

Aerosol NO_3^- and ^{210}Pb distribution over the central-eastern Arabian Sea and their air–sea deposition fluxes

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ABSTRACT

The concentrations of NO_3^- , SO_4^{2-} and ^{210}Pb have been measured in the marine boundary layer over the central-eastern Arabian Sea to investigate the sources of NO_3^- to this region and its deposition flux to the sea surface. Bulk aerosol samples were collected during April–May (intermonsoon) 1994, July–August (monsoon) 1995, 1996 and February–March (winter) 1995, 1997. The NO_3^- and ^{210}Pb concentrations, during the intermonsoon and winter, ranged from 0.4 to 4.1 $\mu\text{g m}^{-3}$ and $(12.3 \text{ to } 70.3) \times 10^{-3} \text{ dpm m}^{-3}$, respectively; with systematically higher concentrations during the winter. Their concentrations were the lowest, 0.2 to 0.8 $\mu\text{g m}^{-3}$ and $(4.0 \text{ to } 17.6) \times 10^{-3} \text{ dpm m}^{-3}$, respectively, during monsoon. The seasonal and spatial distributions of NO_3^- and ^{210}Pb in the aerosols show a significant positive correlation and bring to light the dominant rôle of continental sources in the chemistry of aerosols over the Arabian Sea. The NO_3^- deposition flux to the Arabian Sea surface is determined to be 0.9 $\text{mg m}^{-2} \text{ d}^{-1}$ based on the $\text{NO}_3^-/^{210}\text{Pb}$ ratio (43 $\mu\text{g dpm}^{-1}$) and the measured ^{210}Pb deposition flux of 20 $\text{dpm m}^{-2} \text{ d}^{-1}$. The atmospheric NO_3^- flux to the mixed layer is insignificant compared to that fixed by primary production in this region and that supplied to the mixed layer from the base of the euphotic zone. The annual mean ^{210}Pb concentration ($25 \times 10^{-3} \text{ dpm m}^{-3}$) and its atmospheric deposition flux ($20 \text{ dpm m}^{-2} \text{ d}^{-1}$) yield an effective deposition velocity of $\sim 0.9 \text{ cm s}^{-1}$ for ^{210}Pb aerosols; similar to that used for deriving NO_3^- and NH_4^+ deposition fluxes. The seasonal trend for SO_4^{2-} concentrations is quite similar to that of NO_3^- , with the non-sea-salt component of SO_4^{2-} being generally higher during the winter and the intermonsoon periods.

1. Introduction

Marine aerosol particles consisting of sea salts, non-sea-salt sulphate, nitrate and mineral dust play an important rôle in the global geochemical cycling processes (Duce et al., 1991). During the past two decades, there has been considerable interest to assess the atmospheric deposition fluxes of nitrogen and phosphorus to the ocean surface

and their rôle in contributing to “new” nutrients to surface waters (Graham and Duce, 1979; Knap et al., 1986; Cornell et al., 1995). It has been suggested that episodic inputs of these chemical species via precipitation and aerosol deposition may have significant influence on the marine biological productivity (Duce, 1986; Duce et al., 1991; Owens et al., 1992). In this context, considerable amount of data have been gathered on the nitrate (and other nitrogen species) distribution in marine air over the Pacific and the Atlantic Oceans (Duce, 1986; Savoie et al., 1987; Prospero and Savoie, 1989; Savoie et al., 1989a; Cornell et al.,

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1995). Recently, Nakanishi et al. (1995) have estimated mineral aerosol fluxes to the Pacific using environmental plutonium as a tracer of airborne dust.

As a part of the Indian national JGOFS programme, we have measured the temporal and spatial variations in the concentrations of nitrate, ^{210}Pb (half life of 22.3 years, a tracer predominantly of continental origin) and non-sea-salt sulphate in the marine boundary layer over the central-eastern Arabian Sea. These measurements provide information on the sources of nitrate to the Arabian Sea and its deposition flux to the surface waters from the measured ratio of nitrate to ^{210}Pb in the aerosols and the ^{210}Pb deposition flux to the surface ocean. The samples were collected during different seasons, April–May (inter-monsoon) 1994, February–March (winter) 1995, July–August (monsoon) 1995, 1996 and February (winter) 1997 and thus provide a measure of seasonal variations in their distribution and deposition fluxes.

2. Sampling and analysis

Large-volume bulk aerosol samples were collected with a high-volume ($1.2\text{ m}^3\text{ min}^{-1}$) air sampling system set up ~20 m above the sea surface on the upper deck of *ORV Sagar Kanya*. Air was filtered through 20 cm × 25 cm Whatman glass microfibre filters while cruising between stations. Sampling was discontinued whenever the wind direction was unfavourable. The sampling transects are shown by solid lines in Fig. 1, each representing one sample filter. Samples were collected by and large along the same transects during all the sampling periods, except during February 1997 when they were collected only between 17°N to 21°N latitude and 63°E to 71°E longitude (Fig. 1). The filters were typically replaced at an interval of 5–10 h and the volume of air filtered ranged from 400 to 4200 m³. After collection, the filters were sealed in clean polyethylene bags and were stored in the laboratory for 5–6 months prior to analysis. This time lag between sampling and analysis was necessary for the measurement of ^{210}Pb , which was determined from the ingrowth of its grand-daughter ^{210}Po (half life = 138.4 days).

