., 1988] because of the lesser energy involved in nitrate conversion to glycinebetaine (GBT) than sulphate to DMSP [Wyn Jones and Storey, 1981; Turner et al., 1988]. On the contrary, laboratory
experiments have revealed DMSP levels produced by plankton to be independent of nitrate concentrations available [Keller et al., 1999a,b]. One of the main limiting factors of primary production in the northern Indian Ocean is nitrate unlike the Southern Ocean where iron is the limiting nutrient. Figs. 6.10, 6.11 and 6.12 give the relations between nitrate, and DMS and DMSP for the Arabian Sea, Bay of Bengal and the Central Indian Ocean respectively. Here, only the data from the top 50 m have been used to avoid sub-thermocline (where nutrients start increasing with depth) effects. The illustrations do not exhibit clear trends in relations. In general, DMSP and DMS occurred in measurable quantities at low concentrations of nitrate, which seem to be a result of differences in their vertical behaviours. However, these were found in higher abundance even at higher nitrate concentrations in upwelling regions in the Arabian Sea (Fig. 6.10), under turbulent conditions when nutrients are pumped into surface layers in the Central Indian Ocean and the Bay of Bengal (Figs. 6.11, 6.12). The bay also experiences shallow mixed layers where nutrient rich sub-thermocline waters are sunlit. Our observations, therefore, reveal no one to one correlations between nitrate, and DMSP and DMS abundances in the Indian Ocean.

6.4 Mixed layer depth

Mixed layer depths play a very important role in controlling biological processes in the surface ocean. For instance, the Arabian Sea has deeper MLDs during the monsoons due the higher wind speeds while lower wind speeds lead to shallow MLDs during the inter-monsoons. Shallower MLDs
Fig. 6.10. Relations for DMS and DMSP with nitrate in the Arabian Sea; left panels - when nitrate is < 2μM and right panels - in the upper 50 m.
Fig. 6.11. Relations for DMS and DMSP with nitrate in the Bay of Bengal; left panels — where nitrate is < 2 μM and right panels — in the upper 50 m.
Fig. 6.12. Relations for DMS and DMSP with nitrate in the Central Indian Ocean; left panels - where nitrate is < 2 μM and right panels - in the upper 50 m.
imply shallower nutricline, which results in the availability of nutrients within the euphotic zone and helps in increased primary production (secondary chlorophyll maximum) during the inter-monsoons [Naqvi, 2001].

Deep MLDs of over 80 m occurred during SS161 (Arabian Sea) and SK141 (Central Indian Ocean in 1999) but were less deep in SK133 (Central Indian Ocean in 1998) in winter (Fig. 6.13). MLD of about 120 m occurs in Arabian Sea due to winter convection [Madhupratap et al.; 1996] whereas the deep ones in Central Indian Ocean during SK141 are due to intense mixing driven by strong winds, located near the Inter Tropical Convergence Zone (ITCZ, between equator and 10°S). MLDs, on the other hand, were much shallower in SK158 due to strong stratification, which is characteristic of inter-monsoon periods. The ML-DMS range was lower in SK133 (0.9 – 2.3 nM) than in SK141 (1.5 – 13.4 nM) exhibiting significant inter-annual variability since the study period (winter) and area (Central Indian Ocean) were the same but occupied in subsequent years (1998 and 1999). On the other hand, ML-DMS levels were low in inter monsoon (0.9-1.9 nM; SK158) than in winter (0.4-11.3 nM; SS161). These are compared for ML-DMS values evaluated based on 1° drop consideration. This is because of minimal effects of MLD computational considerations on MLD-DMS, in general, that further suggests improved negative relationship (decreased scatter) between MLD and ML-DMS when temperature drop (particularly 1°C) were used. Therefore three points emerge from Fig. 6.13: a) striking inter-annual variation in ML-DMS averages in Central Indian Ocean, b) vastly different ML-DMS values between
Fig. 6.13. ML-DMS relations with MLD and UV (TOMS) in the Indian Ocean. Symbols indicate: ○ - SS 161, △ - SK 133, □ - SK 141 and ◊ - SK 158 cruises. The three vertical panels are for MLDs computed based on the considerations of (a) 0.125 kg dm\(^{-3}\) hike, and (b) 0.5°C and (c) 1.0°C drops compared to that at the surface.
winter and fall inter-monsoon seasons in the Arabian Sea revealing strong seasonal variability and c) negative relation between ML-DMS and MLD irrespective of season and area of study. The relations observed between DMS yields and MLDs through *in vitro* incubation experiments [Simo and Pedros-Alio, 1999] seem to be at variance with those in Fig. 6.13. The incubation experiments showed a negative relation up to MLD of 15-20 m but a positive one thereafter. Despite the consistent negative relations in Fig. 6.13 wide variations in magnitudes of ML-DMS averages between regions and seasons indicate that MLD is not the sole factor in determining the magnitudes of DMS concentrations in the surface Ocean.

