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Aerosols over the Arabian Sea: Atmospheric transport pathways and concentrations of dust and sea salt

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Abstract

This paper provides an overview of dust transport pathways and concentrations over the Arabian Sea during 1995. Results indicate that the transport and input of dust to the region is complex, being affected by both temporally and spatially important processes. Highest values of dust were found off the Omani coast and in the entrance to the Gulf of Oman. Dust levels were generally lower in summer than the other seasons, although still relatively high compared to other oceanic regions. The Findlater jet, rather than acting as a source of dust from Africa, appears to block the direct transport of dust to the open Arabian Sea from desert dust source regions in the Middle East and Iran/Pakistan. Dust transport aloft, above the jet, rather than at the surface, may be more important during summer. In an opposite pattern to dust, sea salt levels were exceedingly high during the summer monsoon, presumably due to the sustained strong surface winds. The high sea salt aerosols during the summer months may be impacting on the strong aerosol reflectance and absorbance signals over the Arabian Sea that are detected by satellite each year.

1. Introduction

The atmosphere is increasingly being recognized as a significant source of nutrient, micronutrient and pollutant material to both open ocean and coastal surface waters. Atmospheric material, usually in the form of aerosols and mainly originating from

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continental regions, is transported out over marine regions, often being carried considerable distances before being deposited to the surface waters. Wet deposition is an important removal mechanism, although dry deposition is important in many regions where the concentration of larger, heavier atmospheric particles is high and rainfall amounts are low or nonexistent. The input of material to the ocean surface is often very episodic and can vary considerably spatially. Many studies have indicated that the input of nutrients and micronutrients from the atmosphere can impact biogeochemical cycles and biological productivity in coastal and open ocean surface waters (Duce, 1986; Maring and Duce, 1987; Betzer et al., 1988; Young et al., 1991; Duce and Tindale, 1991; Paerl, 1993; Martin et al., 1994; Coale et al., 1996) and the flux of material from the surface to the deeper ocean (Buat-Menard and Chesselet, 1979; Jickells et al., 1987). The significance of the input of material from the atmosphere to the ocean will presumably vary with each oceanic basin.

One of the regions most likely to be affected by atmospheric dust inputs is the Arabian Sea. Part of the uniqueness of this region is that it is heavily influenced by atmospheric forcing. Strong seasonal monsoon winds drive ocean current reversals, increase surface mixing and upwelling, and significantly affect productivity (Olson, 1990; Smith et al., 1991). The appearance of the two seasonal monsoons, the Southwest in summer (June–September inclusive) and the Northeast in winter (December–February inclusive) dominates the regional climatology. The two Intermonsoon periods in autumn (October and November) and spring (March and April) are transitional periods (Olson, 1990; Schott et al., 1990; Smith et al., 1991). A compilation of the average monthly surface airflow for the Arabian Sea region is included in a UK Meteorological Office monograph by Findlater (1971), after whom the strong, low-level, atmospheric jet that is associated with the Southwest Monsoon, is commonly named. The strong atmospheric flow also provides a mechanism to uplift and transport particulate material from the land to the ocean. The Arabian Sea is bounded on three sides by arid and semi-arid land areas that are acknowledged sources of desert dust and dust clouds, particularly areas to the north of the Arabian Sea, in the Middle East, Iran, and Pakistan (Pye, 1987). Therefore, dust production and transport should exhibit a strong seasonal signal associated with the two monsoon periods. The seasonal signal also should be evident in precipitation that could significantly impact dust production and removal from the air.

The flux of dust to the Arabian Sea depends on deflation and vertical uplift at the source areas (related to surface characteristics and cover, soil moisture, wind strength and direction), the atmospheric transport pathways (wind strength and direction, cloud and rain processes), and deposition (wet and dry). Other sources of aerosols include locally produced marine aerosols (sea salt), anthropogenic sources (from wood stoves, cooking fires, light industry, and urban areas that ring the Sea), and organic aerosols (from both terrestrial and oceanic sources).

The United States' Joint Global Ocean Flux Study (US JGOFS) Arabian Sea Process Study provided an opportunity to study the source, transport, input, and importance of atmospheric fluxes to the ocean. The US JGOFS goals included: (1) to determine and understand processes controlling time-varying fluxes of carbon and associated biogenic elements in the ocean; and (2) to predict the response of marine

biogeochemical processes to climate change. Specific questions related to atmospheric fluxes included: "What was the influence of aeolian dust on primary productivity; and, how did this input vary during the different monsoon seasons?" (Smith et al., 1991). Our role in the Arabian Sea Process Study was primarily to identify and quantify the dust source regions, transport, and input. This paper provides an overview of dust transport pathways and concentrations over the Arabian Sea during the US JGOFS Process Study.

2. Methods

Aerosol samples were collected on six of the US JGOFS cruises during 1995, and three of the US Office of Naval Research (ONR) sponsored Forced Upper Ocean Dynamics Program cruises (cruise numbers and dates: TN043, 1 Jan.–4 Feb.; TN044, 8 Feb.–25 Feb.; TN045, 14 Mar.–10 Apr.; TN048, 21 Jun.–13 Jul.; TN049, 17 Jul.–15 Aug.; TN050, 17 Aug.–15 Sep.; TN051, 18 Sep.–11 Oct.; TN053, 28 Oct.–26 Nov.; and TN054, 29 Nov.–24 Dec.). Samples were obtained during both monsoon periods and in the intervals between them. The actual transitions between seasons should be considered a gradual shifting over several days or more and not an abrupt transition. Dust transport to the sea should vary depending on seasons. To provide information on the possible origin of the air that the aerosol samples were collected from, transport pathways for individual parcels of air were calculated using a global isentropic trajectory model.