At the time of analysis, one-half of the filter was soaked in Milli-Q water (18.2 MΩ resistivity) and

refluxed for 10–12 h. The concentrations of Cl^- , NO_3^- and SO_4^{2-} were determined in the aqueous extract by suppressed ion-chromatography (Dionex Model 2000i) using Ion-Pac AS4A separator column (4 × 250 mm) coupled with AG4A guard column. The eluant used was 1.8 mM Na_2CO_3 /1.7 mM NaHCO_3 and maintained at a constant flow rate of 1.8 ml min⁻¹. An anion self regenerating suppressor (Dionex ASRS-I) was placed in line after the separator column and operated in the auto-suppression recycle mode (Sarin and Rao, 1998). The linear response of the conductivity detector was interfaced with an integrator (Spectra Physics Model 4290) for recording the chromatograms. For ^{210}Pb analysis, 25% of the filter was digested in 6N HCl in presence of ^{209}Po spike (added as yield monitor). From the acid extract, Po isotopes (^{209}Po and ^{210}Po) were auto-plated onto silver disc and assayed by alpha spectrometry (Sarin et al., 1992). The ^{210}Pb concentration in the aerosols, at the time of collection, was calculated from the measured activity of ^{210}Po . The filter blanks for NO_3^- and ^{210}Pb were less than 1 µg and 0.2 dpm/filter; while that for Cl^- and SO_4^{2-} they were 15 and 10 µg/filter, respectively. In all samples, the filter blanks account for less than a percent of the measured signal levels. The overall error ($\pm 1\sigma$) in the concentrations of anions are ± 5 to $\pm 7\%$ and include uncertainties arising from calibration and reproducibility of measurements.

3. Results

The concentrations of NO_3^- , non-sea-salt sulphate (nss-SO_4^{2-}) and ^{210}Pb are presented in Figs. 1–3 and summarized in Table 1. The chloride content of the samples was used to calculate the sea-salt contribution of SO_4^{2-} ; the sea-salt correction is negligible for NO_3^- and ^{210}Pb . The nss-SO_4^{2-} was calculated as:

$$\text{nss-SO}_4^{2-} = [\text{total SO}_4^{2-}] - [0.140 \times \text{Cl}],$$

where 0.140 being the mass ratio of $\text{SO}_4^{2-}/\text{Cl}^-$ in surface sea water. The nss-SO_4^{2-} ranged from 28 to 98% of the total SO_4^{2-} , with higher contributions recorded in winter samples and consistently lower proportion characterizing the monsoon aerosols. The use of chloride as an index to derive the sea-salt contribution may overestimate the