### 6.5 Ultra-violet (UV) radiation

Chlorophyll levels are found to be affected by UV radiation in the Bay of Bengal (Fig. 3.9). The maximal DMS concentrations in surface layers of the Indian Ocean are generally decoupled from peaks of chlorophyll [Shenoy et al., 2002] suggesting that near surface processes are important in DMS formation of which radiation could be significant. Fig. 6.13 (right panels) suggests that intensity of ultra-violet radiation (300-400 nm) exhibited zonal bands; higher intensity occurred in Central Indian Ocean than in Arabian Sea. In Arabian Sea the difference in incident UV radiation between winter (when cloud cover is expected) and fall inter-monsoon (clear sky) seems to be insignificant. As in the case of MLD the strength of relationships (in left panels of Fig. 6.13) became better from (a) to (c) with clear positive relations between UV and ML-DMS, particularly at lower concentrations. Relations between
intensity of UV radiation and ML-DMS averages suggest: a) trends in relations remained unchanged even though higher incident radiation occurred in Central Indian Ocean than in Arabian Sea, b) in both regions ML-DMS increased with UV intensity irrespective of different DMS magnitudes (at lower ML-DMS levels) and c) higher ML-DMS values in all the cruises do not exhibit strong dependence on UV intensity. These observations suggest, as in the case of MLDs, that incident radiation alone does not lead to different ranges of ML-DMS observed.

Higher ML-DMS averages, which did not seem to depend on UV intensity mostly correspond to shallow MLDs ($\leq 40$ m; see Fig. 6.13c) indicating that a strong coupling between incident UV and shallow MLDs facilitated the occurrence of higher DMS concentrations. This is in excellent agreement with a near 100% DMS yield from DMSP in shallow MLDs [Simo and Pedros-Alio, 1999]. Shallower MLDs will receive intense UV radiation in comparison to deeper MLDs.

Non-dependence of high ML-DMS values on UV intensity when MLDs were $\leq 40$ m is complimented by the observation [Morrow and Booth, 1997] of penetration of the most damaging UV-B (305 nM) radiation up to 40 m in clear equatorial waters off the coast of Nauru in the Pacific Ocean. Trends in Fig. 6.13 are, in general, consistent with penetration of UV of 320 and 340 nm radiation down to levels over 60 and 90 m, respectively [Morrow and Booth, 1997]. UV penetration, however, could be a strong function of dissolved organic matter that will undergo photolysis after absorption [Herndl et al.,
Signatures of ML-DMS formed in short-term mixed layers appear to be preserved even in seasonal MLDs in Fig. 6.13. Accordingly, the relation of MLDs with ML-DMS in particular, improved from density increment (indicative of wind and salinity forcing, (a)), to temperature drop (reflects seasonal mixed layer, (c)), respectively, considerations in MLD calculations. This indicates that effect of UV radiation on ML-DMS could be realized on a short-term scale (days) whereas that of MLD on a seasonal scale. Thus MLD and UV radiation complement each other in fine-tuning the DMS levels in the mixed layers of the Ocean but do not seem to account for large regional, seasonal and inter-annual variability in ML-DMS inventories observed.