One significant problem with reporting atmospheric data collected from ships is that the data are obtained neither in the Lagrangian nor Eulerian frame of reference. Most atmospheric monitoring data are collected from land-based air sampling stations, and the data typically reflect the passage of different air masses over the sampling site. Alternatively, data collected from aircraft or free-floating balloons are often Lagrangian in that the aircraft or balloon can move with the air. The aircraft or balloon data thus ideally reflect processes occurring within that particular air mass. Sampling from a ship unfortunately adds a complication in that during a typical, month-long, sampling cruise, not only do air masses pass over the ship, but the ship also can move from one different atmospheric or climatic region to another. An obvious example is that the ship can move from nearshore to offshore waters over a several day period, increasing the distance from terrestrial sources of aerosols, and changing the relative impact of marine and aerosol sources of material to the ocean surface.

2.1. Aerosol sample collection

The aerosol samples were collected by pulling air through cellulose matrix filters located in precleaned polyethylene filter holders. The filters were mounted on the outside of the tower rails at the top of a 6 m, walk-up, aluminum-scaffolding tower erected near the bow of the R/V *Thomas G. Thompson*. Samples were collected when the wind was blowing from over the bow and the relative wind speed was at least

$2\ m\ s^{-1}$. Air sampling was discontinued if other ships were upwind and there was a possibility of sampling their plumes, or if the operation of the R.V. *Thompson* would lead to it potentially passing through its own plume. The relative wind speed and direction were monitored when sampling, but the meteorological data discussed in this paper were from the IMET systems installed on the ship and on the Woods Hole central buoy (Weller et al., 1998).

The air sampling pumps, controller, electronics, and a clean bench were mounted in a 6-m shipping container located on the foredeck's container storage rack. The air sampler was a HiVol system loaded with a single unwashed Whatman 41® filter and with a flow rate of ~ 1.2–$1.4\ m^3\ min^{-1}$. Air flow rates were measured daily using an orifice-type flow tube that had been calibrated to a National Institute of Standards and Technology (NIST) certified EG&G FT32 turbine flowmeter. Air volume errors were between 5 and 10%; the total combined air volume and analytical error was about 10%. The experimental equipment was similar to that described in Schwartze et al. (1988) and used on previous atmospheric-oceanographic programs (Betzer et al., 1988).

One problem with using the HiVol sampler was that the filter holder was sheltered, to prevent rain and sea spray from reaching the filter. Unfortunately, the shelter also prevents dust particles larger than about 20–30 μm from reaching the filter. It is therefore highly probable that we were undersampling the total mass of aerosol material in the atmosphere by some unknown fraction, especially during periods when larger dust particles were present. Therefore, the dust values reported here should be considered lower limit values.

The aerosol filter samples were changed and processed in a Class-100 clean hood located in the bow laboratory van. The exposed filters were removed from the filter holders, folded, and stored in heat-sealed clean polyethylene bags for return to the laboratory at Texas A&M University for analysis. The samples were processed in our laboratory at Texas A&M within a Class-100, polypropylene, trace-metal free, clean hood. Between handlings, the samples were kept sealed and stored in an upright freezer ($-4°C$). An eighth of each sample was cut out for analysis using trace-metal clean plastic scissors. This portion of the filter was then compressed into a small pellet using a stainless steel press fitted with titanium end caps and a Delrene™ liner. The pellets were chemically analyzed by instrumental neutron activation analysis (INAA) using the 1 MW research reactor at the Texas A&M University Nuclear Science Center. Sample preparation and analysis techniques were similar to those used in earlier studies (Duce et al., 1983; Schwartze et al., 1988).

2.2. Air-mass back trajectories

To aid in the interpretation of the aerosol data collected onboard the ship, daily air mass transport trajectories were calculated for the periods during which each sample was collected. These "reverse" trajectories were calculated back in time and space from the location of the ship when the sample was collected. Often the ship was moving during the sampling period, so the mid-point of the ship's position was used as

the starting location for the air mass trajectory calculation. Most of the back trajectories were calculated for 5-day periods. Occasionally, missing wind-field data limited the length of time for which a back trajectory could be calculated, or prevented the calculation from being made at all.

The back-trajectory model itself is an isentropic wind-field surface model in which the movement of a parcel of air is dependent on the wind speed and direction at the location of the air parcel, pushing it along a surface of constant potential temperature. The trajectory model used in this study is similar to the early models used by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) Atmospheric Trajectories group and others that have been used to study the transport of material in the atmosphere (Harris, 1982; Merrill, 1985; Harris and Kahl, 1994). Wind, pressure, and temperature input to the trajectory model is in the form of 2.5×2.5 degree latitude–longitude gridded analysis data from the US National Centers for Environmental Prediction's (NCEP) medium-range weather forecast (MRF) model.

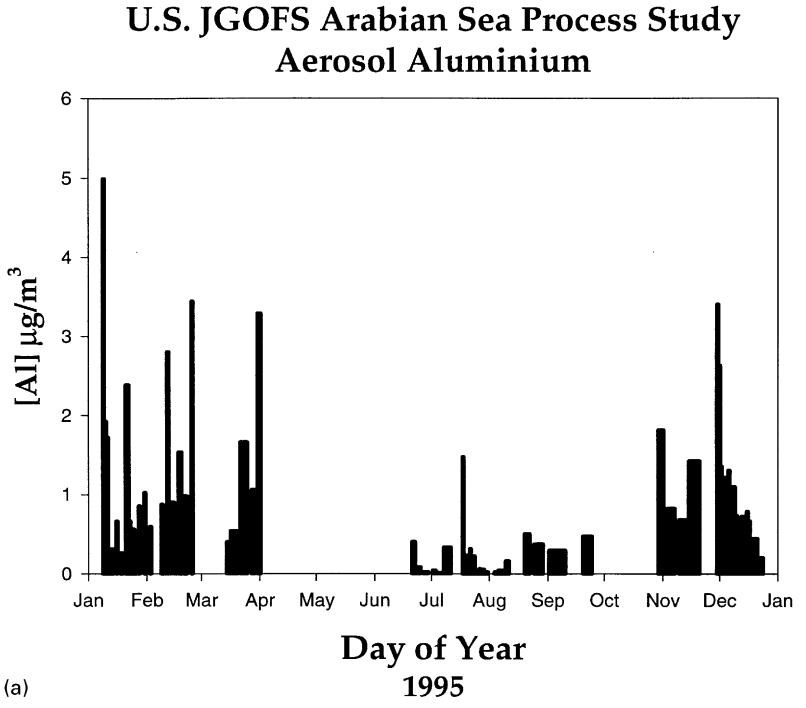
It is important to remember that the trajectory model provides a representative pathway of air mass movement in the regional, large-scale circulation, not the actual movement of any particular small parcel of air. There are many uncertainties in this type of model and analysis including the lack of spatially relevant meteorological data from oceanic areas and the effect of interpolation to provide sub-grid scale detail. However, the trajectories produced by the model can provide useful suggestions as to the source region(s) of particular aerosol samples and the general atmospheric transport conditions for the study region during the periods the samples were collected. Uncertainties associated with the use of air mass trajectory models have been discussed in more detail by a number of authors (Merrill et al., 1985; Harris, 1992; Kahl, 1993).