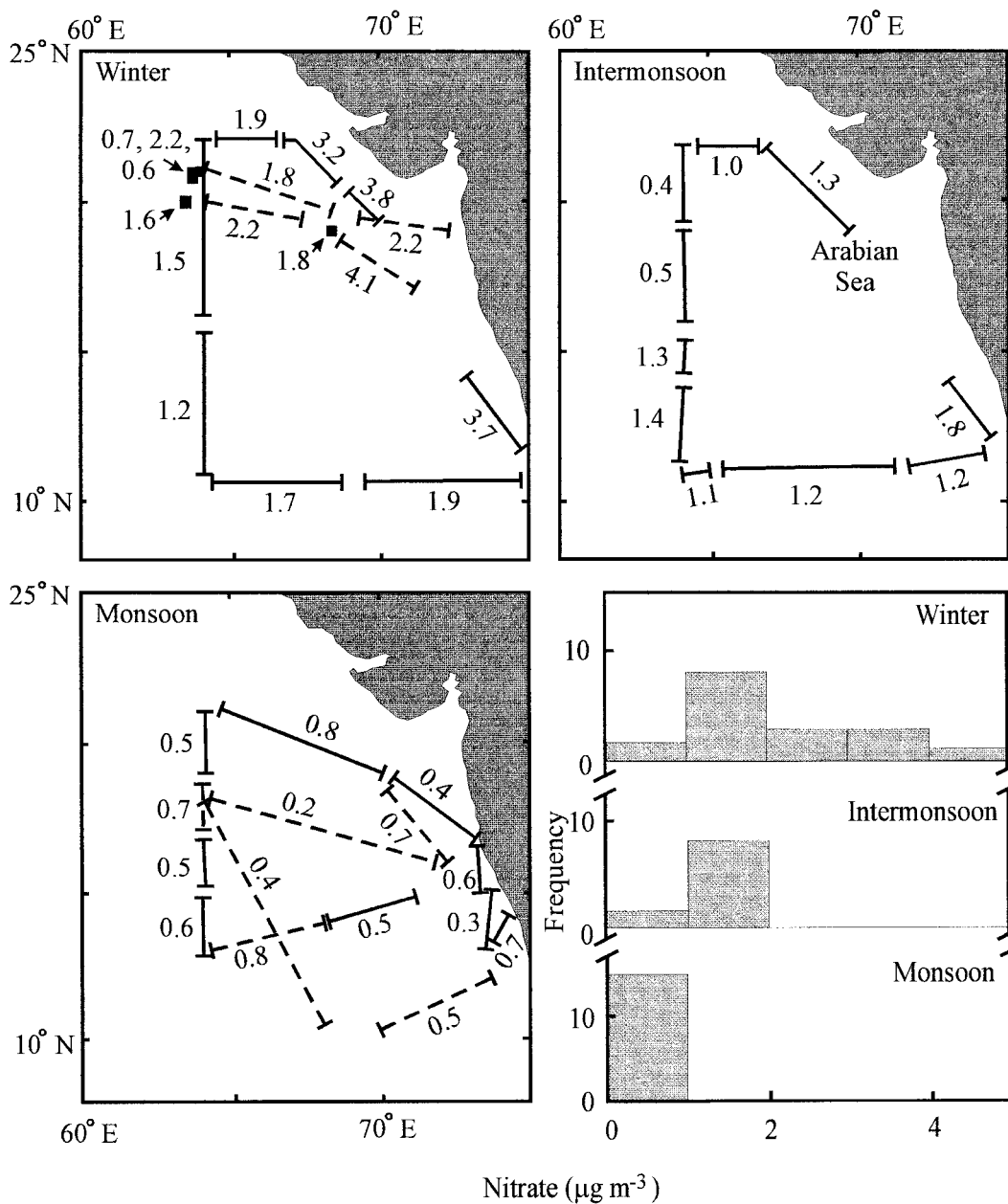


Fig. 1. Temporal and spatial variations in aerosol nitrate concentrations over the central-eastern Arabian Sea. Higher nitrate concentrations during winter and intermonsoon along the coast and north of 15°N are transported by wind from land. Samples shown by solid squares were collected over different days during February 1997. The frequency distribution of nitrate concentration during different seasons is also shown, the distinctly low values during monsoon are clearly evident.