If both the UV and MLDs do not account for DMS variations the only other possible mechanism would be biological. Following the iron injection in water DMS reached higher levels after 13 days during the Southern Ocean iron-release experiment (SOIREE) [Boyd et al., 2000]. A combination of prymnesiophytes and microzooplankton is believed to have led to increased DMSP and DMS levels though diatom blooms are also found to be significant. In the days following iron/nutrient injection phytoplankton blooms occur and will have a large proportion of cells with sound physiology. Winter convection pumps nutrients into the surface layers and promotes biological production in the Arabian Sea. An important biological feature in the Arabian Sea is the occurrence of abundant zooplankton throughout the year [Madhupratap et al., 1996] and is known as 'zooplankton paradox'. Hence, higher production of DMS could be expected following nutrient injection into the surface layers.
(driven by physical forcing) and subsequent increase in phytoplankton aided by the presence of perennial zooplankton in the Arabian Sea. Nearly doubled (Table 6.1) ML-DMS (average = 2.9 nM) concentrations were observed, in the Arabian Sea, in winter than in fall-intermonsoon (mean = 1.5 nM) even though the ML-DMSP values were lower in the former season (6.8-7.4 nM, average 7.1 nM) than in the latter (6.5-28.9 nM, mean of 15.0 nM). In the central Indian Ocean, however, both the DMSP and DMS were higher in 1999 (Table 6.1) due to turbulent conditions driven by strong winds. Such an intense mixing led to an upward transport of nutrients in 1999. The upper layers were stratified down to 200 m in 1998 when nutrient pumping from subsurface has been minimal [Shenoy et al., 2002]. Although the measured chlorophyll a values in 1999 (SK 141) were lower than found in 1998 (SK 133) the freshly produced phytoplankton might have dominated biological community. Chlorophyll a found in 1998 might actually represent aged and decaying plankton in the central Indian Ocean, following the anomalous high biological production off Sumatra in October-November 1997 due to the occurrence of El Nino in 1997-98 [Murthugudde et al., 1999], in contrast to that freshly produced in the Arabian Sea. Interestingly, while the Arabian Sea waters contained higher levels of DMSP and DMS in January 1998 these were lower in February-March of the same year in the central Indian Ocean. The winter convection was active in the Arabian Sea when the equatorial waters were well stratified. Hence, assuming that DMSP lyase activity is higher in surface waters in Indian Ocean also, as observed elsewhere
[Steinke et al., 2002], more DMSP produced by plankton activity account for larger DMS levels in 1999 (ML-DMS average of 5.8 nM; ML-DMSP= 9.9 – 25.1 nM with a mean of 21.1 nM) than in 1998 (ML-DMS average of 1.2 nM; ML-DMSP= 3.4 – 6.5 nM with 4.7 nM) in the central Indian Ocean. From the foregoing discussion it is evident that the variability of DMS in the Indian Ocean is largely regulated by efficiency in biological and radiative conversion of DMSP to DMS and not necessarily by DMSP levels.

We undertook measurements of chlorophyll a and bacterial population along with DMS and DMSP in intermonsoon in the Arabian Sea (SK 158) to check the influence of physical factors on biological and DMS species production. Though the levels of chlorophyll a and bacterial populations decreased with increasing UV intensities (Fig. 6.14) the dominance of bacteria over phytoplankton in intermonsoon, as discussed above, might have led to lower DMS concentrations. The DMSP levels were higher in intermonsoon (Fig. 6.15) than found in winter (SS 161). Simultaneous decreases in the ML-DMSP and ML-DMS with enhanced MLD in Fig. 6.15 clearly reveal that a significant part of DMSP may be converted to non-DMS compounds (e.g. an increase of 25 nM of DMSP against an increase of only 1.6 nM of DMS).