Wind speed and direction data from the NCEP analysis also were used to create surface level (1000 mb) wind-fields for the Arabian Sea and surrounding region. The wind-field maps could be compiled for daily, monthly, and seasonal averages and for the duration of each cruise. Each wind-field map is an average of the 12-hour, model derived, wind velocity fields at the surface over the period of interest.

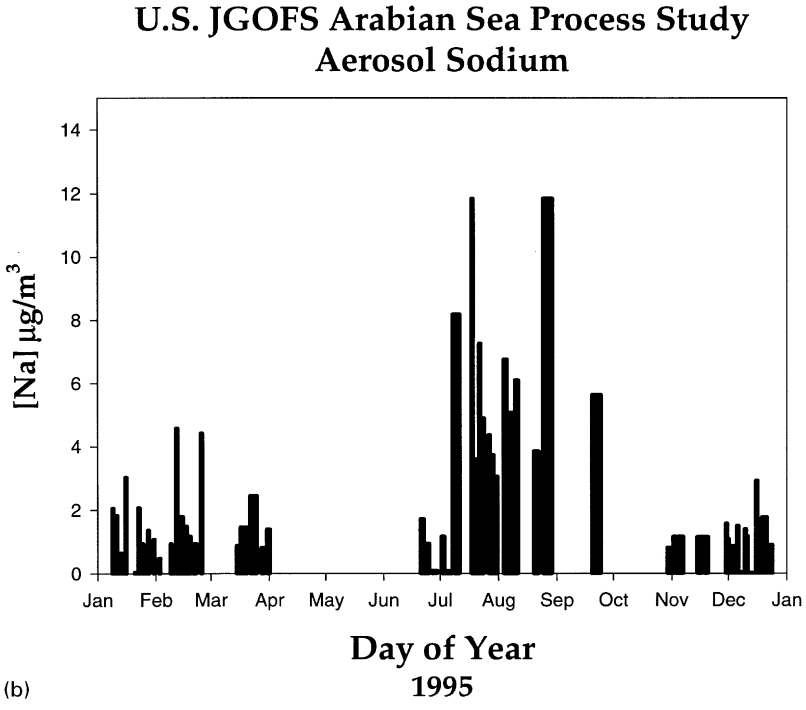
3. Results

The number of aerosol samples collected on each cruise varied as a result of the air sampling conditions, which were affected primarily by weather, sea conditions, and operation of the ship. Some samples were known to be contaminated or lost because of mishandling or sampling problems. These samples were discarded and not included in the data set.

Results for the aerosol aluminum concentration in the Arabian Sea atmosphere are presented in Fig. 1a. The large gaps in the data record, particularly during early summer and October, were due to cruises in which we did not participate. Aluminum concentrations in the air, as measured from the ship, showed considerable variability,


U.S. JGOFS Arabian Sea Process Study
Aerosol Aluminium
[Al] µg/m3
0
1
2
3
4
5
6
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Day of Year
1995

(a)


U.S. JGOFS Arabian Sea Process Study
Aerosol Sodium
[Na] µg/m3
0
2
4
6
8
10
12
14
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Day of Year
1995

(b)

often from day to day. Concentrations ranged from 0.01 to almost 5.0 micrograms of material per cubic meter of air. Aluminum is typically used as an indicator of mineral material (Duce et al., 1991), and assuming the ratio of Al in dust to be the same as in upper crustal material (8.04%, Taylor and McLennan, 1985), this translates into dust values of 0.12–60 $\mu g\, m^{-3}$.

Interestingly, the mean crustal ratio of 8.04% did not apply to surface "silt/clay" samples (dry-sieved surface soil particles < 63 μm) collected from the desert and wadis in coastal Oman. These samples were composed typically of a mixture of fine silt, clay and carbonate material. The average ratio of Al to mass in these surface samples was consistently lower, around 2.8%. Trace mineral ratios for these samples also differed considerably from crustal ratios (Pease et al., 1998). The elemental ratios in the aerosol samples were also non-crustal and appeared to vary as a function of aerosol sample location (Pease et al., 1998). Aerosol samples collected in the NE Arabian Sea region had elemental ratios that tended to the Oman silt/clay values, indicating that the local sources of mineral aerosols were contributing to the samples, and were likely predominant in some cases (Pease et al., 1998). Elemental and mineralogical analysis of individual dust particles collected during the TN049 cruise (17 July–15 August), using scanning electron microscopy/energy dispersive X-ray analysis (SEM/EDXA), also gave noncrustal elemental ratios for particle diameters from 0.1 to 5 μm (Seymour et al., unpublished data). The aerosol and silt/clay samples also contained significant carbonate material (as much as 30% and variable depending on particle size fraction) thus preventing mineral aerosol weights from being determined by high-temperature ashing and weighing. Based on the significant influence of local dust sources on our aerosol samples, the average ratio of Al in Omani silt was used in this paper to calculate estimated seasonal atmospheric mineral dust loadings from about 0.3 to 180 $\mu g\, m^{-3}$ (Fig. 2). Using the Omani ratio overpredicts dust levels in the southern reaches of the Arabian Sea but represents higher levels for samples collected closer to the coast. The Al (and dust) levels are comparable to, and within the range of, previous values reported for this general region (Sadasivan, 1978; Chester et al., 1985; Savoie et al., 1987; Chester et al., 1991).