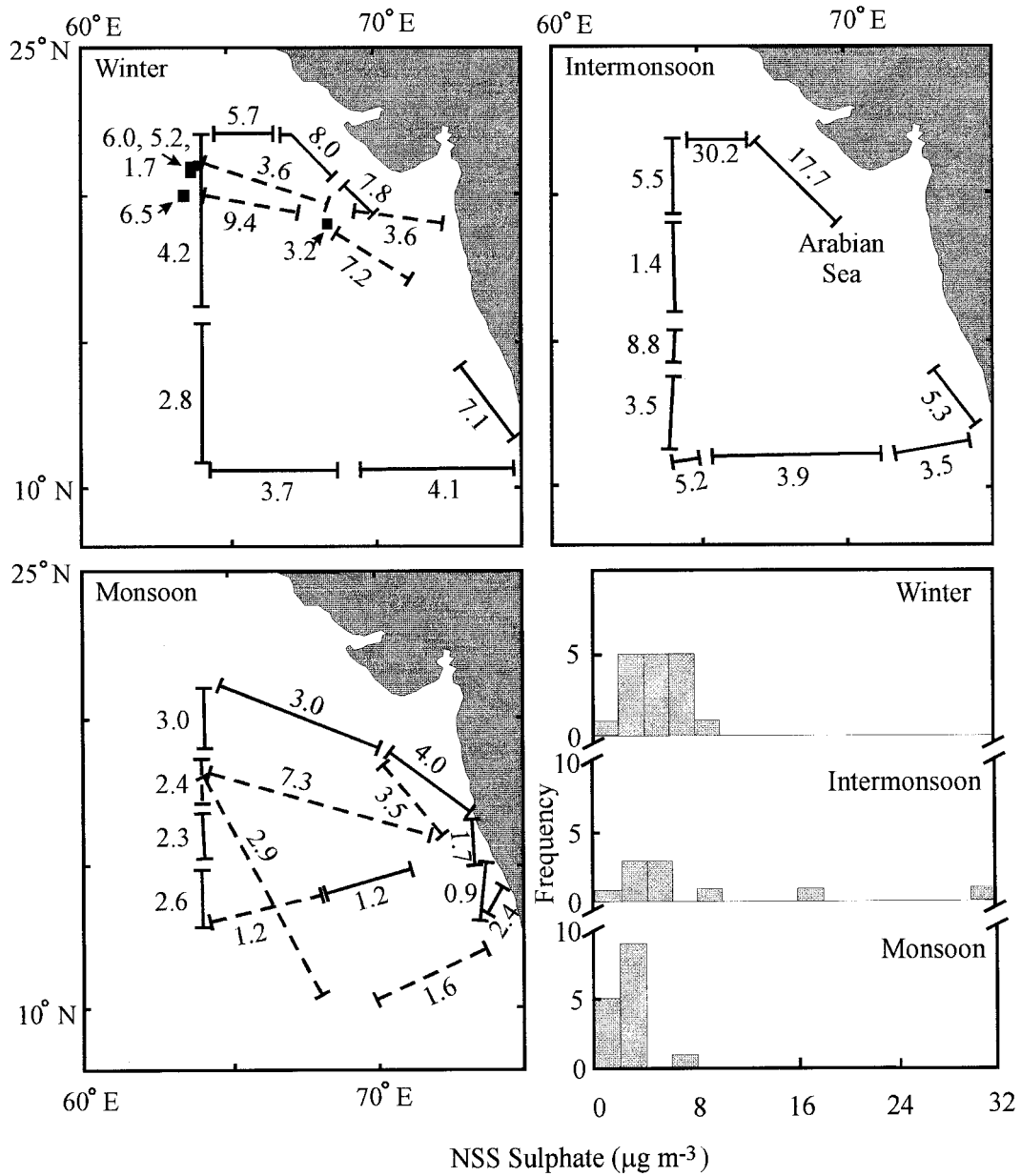


Fig. 2. Temporal and spatial variations in aerosol nss-sulphate concentrations. Two of the data points with exceptionally high nss-sulphate (30.2 and 17.7 $\mu\text{g m}^{-3}$) during the intermonsoon have been excluded from statistical analysis discussed in the text.

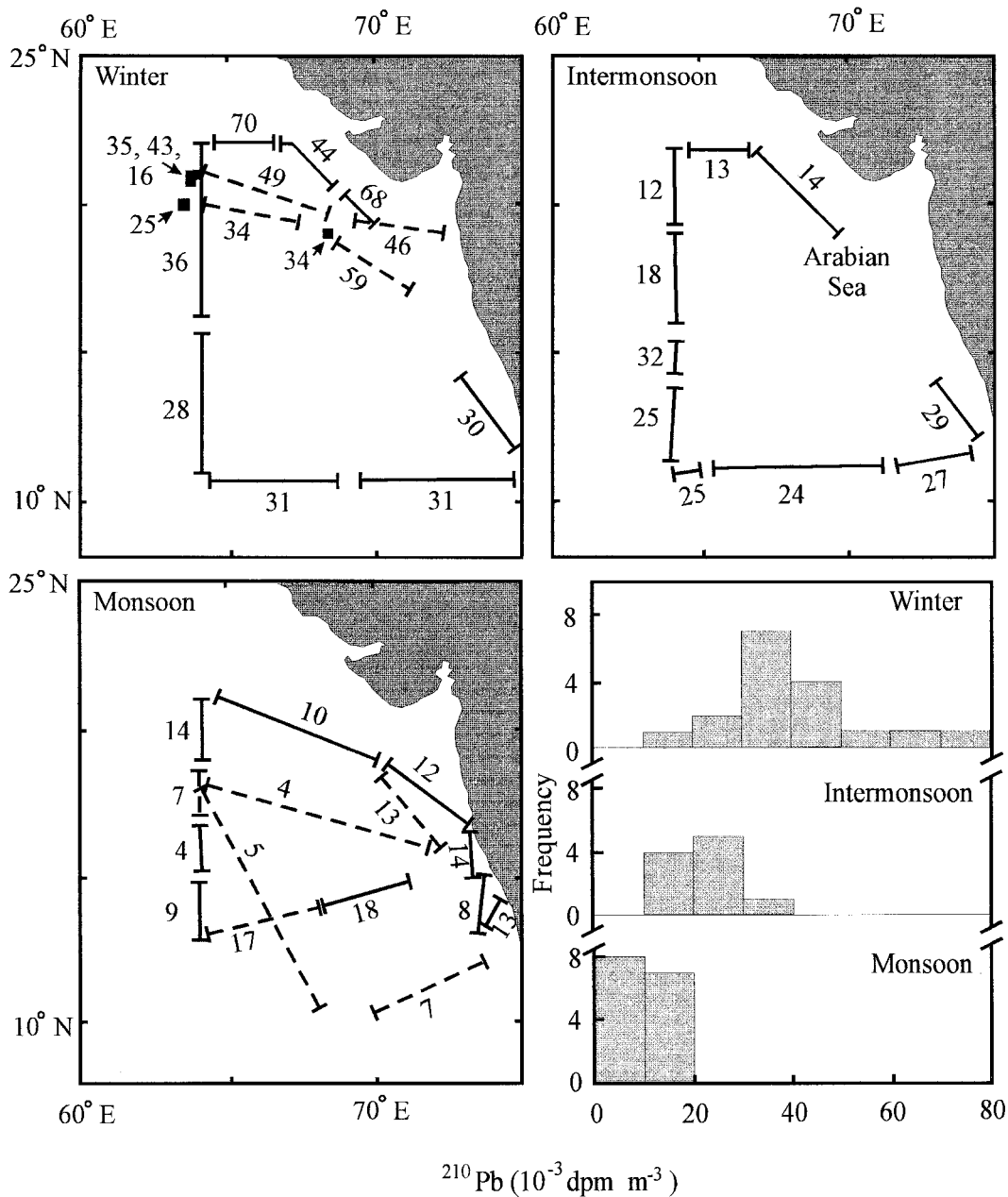


Fig. 3. Temporal and spatial variations in aerosol ^{210}Pb concentrations. The highest ^{210}Pb values occur during winter consistent with land to sea wind trajectories during this season. The frequency distribution in ^{210}Pb concentrations shows that the peak shifts from lowest in monsoon to highest in winter.