If we have to realistically predict DMS concentrations in the surface ocean it is important that parameters representing DMSP lyase and bacterial activities (in forms of relevant pigments etc.) have to be incorporated in the algorithms besides the MLDs and UV intensities.
Fig. 6.14. Decreases in ML-chlorophyll and ML-bacterial abundances (SK 158) with increase in incident UV radiation (TOMS) in the Arabian Sea.
Fig. 6.15. Relationships for mixed layer DMS and mixed layer DMSP with mixed layer depth.)
6.6 A hypothesis

Correlating physical variables, temperature and salinity or even nutrients, found at the time of sampling, to the DMSP and DMS will be of limited use since magnitudes of these sulfur compounds are associated with the extent and changes in trophic levels that follow the physical forcing with a time lag (i.e., the biological processes are manifestations of physical forcing occurred sometime before). Changing relations between DMSP and nitrate are the best examples in this context. Higher nitrates in surface waters, due to winter entrainment as indicated by low mixed layer temperatures, trigger photosynthetic production during which the DMSP production is not proportional to nitrate (Table 6.1). The DMSP content was higher in the central Indian Ocean (SK 141) than in the Arabian Sea (SS 161) despite the stronger nitrate supply at higher latitudes. During the winter bloom formation nitrate in water is consumed but the DMSP release might be significantly occurring in the intermonsoon. Once the nitrate supplied by circulation and mixing is (nearly) exhausted through primary production (i.e., in winter) its further supply occurs through regeneration processes (e.g., in intermonsoon) in the photic zone. At this stage (intermonsoon) the extent of primary production will depend on trace levels of nitrate available in water when the DMSP release will also be significant because of the presence of grazers in abundance. This situation might have led to a positive relation between DMSP and traces of nitrate (Table 6.1, except in SS 161). Hence, while the physical forcing determines the extent of photosynthetic production the magnitudes
TABLE 6.1. Means of incident UV radiation, mixed layer depth and mixed layer (ML) averages of properties in Indian Ocean

<table>
<thead>
<tr>
<th>Area</th>
<th>Cruise No.</th>
<th>UV (J m$^{-2}$)</th>
<th>MLD (m)</th>
<th>T ($^\circ$C)</th>
<th>NO3 (µM)</th>
<th>DMSP (nM)</th>
<th>DMS (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIO</td>
<td>SK 133</td>
<td>6939</td>
<td>56</td>
<td>29.4</td>
<td>0.25</td>
<td>4.7</td>
<td>1.2</td>
</tr>
<tr>
<td>CIO</td>
<td>SK 141</td>
<td>5563</td>
<td>49</td>
<td>27.1</td>
<td>0.50</td>
<td>21.1</td>
<td>5.8</td>
</tr>
<tr>
<td>AS</td>
<td>SS 161</td>
<td>3681</td>
<td>71</td>
<td>26.4</td>
<td>2.72</td>
<td>7.1</td>
<td>2.9</td>
</tr>
<tr>
<td>AS</td>
<td>SK 158</td>
<td>4638</td>
<td>31</td>
<td>29.0</td>
<td>0.47</td>
<td>15.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>
and nature of trophic levels/succession are mainly responsible in maintaining DMS seasonal inventories in seawater.

The salient features of this chapter are:

1. Salinity does not seem to have a direct control over the production of DMS and DMSP except in the Bay of Bengal where the sharp gradients in salinity facilitate higher DMS and DMSP production to some extent.

2. Chlorophyll seems to correlate well with DMS in the Arabian Sea, but not in the Bay of Bengal and the Central Indian Ocean.

3. Nitrate does not correlate with either DMS or DMSP in the Indian Ocean.

4. Mixed layer depth shows a clear negative relation with DMS but does not seem to be a prime controlling factor on its own. MLD together with UV radiation appears to control the DMS inventories on short-term scales.

5. Biological processes, not the physical variables, are hypothesized to regulate seasonal DMS and DMSP abundances in the Indian Ocean.