The observed aluminum concentrations peaked in the winter and spring months, were slightly lower during the fall period, and lowest during the summer (Table 1). Average values of dust for summer were around 8 $\mu g\, m^{-3}$, whereas winter and spring values were over 40 $\mu g\, m^{-3}$ (using Al/Omani "silt/clay" ratio). Other elements associated with mineral material, such as Fe, had a similar distribution and relative levels (Table 1). Day-to-day variations in elemental concentrations could be more than an order of magnitude. Elemental ratios also varied depending on season and sampling location (Pease et al., 1998). In an almost completely opposite pattern to the mineral aerosols, sea salts showed a pronounced peak during the summer Southwest Monsoon period (Fig. 1b). The enhanced sodium signal in the atmospheric boundary layer correlates to increased surface wind speeds observed during the summer monsoon

Fig. 1. (a) Aerosol aluminum over the Arabian Sea during the US JGOFS Process Study in 1995. (b). Aerosol sodium over the Arabian Sea during the US JGOFS Process Study in 1995.

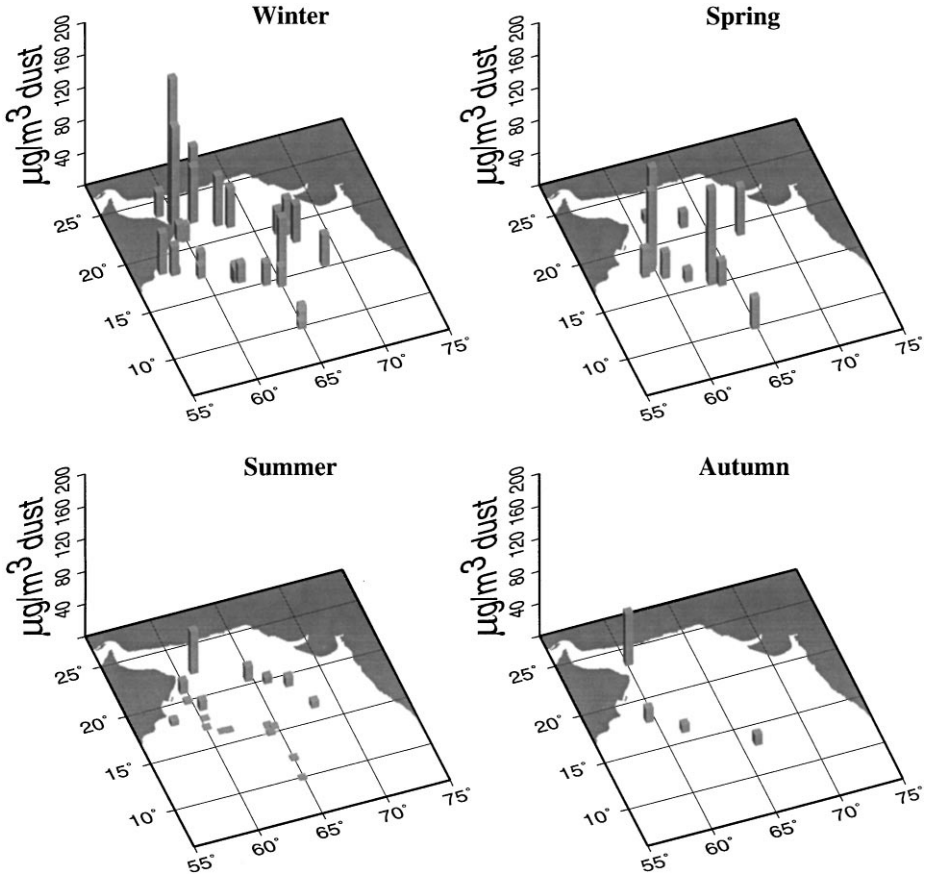


Fig. 2. Aerosol aluminum: seasonal 3D spatial plot of all samples.

Table 1
Seasonal mean concentrations of selected elements in 70 aerosol samples

		Winter	Spring	Summer	Fall
Na	Range (µg m^{-3})	0.12–4.58	0.71–2.40	0.07–11.83	0.81–11.84
	Mean (µg m^{-3})	1.25	1.28	4.45	2.15
	Mean ratio	3.93	4.54	140.26	11.52
A1	Range (µg m^{-3})	0.20–4.99	0.32–3.29	0.01–1.47	0.29–1.81
	Mean (µg m^{-3})	1.19	1.21	0.23	0.86
Fe	Range (µg m^{-3})	0.15– 2.64	0.32– 2.13	0.03–0.95	0.23– 0.88
	Mean (µg m^{-3})	0.88	1.17	0.32	0.42
	Mean ratio	1.49	2.04	2.27	1.6

Note: In µg m^{-3} and as a ratio of "dust" as calculated from A1 concentration, based on average of surface "silt/clay" samples collected in Oman.