Table 1. Range and mean concentrations of NO_3^- , nss-SO_4^{2-} and ^{210}Pb in aerosols over the Arabian Sea

Sampling period	<i>n</i>	NO_3^-		nss-SO_4^{2-}		^{210}Pb	
		range	mean	range	mean	range	mean
<i>Intermonsoon</i>							
April–May 1994	10	0.4–1.8	1.1 ± 0.4	1.4–8.8*	$4.6 \pm 2.2^*$	12.3–32.2	22.0 ± 7.1
<i>Winter</i>							
February–March 1995	8	1.2–3.8	2.4 ± 1.0	2.8–8.0	5.4 ± 2.0	28.4–70.3	42.5 ± 17.3
February 1997	9	0.6–4.1	1.9 ± 1.0	1.7–9.4	5.2 ± 2.4	15.9–58.8	38.0 ± 12.9
(All Data)	17	—	2.1 ± 1.0	—	5.3 ± 2.1	—	40.0 ± 14.9
<i>Monsoon</i>							
July–August 1995	15	0.2–0.8	0.5 ± 0.2	0.9–7.3	2.7 ± 1.6	4.0–17.6	10.2 ± 4.4
July–August 1996							

n refers to number of samples. Concentrations are in $\mu\text{g m}^{-3}$ for NO_3^- and nss-SO_4^{2-} and 10^{-3} dpm m^{-3} for ^{210}Pb (dpm = disintegration per minute = 0.0167 Bq).

* Two data points with exceptionally high nss-sulphate have been excluded (Fig. 2).

nss-SO_4^{2-} as there could be volatile loss of chloride during the production of sea-salt aerosols (Cicerone, 1981; Keene et al., 1986). This has led to the use of Na and/or Mg as proxies to derive sea salt component of aerosols (Keene et al., 1986). This approach, however, could not be adopted in this study because of the contribution of Na to the samples from the glass fibre filters.

4. Discussion

Among the three seasons sampled, lowest concentrations of nitrate, 0.2 to $0.8 \mu\text{g m}^{-3}$ were recorded during the monsoon (July–August 1995 and 1996, Fig. 1). During the intermonsoon (April–May 1994), aerosol nitrate concentrations were relatively higher and ranged between 0.4 to $1.8 \mu\text{g m}^{-3}$. By far, the highest NO_3^- concentrations (0.6 to $4.1 \mu\text{g m}^{-3}$) were observed during winter (February–March 1995 and February 1997); particularly in the sections along the coast and in the 20° – 22°N latitudinal belt (Fig. 1). The mean aerosol NO_3^- concentration over the central-eastern Arabian Sea during winter is $2.1 \pm 1.0 \mu\text{g m}^{-3}$, about 4 times higher than that during the monsoon (Table 1). In comparison, Savoie et al. (1987) have reported nitrate concentrations in aerosol samples collected over the north-western Indian Ocean during January–June 1979; covering winter and intermonsoon periods. They concluded that nitrate abundance is related to

mineral dust loading of the atmosphere, with mean nitrate values of 0.43 and $1.01 \mu\text{g m}^{-3}$ for low and high dust loadings, respectively. These nitrate concentrations are lower than those observed in this study for the same seasons over the central-eastern Arabian Sea but are comparable to those measured during July–August (monsoon). This probably reflects spatial variations in the nitrate concentrations over the Arabian Sea and/or increase in the nitrate loading of the atmosphere between 1979 to 1995. The nitrate concentrations reported in this study for the non-monsoon period are also higher than those measured at the island stations in the North Atlantic (Barbados) and the Pacific (Savoie et al., 1989a; Savoie et al., 1989b; Savoie et al., 1992).