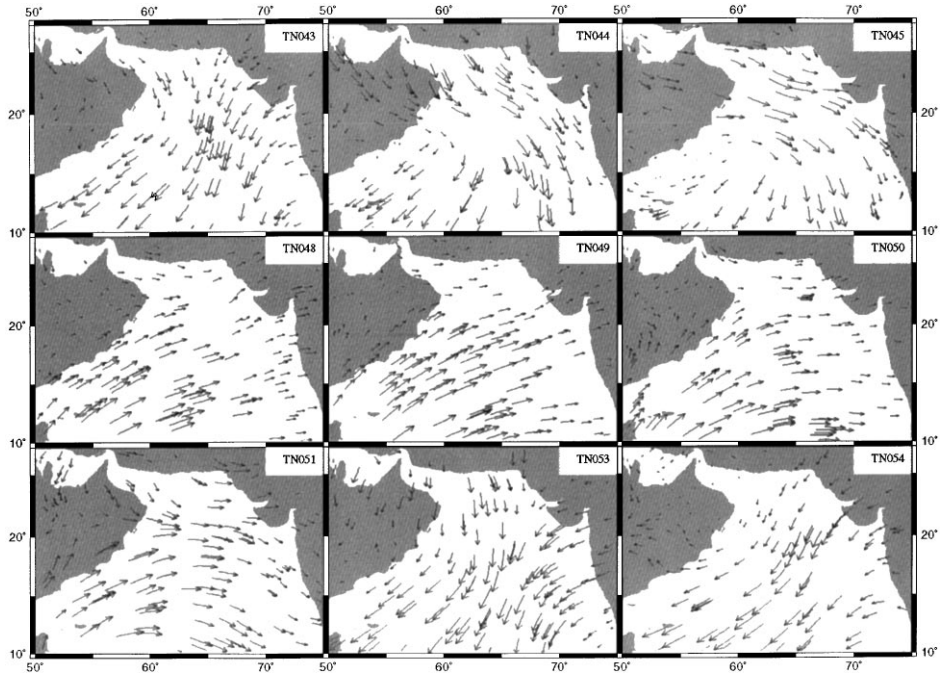


Fig. 3. Model-derived, surface wind-field (1000 mb) plots for each US JGOFS cruise on which samples were collected. Each wind-field plot is the average of surface wind conditions for that cruise.

cruises (Weller et al., 1998), and to the average wind velocities for the cruises during this period (Fig. 3). The observed sea salt concentrations up to $30\,\mu g\,m^{-3}$ are comparable to those predicted for the region using a wind-speed-dependent model of production (Erickson et al., 1986). There was excellent agreement between the model prediction and the observed sea-salt levels at high winds, but the model overpredicted levels during calmer conditions.

While the two-dimensional Fig. 1a presents the daily-to-seasonal variation in aerosol aluminum values for the JGOFS study, it does not provide any information on the spatial variability of aerosol concentrations. The US JGOFS sampling strategy included a range of stations that covered much of the Arabian Sea from off the coast of Oman down to 10°N and from about 55°E to almost 70°E. To appreciate better the spatial distribution of the aerosol material, dust values are plotted in a seasonal, 3D-geographical distribution (Fig. 2). In general, higher dust concentrations were found in samples collected closer to the Omani coastline and the entrance to the Gulf of Oman. For practically all cruises, dust concentrations decreased as the ship moved further offshore. There was also a strong seasonal signal, being higher in winter and spring and lower in summer and autumn, although the sampling was not continuous throughout the year, with particularly few samples collected during the autumn. Overall results indicate that both temporal and spatial variability of dust production and transport is important for determining dust levels over the Arabian Sea.

3.1. Atmospheric transport

While the distance from the dust-source regions surrounding the Arabian Sea varied depending on the location of the ship, the transport pathway that the air had to take to get to the ship was also important. Even though the aerosol samples were collected effectively at sea level, the air that reached the ship's location could have come from several directions and altitudes, and could have passed over more than one dust source region depending on the atmospheric transport pathway and mixing. Air-mass back-trajectories reflected the general meteorological flow for that region and season. The average 1000 mb wind-field maps for each cruise showed clear patterns of surface winds associated with each monsoon season and the transitional intermonsoon periods (Fig. 3). Based on the wind-field maps, and air-mass back-trajectories, air-mass transport pathways have been separated into somewhat distinct source directions depending on ship location and season. Many of the trajectories for samples collected close to shore originated from the Middle East, passed directly over the Arabian peninsula, and then out over the Arabian Sea. Other trajectories showed a similar pattern but originated more from Iran, Pakistan, or occasionally northern India. This flow from the north was particularly apparent during the Northeast Monsoon and Intermonsoon periods. Occasionally some trajectories indicated that the air had come from the south and southwest and was mainly marine air associated with weak winds and low aerosol levels. Conversely, for samples collected offshore, particularly those collected near the southern limit of the study region, many of these trajectories reached back into the equatorial area and even into the Southern Hemisphere. Seasonally, the air-mass trajectories showed the influence of the respective monsoons although the actual transport direction appeared also dependent on the location of the ship relative to the coastline (a more detailed analysis of the impact of trajectories on aerosol geochemistry is included in Pease et al., 1998).

4. Discussion

4.1. Southwest Monsoon

While the observed aerosol values in the Arabian Sea regions generally agreed with previous observations, mineral dust concentrations were remarkably low during the summer Southwest Monsoon period. This is the seasonal period where satellite images had indicated aerosol reflectance and absorbance values are at their highest (Sirocko and Sarnthein, 1989; Codispoti, 1991; Husar et al., 1997; Herman et al., 1997). The frequency of haze, as reported in routine ship observations of maritime weather, also was highest in summer (Pye, 1987). In addition, the intense low-level jet associated with the Southwest Monsoon, the Findlater Jet (Findlater, 1971), could provide a rapid pathway for dust to reach the central Arabian Sea from the Horn of Africa, particularly the desert areas in Somalia (Clemens et al., 1991).

Even though the dust levels were generally lower during the Southwest Monsoon period, there was considerable day-to-day variability in values, and the higher

summer values were still elevated compared to dust levels in most other marine regions around the world (Duce, 1995). Sampling conducted by Savoie and colleagues off the coast of Africa in the northwest Indian Ocean showed a similar pattern of lower values during summer which they attributed to southern hemisphere air mixing in from the equator (Savoie et al., 1987). Dust levels in the southern hemisphere are generally much lower due to a relative absence of dust source regions (Duce, 1995).