The sources and transport of nitrate to the marine atmosphere over the Arabian Sea have been investigated in relation to non-sea-salt sulphate and ^{210}Pb concentrations in the aerosols. Similar to the seasonal trend for nitrate, relatively higher concentrations of nss-sulphate (1.4 to $9.4 \mu\text{g m}^{-3}$), with an overall mean of $5.1 \pm 2.0 \mu\text{g m}^{-3}$, have been observed during the winter and the intermonsoon periods (Fig. 2). It is also noteworthy that during these two seasons, nss-sulphate constitute as much as 80–98% of the total-sulphate. During monsoon, nss-sulphate ranged between 0.9 to $7.3 \mu\text{g m}^{-3}$ with a mean concentration of $2.7 \pm 1.6 \mu\text{g m}^{-3}$, which is lower by a factor of ~ 2 than that during the non-monsoon periods (Table 1, Fig. 2). The sea-salt

sulphate accounts for 18–72% of the total sulphate; suggesting that during monsoon the influence of continental sources is relatively less pronounced. The earlier results from the Arabian Sea also show notably low nss-sulphate during May–September 1977 (Horvath et al., 1981). Savoie et al. (1987) have reported mean nss-sulphate concentrations of 1.1 and $2.7 \mu\text{g m}^{-3}$ in the aerosols over the north-western Indian Ocean during low and high dust loadings. It is also suggested that the highest concentrations of nss-sulphate in aerosols over north-western Indian ocean may be derived from gypsum in the soil material associated with dust outbreaks transported from the desert regions of Arabia, Iran, Pakistan and India (Savoie et al., 1987). During our sampling over the Arabian Sea, a dust storm was encountered at $20^{\circ}\text{N } 64^{\circ}\text{E}$ on 9th February 1997 lasting for ~ 15 h. The SO_4^{2-} concentration in samples collected during this time were generally higher relative to those collected before and after the dust storm. The impact of gypsum and soils in contributing to the high SO_4^{2-} , however, could not be assessed as Ca and dust concentration measurements were not made in these samples.

The scatter plot between nitrate and nss-sulphate exhibits strong seasonal variation with distinctly different trends during the monsoon and non-monsoon (intermonsoon and winter) periods (Fig. 4). This observation suggests that the relative contributions of these two species from various sources are different during the two seasons. The nitrate concentrations are higher during the non-monsoon periods and show an overall positive correlation with nss-sulphate; albeit scatter in the data (Fig. 4). The nitrate to nss-sulphate mass ratio (0.40) during February–March 1995 and February 1997 (Table 1) is nearly identical to that reported for the north-western Indian Ocean (0.38) by Savoie et al. (1987). During monsoon (July–August 1995, 1996), the nitrate concentrations are low and are nearly independent of nss-sulphate. The contribution from continental sources to the aerosols over the Arabian Sea is expected to be low during monsoon as the wind trajectories are from sea to land. This coupled with the generally higher biological productivity during this season would make oxidation of DMS an important component of nss-sulphate (Savoie et al., 1989). The rôle of continental aerosols would be more pronounced during winter when the winds are

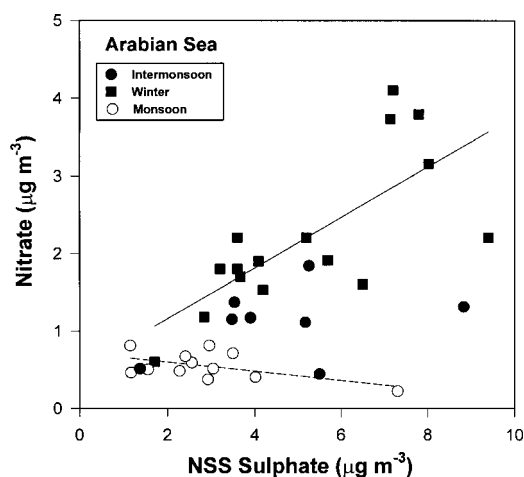


Fig. 4. Scatter plot of nitrate versus nss-sulphate. The data is suggestive of two distinct trends. Regression analysis of the winter and intermonsoon data ($n = 24$), yields correlation coefficient, $\gamma = 0.60$ ($P < 0.005$).

from land to sea. As discussed below, the measurements of nitrate and ^{210}Pb attests to this suggestion.

A better understanding of aerosol transport and the associated seasonal and spatial variations can be made using ^{210}Pb , a tracer of continentally derived aerosols. In this study, ^{210}Pb concentration has been determined during all the sampling seasons (Fig. 3) and provide the first measurements of aerosol ^{210}Pb over the central-eastern Arabian Sea. The ^{210}Pb concentrations (Fig. 3) in the samples show a steady increase from monsoon (4.0 to 17.6) $\times 10^{-3}$ dpm m^{-3} to intermonsoon (12.3 to 32.2) $\times 10^{-3}$ dpm m^{-3} and to the highest values during winter (15.9 to 70.3) $\times 10^{-3}$ dpm m^{-3} . The mean concentration of ^{210}Pb , $(40 \pm 14.9) \times 10^{-3}$ dpm m^{-3} during winter (Table 1) is factor of about 4 higher than that during monsoon $(10.2 \pm 4.4) \times 10^{-3}$ dpm m^{-3} . The mean ^{210}Pb concentration over this oceanic region, during monsoon, is comparable to those reported for the island stations from similar latitudes (as that of Arabian Sea) in the Pacific (Turekian et al., 1989). The higher concentrations of ^{210}Pb over the Arabian Sea during winter are attributed to greater influence of continentally derived aerosols consistent with wind trajectories, from land to sea during this season.