There are several possible explanations for the lower summer dust levels. Surface level winds and back trajectories indicate that the air reaching the central Arabian Sea during the Southwest Monsoon was predominately from the west, southwest, or even south, depending on how far off the Omani coast the ship was (Fig. 3). This suggests that dust sampled closer to shore had originated possibly from Iran, or the Arabian Peninsula (Oman, Saudi Arabia or possibly Yemen, or from further upwind). Samples from the southwest Arabian Sea may have originated from the Horn of Africa region. In contrast, samples collected in the center of the Arabian Sea and/or closer to India often had associated surface-level wind-field patterns that originated from off the coast of Africa in the equatorial region or from the open ocean further south, even the Southern Hemisphere. Thus, the atmospheric boundary layer appears to exhibit a similar circulation pattern at the surface as do the ocean currents. Air appears to be swept or diverted into the core of the Findlater Jet from adjacent geographic locations. The source regions for this air are controlled by the location of the jet, particularly the location of the axis of the jet. The axis of the low-level jet typically lies southwest–northeast, and the Arabian Sea receives air from the corresponding flanks of the jet, isolating the two sides. As the jet forms in the equatorial region near the coast of Africa, relatively dust-free, surface-level air is carried up into the Arabian Sea region by the Findlater Jet. This scenario is consistent with the monthly NCEP, average, surface-wind profiles (Fig. 3) and the monthly mean airflow records at 1 km altitude (Findlater, 1971). Northwest of the axis of the Findlater Jet, the surface flow is either parallel to the Oman coast or offshore, depending on how close the axis is to the coastline. The offshore winds, whose intensities depend on the closeness of the jet, could bring air from the deserts out into the northern Arabian Sea. Thus, dust concentrations would be expected to be higher closer inshore and towards the northern Arabian Sea and Gulf of Oman, than further south or southwest.

Another atmospheric phenomenon that affects dust production and transport is the Shamal, a persistent, regional-scale wind that blows from the north and northwest during the summer and is stronger during the day than at night (Membery, 1983). Dust storms are often associated with the Shamal, and it impacts the Arabian Gulf, Gulf of Oman, and coastal waters of the northern Arabian Sea (Membery, 1983). More local, coastal, land-sea breeze effects off the coast of Oman, which could be part of the Shamal, may also play a role in moving dust offshore. Larger-scale features of the Shamal should be included in the NCEP windfield analysis in Fig. 3.

In addition to the effect of the low level jet, a decoupling of air masses appears to be occurring, with the air aloft being distinct from the boundary layer air. Air-mass back-trajectories, that started from higher altitudes above the sampling site, typically travel back in different directions compared to that of the air movement at the surface (Fig. 4). The trajectories in Fig. 4 indicate about a 180° change in the source direction

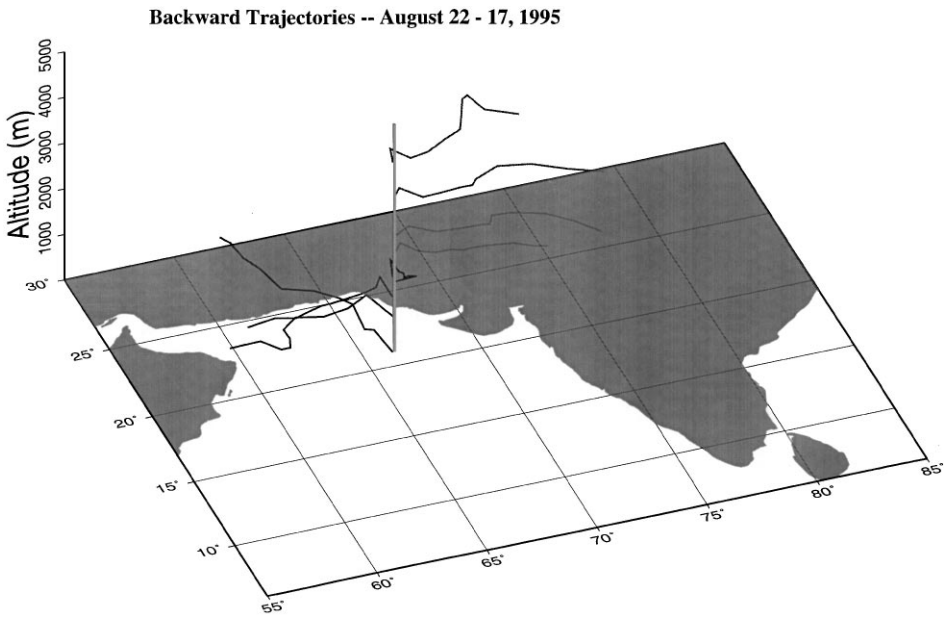


Fig. 4. Vertical profile of air-mass back-trajectories.

of the air masses. While back trajectories right at the surface indicate that there may be some air flowing in locally from coastal Oman, the main lower level back trajectories in Fig. 4 are from the northwest–west, part of the Southwest Monsoon flow. Air above this, at middle and upper levels, comes from the north and east, respectively. This suggests that the air masses are decoupled and that the source of air in the upper layers is different from that of the boundary layer in which the Findlater Jet is located. Dust transport aloft, above the low-level jet, was proposed as part of an earlier dust case study in the region (Ackerman and Cox, 1989). While their analysis was based on a study of Rawinsonde temperature profiles, and not direct dust measurements aloft, the presence of a temperature inversion indicates that the dust should be found in a layer somewhere between ~ 400 and 600 mb (~ 4000 and 6500 m), consistent with transport above the Southwest Monsoon jet from the north, or possibly east, depending on the height of the inversion layer (Fig. 4). As a result, dust concentrations and direction of transport would presumably vary with height during the Southwest Monsoon.