Fig. 5 is a scatter plot of ^{210}Pb versus nitrate

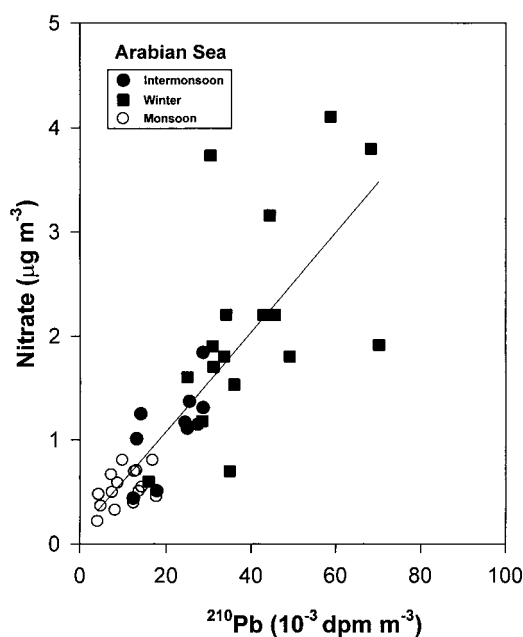


Fig. 5. Scatter plot of nitrate versus ^{210}Pb . Regression analysis of the data ($n=42$) yields the equation $\text{NO}_3^- (\mu\text{g m}^{-3}) = [43.3 \pm 1.0] ^{210}\text{Pb} + [0.07 \pm 0.01]$. A tight correlation ($r=0.81$, $P < 0.005$) between the two suggests the dominance of continental source for NO_3^- .

concentrations in the samples analyzed. Regression analysis of the data shows an overall positive correlation ($r=0.81$, $n=42$) between these two species and yields the following equation:

$$\text{NO}_3^- (\mu\text{g m}^{-3}) = [43.3 \pm 1.0] ^{210}\text{Pb} (\text{dpm m}^{-3}) + [0.07 \pm 0.01].$$

This correlation between ^{210}Pb and nitrate provides a strong evidence for continental source for nitrate. Based on a similar correlation between NO_3^- with ^{210}Pb concentrations at Barbados, Savoie et al. (1992) have concluded that NO_3^- is derived principally from continental sources. These observations are unlike those between nss-sulphate and ^{210}Pb concentrations which show large scatter without any discernible seasonal trends. This may be because nss-sulphate over ocean is derived from a variety of continental sources as well as from the oxidation of DMS. The average nss- $\text{SO}_4^{2-}/^{210}\text{Pb}$ ratio over the Arabian Sea during the monsoon is $260 \mu\text{g dpm}^{-1}$

which decreases to $\sim 133 \mu\text{g dpm}^{-1}$ during the winter (Table 1). A similar magnitude of decrease has also been observed in the nss- $\text{SO}_4^{2-}/\text{NO}_3^-$ ratio during these seasons. It is inferred from this comparison that ^{210}Pb and NO_3^- are derived from the same sources.

The dry deposition flux of nitrate over the Arabian Sea can be estimated from the measured NO_3^- concentrations and from the knowledge of the dry deposition velocity of nitrate aerosols. Over the oceans, nitrate aerosol has a mass median diameter of few micrometers and its mass being distributed on the surfaces of sea salt aerosol (Duce et al., 1991). The dry deposition velocities of these aerosols are in the range of 0.2 to 1.0 cm s^{-1} . Using typical deposition velocity of 0.3 cm s^{-1} (Duce et al., 1991) and aerosol NO_3^- concentrations of 0.5 , 1.1 and $2.1 \mu\text{g m}^{-3}$ during monsoon, intermonsoon and winter, respectively (Table 1), the corresponding dry deposition fluxes of nitrate to surface Arabian Sea are calculated to be 0.13 , 0.3 and $0.6 \text{ mg m}^{-2} \text{ d}^{-1}$. The wet deposition flux of nitrate is more difficult to estimate as data on the precipitation and scavenging ratio at the sampling sites are not available. However, using a value of 100 cm yr^{-1} for precipitation and scavenging ratio of 350 , typical of inland stations (Duce et al., 1991; Galloway et al., 1993), and aerosol NO_3^- concentration of $0.5 \mu\text{g m}^{-3}$ during monsoon (Table 1); the wet deposition nitrate flux is estimated to be $0.4 \text{ mg m}^{-2} \text{ d}^{-1}$. These calculations yield a value of $0.53 \text{ mg m}^{-2} \text{ d}^{-1}$ for the total deposition (dry + wet) flux of nitrate over the central-eastern Arabian Sea during monsoon; the wet deposition being the dominant component. The estimates of Duce et al. (1991) for the northern Indian Ocean also show that wet deposition accounts for $\sim 75\%$ of the total nitrate air-sea flux.