The transport of desert dust out over the ocean at different distinct altitudes is not unusual and has been observed in several regions including in the Asian air masses above Japan (Iwasaka et al., 1983) and in the transport of Saharan dust plumes out over the Atlantic Ocean off the coast of Africa (Prospero and Carlson, 1972). The decoupling and separation of source regions with altitude would help explain the relatively low concentrations measured at the surface and yet the apparently high values observed by the CZCS satellite during earlier summer seasons (Codispoti, 1991). These high aerosol reflectance values could be due to the presence of dusty air

aloft. A complete study of dust transport in this region during the summer season would require vertical profiles and transport aloft in addition to surface measurements and satellite observations.

Dust levels in the surface boundary layer also may be depressed due to effective removal of aerosols by wet deposition within the atmospheric boundary layer. Even scattered showers can effectively remove particulate material from the lower atmosphere (Duce, 1995). Scattered showers were observed in the vicinity of the ship during several of the Southwest Monsoon cruises (J. Seymour, pers. comm.). Overall, while the Southwest Monsoon is noted for increased intense precipitation in India and Pakistan, there appeared to be little precipitation increase over the open ocean study region (Weller et al., 1998). Gravitational settling of the larger dust particles, including those from the proposed higher dust levels aloft, also would contribute to the input of mineral material to the ocean surface.

Particulate levels in the marine boundary layer also could be reduced by the high levels of sea-salt aerosols that are produced by the strong winds, and that are evident in the aerosol sodium concentrations (Table 1). Sea salts can form large aggregates with mineral particles, the resulting particles having an increased deposition velocity to the ocean surface (Betzer et al., 1988; Schneider et al., 1990). The amount of aggregate formation would depend on the lifetime of the aerosols and whether cloud processing was occuring. The single particle analysis of samples collected during the July–August cruise (TN049) revealed that at least some of the particles analyzed were internal mixtures of sea-salt and dust particles. The enhanced levels of sea-salt aerosols associated with the summer months (Fig. 1b) also may be partially responsible for the reports of visible surface-level haze in the region (Pye, 1987).

4.2. Northeast monsoon and intermonsoon periods

Other earlier studies in this region were during the Northeast Monsoon, and they reported high levels of aluminum (Al) very similar to our study (Sadasivan, 1978; Chester et al., 1985). The highest levels of Al reported by Chester et al. (1985) were 3 to 4 times the highest levels in Fig. 1a, but were from samples collected close to the coast of Iran, with prevailing winds directly from the Rajasthan Desert in eastern Iran and Pakistan. Aluminum values appear to be higher, in general, over the entire basin than during the Southwest Monsoon. Again, higher values closer inshore to the continental source regions were seen, suggesting that local sources and transport are important, particularly from the north, northeast, and northwest (Fig. 2). There was still considerable variability in aluminum concentrations during these seasons, indicating that mesoscale turbulence and mixing affect aerosol concentrations over time-scales of at least a day. The two Intermonsoon periods also had high aluminum values (Table 1). Concentration levels during winter and spring were very similar, with autumn values being slightly lower.

It is also worth noting that temporal variability of the geochemical signal in the mineral aerosols supports the idea of distinct seasonal source regions for dust contribution. In general, nonmarine geochemical signatures were similar for the

winter and spring seasons (Pease et al., 1998). Likewise, a similar chemical pattern existed between summer and autumn seasons, but it was dissimilar to the winter/spring signal (Pease et al., 1998). This suggests a distinct source region associated with each major monsoon pattern.

To summarize, sea-salt levels, indicated by Na concentrations (Fig. 1b) were lower during winter and spring. Sea-salt levels in the atmosphere followed the pattern of average wind speeds for the region (Weller et al., 1998). At low wind speed, or during periods where the wind fetch over the ocean was limited, the observed levels were somewhat lower than those predicted by a production model dependent on wind speed (Erickson et al., 1986).

4.3. Relevance to sediment and satellite records

The high dust levels over the Arabian Sea must be recorded in the marine sediment record and be detectable by several satellite sensors. Deep-sea, marine, sediment cores do contain a distinct record of aeolian dust inputs to the Arabian Sea. For the open ocean area, atmospheric sources are thought to dominate fluvial inputs (Sirocko and Sarnthein, 1989; Clemens et al., 1991). Quartz data from the last 8000 years of the marine sediment record in the Arabian Sea indicate that the Southwest Monsoon does not bring material out from Somalia (Sirocko and Sarnthein, 1989). Quartz originates only on land and has been used as a tracer of aeolian material in deep-sea sediments (Kennett (1982) and references within). The quartz record reported by Sirocko and Sarnthein (1989) shows increased accumulation rates in the sediments in the northern Arabian Sea and entrance to the Gulf of Oman, but decreased levels approaching the tip of the Horn of Africa. If the Findlater Jet is responsible for transporting aeolian material into the Arabian Sea from Africa, then there should be a distinct profile of quartz extending out along the axis of the jet. But in fact, quartz fluxes to the sediments off the African coast are lower than those in the central Arabian Sea (Sirocko and Sarnthein, 1989). The mineral aerosol distribution (Fig. 2) is very similar to the sediment record and suggests that the present pattern of dust levels and transport over the Arabian Sea is consistent with the formation of lithogenic sediments offshore (Sirocko and Sarnthein, 1989).

Satellite observations reported in the same paper indicated that aerosol levels were highest during the Southwest Monsoon period. Aerosol turbidity was apparently correlated with wind speed, being highest during the summer period (Sirocko and Sarnthein, 1989). While their satellite images were processed based on the grain size and optical properties of mineral dust, and the resulting optical depth was attributed to dust, it is not clear whether the very high sea-salt aerosol concentrations were considered. Mineral dust has distinctly different optical properties from the sea-salt aerosol; it is not clear whether the satellite image processing of Sirocko and Sarnthein (1989) took into account the presence of more than one aerosol component (e.g., for CZCS images see Carder et al., 1991).