An independent estimate of nitrate deposition flux can be obtained from the measured $\text{NO}_3^-/^{210}\text{Pb}$ ratio in the aerosols and ^{210}Pb deposition flux in the region. This approach assumes that ^{210}Pb and NO_3^- are deposited on the sea surface in the same ratio as their measured abundances in the aerosols. This would require that NO_3^- and ^{210}Pb are associated with similar size of aerosols and that their scavenging efficiencies from the atmosphere are the same. Available data on the size distribution of atmospheric nitrate and ^{210}Pb show that ^{210}Pb is associated with sub-micrometer size aerosols (Knuth et al., 1983), significantly smaller than the micrometer size

nitrate aerosols. This would make the ratio of the dry deposition fluxes of nitrate to ^{210}Pb much higher than the $\text{NO}_3^-/^{210}\text{Pb}$ abundance ratio in aerosols. In contrast, the wet $\text{NO}_3^-/^{210}\text{Pb}$ deposition flux ratio is expected to be quite similar to their abundance ratio in aerosols as their scavenging ratio, by precipitation are similar, with values of ~ 350 (Knuth et al., 1983; Duce et al., 1991; Galloway et al., 1993). Thus, the total deposition (dry + wet) flux ratio of nitrate to ^{210}Pb could be higher than the $\text{NO}_3^-/^{210}\text{Pb}$ ratio in aerosols over the sea surface because of the relatively higher dry-deposition of nitrate.

We have measured the ^{210}Pb deposition flux in the Arabian Sea at 130–150 m below the surface by deploying floating sediment traps for 3–5 days during April–May 1994, February–March 1995 and 1997 at 21°N , 64°E and 15°N 64°E . The trap fluxes are a direct measure of the atmospheric deposition as it is the dominant source of ^{210}Pb to surface waters (the in-situ production of ^{210}Pb from the decay of ^{226}Ra in surface waters is insignificant compared to its atmospheric fallout). The ^{210}Pb supplied to surface waters is adsorbed onto particles and removed with a residence time of ~ 1 year. A major uncertainty in using the shallow traps to obtain atmospheric ^{210}Pb deposition fluxes relates to their collection efficiency for the settling particles. In this study, the collection efficiency of the traps have been calibrated by comparing the ^{234}Th fluxes measured in the traps with that expected based on $^{234}\text{Th} : ^{238}\text{U}$ disequilibrium measured in the water column (Sarin et al., 1999; manuscript in preparation). The measured ^{210}Pb fluxes, after correcting for trap efficiency, are in the range of 10 to 26 $\text{dpm m}^{-2} \text{d}^{-1}$ similar to those based on model predictions (Turekian et al., 1977).

The regression analysis of the data in Fig. 5 yields a value of $43.3 \pm 1.0 \mu\text{g dpm}^{-1}$ for the $\text{NO}_3^-/^{210}\text{Pb}$ ratio. Using this ratio and the depositional flux of ^{210}Pb as $20 \text{ dpm m}^{-2} \text{d}^{-1}$, the nitrate deposition flux over the central-eastern Arabian Sea is calculated to be $0.9 \text{ mg m}^{-2} \text{d}^{-1}$. The NO_3^- flux thus computed over the Arabian Sea is comparable to that estimated earlier based on assumed values for deposition velocities, scavenging ratio and precipitation. The atmospherically derived nitrate flux ($0.9 \text{ mg m}^{-2} \text{d}^{-1}$) to the mixed layer, however, is insignificant compared with NO_3^- fixed by the primary production,

$225\text{--}800 \text{ mg m}^{-2} \text{d}^{-1}$ in this region (Bhattathiri et al., 1996), and with the nitrate flux of $\sim 60 \text{ mg m}^{-2} \text{d}^{-1}$ supplied from the base of the euphotic zone (Sarin et al., 1994). The measured concentration of ^{210}Pb in the aerosols and its deposition flux over the study region allow us to calculate the “effective deposition velocity” of ^{210}Pb aerosols. The annual mean ^{210}Pb concentration of $25 \times 10^{-3} \text{ dpm m}^{-3}$ (Table 1, Fig. 3) and its measured flux of $20 \text{ dpm m}^{-2} \text{d}^{-1}$ would yield the deposition velocity of $\sim 0.9 \text{ cm s}^{-1}$. This falls within the range of values, 0.2 to 1.0 cm s^{-1} , used for aerosol deposition.

5. Conclusions

The transport of chemical constituents from continental sources plays a dominant rôle in the chemistry of aerosols over the central-eastern Arabian Sea as reflected by the enhanced concentrations of NO_3^- , nss-SO_4^{2-} and ^{210}Pb during the winter and intermonsoon. Based on the measured NO_3^- and ^{210}Pb concentrations in the aerosol and ^{210}Pb deposition flux at ~ 150 m in the Arabian Sea, the air–sea NO_3^- deposition flux is computed to be $0.9 \text{ mg m}^{-2} \text{d}^{-1}$. This is comparable to that calculated using typical values of dry deposition velocity, scavenging ratio and precipitation. The atmospheric deposition of NO_3^- is not a significant source of “new” nitrate to the eastern-central Arabian Sea surface waters. These results have brought to focus the use of ^{210}Pb for better understanding of the sources and transport of aerosols and their deposition fluxes over the Arabian Sea.

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