A recent study of marine aerosols over the tropical Indian Ocean found that aerosol optical depths increased nearly exponentially with average, surface wind speed (Moorthy et al., 1997). This study focused on open-ocean, marine air masses where

continental influences, including dust, were minor. At a wavelength of 650 nm, and sustained wind speeds from 25 to 35 knots, the calculated aerosol optical depth due to marine aerosols should vary from 0.45 to over 1.0. Clearly, the relationship of Moorthy et al. (1997) will break down at higher wind speeds, but even at sustained wind speeds of 25 knots, which are not uncommon during the Southwest Monsoon, the predicted aerosol optical depth due to marine aerosols alone is 75% of that determined for the Arabian Sea region using Advanced Very High Resolution Radiometer (AVHRR) observations at a similar wavelength (630 nm; Husar et al., 1997). This suggests that the marine aerosols could have a significant impact on the total aerosol retrieval. There are two main components of marine aerosols, the sea-salt particles and the non-sea-salt (NSS) sulfate aerosols produced from marine dimethyl sulfide (DMS). However, concentrations of both increase with higher wind speeds, and both could impact the aerosol optical depth. Direct observations from the recent Aerosol Characterization Experiment (ACE-1) in the Southern Ocean show that, for aerosols larger than 0.13 μm, sea-salt particles were responsible for the majority of light scattering due to aerosols (Murphy et al., 1998). The ACE-1 results indicate that, at least in the Southern Ocean marine boundary layer, radiatively important aerosols can include sea salt.

Globally, the contribution of sea-salt aerosols to the planetary albedo is thought to be of a magnitude similar to that attributed to the present anthropogenic increase of atmospheric CO_2 (~ 1.25 W m^{-2}), but of opposite sign (-2.0 W m^{-2}; Winter and Chylek, 1997). This is about twice the magnitude of the natural effect due to mineral dust alone (~ 1 W m^{-2}; Andreae, 1994). The radiative impact of sea-salt aerosols will become more important with stronger winds (Winter and Chylek, 1997) and thus may be a significant component of aerosol remote sensing in the Arabian Sea region during the Southwest Monsoon.

The distribution of UV-absorbing aerosols as detected by the Total Ozone Mapping Scanner (TOMS) shows a persistent, year-round, dust source in the coastal regions of Oman (Herman et al., 1997). Presumably, this locally generated dust remains at the surface and is carried out over the ocean by the persistent offshore or alongshore surface winds (Fig. 3). It must be noted that the TOMS instrument measures aerosol absorption, not scatter, and that the relationship between the TOMS "aerosol" signal and that detected by other satellite instruments is still under investigation (Herman et al., 1997).

5. Conclusions

Similar to many other oceanic regions, high concentrations of aeolian dust were found above the Arabian Sea during 1995. Dust levels varied considerably, by the day, week, month, and seasons. A strong seasonal signal in dust concentrations was apparent, and it was linked to monsoon activity and associated winds. What was surprising was that the peak in average dust levels at the surface occurred in winter and spring, not during the Southwest Monsoon period (summer) as predicted. A detailed analysis shows that our results are generally in good agreement with previous

studies of dust reported for this region. Atmospheric transport processes for dust plumes appeared complex, evidenced by the spatial and temporal variability in concentrations and air-mass trajectory analyses. Overall, atmospheric transport appeared driven by regional and mesoscale atmospheric processes that were dominated by the larger-scale flow during the monsoon periods. This was particularly evident during the Southwest Monsoon when the strong, low-level Findlater Jet appeared to control the source and transport of dust over the Arabian Sea. The Findlater Jet appeared to act as a barrier to the transport of air from the dust-source regions northwest and north of the Arabian Sea. Dust-free marine air from the equatorial Indian Ocean region, and possibly the Southern Hemisphere, was drawn up into the open ocean side of the axis of the jet.

Aloft, the transport of air and dust above the marine boundary layer appears to depend on the height of the Findlater Jet and the effective decoupling of the boundary layer air from that above. The proposed high aerosol concentrations aloft are probably responsible for the enhanced aerosol optical depths and absorbance that are typically detected by the Coastal Zone Color Scanner (CZCS), AVHRR, Geostationary Operational Environmental Satellite (GOES), and TOMS. Modeled back- trajectories indicate that air aloft can come from the Middle East and Himalayan regions as well as from Pakistan and India. Based on the shipboard sampling, the analysis of back-trajectories and wind fields, and the position of the Findlater Jet, it does not appear that the Horn of Africa (including the deserts of Somalia) is a dominant source of dust to the Arabian Sea.

Sea-salt aerosols showed almost an opposite pattern to the dust. Levels were generally very low during the year except when the Southwest Monsoon winds were blowing. The resulting high levels of sea salt in the air during summer may be affecting the satellite imagery and be at least partially responsible for the increased reports of haze during this season.

Overall, the transport and input of mineral material to the surface waters of the Arabian Sea depends on a number of factors, including the air-mass transport pathways, the source regions for the air masses and dust, the vertical stratification and mixing of the air column above the sampling site, the removal of particulate material from the atmosphere, the season, and geographical location of the sampling site. Precipitation patterns over the region may be particularly important in determining overall dust fluxes during the wetter, Southwest Monsoon.

Concerning the potential impact of atmospheric inputs of mineral material to the surface waters, the regions most likely to be affected during the Southwest Monsoon appear to be within 5° of the coast of Oman and in the northern to northeastern reaches of the Arabian Sea. The ultimate fate of the proposed dust layer aloft, above the Findlater Jet, is unknown at this time. Presumably washout in the Indian monsoonal rains and/or in the ITCZ would transport the mineral material to the surface. During the Northeast Monsoon and Intermonsoon periods, dust inputs would be spread over the whole region, with smaller mesoscale atmospheric features perhaps becoming more important. During that season dust input was higher inshore, closer to the continental sources.

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