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Aerosols over the Arabian Sea: geochemistry and source areas for aeolian desert dust

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The temporal and spatial patterns of dust concentrations and geochemistry of aerosols collected over the Arabian Sea, along with atmospheric transport models, were used to identify source areas from the surrounding desert environments. Seasonally, the highest dust levels occurred during the winter and spring, with probable source areas in India/Pakistan/Iran and the Arabian Peninsula. Spatially, the highest dust levels were found off the Omani coast and over the Gulf of Oman, where high dust levels persisted throughout the year, suggesting that the Arabian Peninsula, and perhaps Oman specifically, are the most prominent contributors to the annual dust load in the region.

Keywords: dust; aerosol; Arabian Sea

Introduction

Mineral dust transported from desert regions provides a major source of aerosols in many areas of the world (Pye, 1987; Prospero *et al.*, 1987; Arimoto *et al.*, 1989). Studies of dust transport from the Sahara and Gobi Deserts have shown that enhanced atmospheric dust levels over a wide region can result from a single dust-producing area (Ganor & Mamame, 1982; Middleton, 1986*a*; Prospero *et al.*, 1987; Zhang *et al.*, 1993; Measures & Brown, 1996). Mineral dust has been increasingly recognized as a significant influence on regional and global atmospheric conditions (Pye, 1987; Middleton, 1997). The effect and importance of aerosols on global and local climate, agriculture, and human health has been discussed by O'Hara (1997), Pye (1987), and Bar-Ziv & Goldberg (1974). More recently, mineral dust has been suggested to have an influence on the primary productivity of ocean surface waters through the supply of nutrients and micronutrients (Maring & Duce, 1987; Betzer *et al.*, 1988; Young *et al.*, 1991; Martin *et al.*, 1994; Measures & Brown, 1996; Coale *et al.* 1996).

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The Arabian Sea and the surrounding land masses have been identified as areas of high dust levels (Kolla & Biscaye, 1977; Middleton, 1986*a*; Sirocko, 1991). Satellite images indicate seasonal periods of high dust over the Arabian Sea (Sirocko & Sarnthein, 1989) and sediment cores from basins in the Arabian Sea and the Indian Ocean suggest the deposition of mineral dust has continued for thousands of years (Kolla & Biscaye, 1977; Sirocko & Sarnthein, 1989).

The aim of this study is to determine the temporal and spatial significance of dust production from deserts surrounding the Arabian Sea using geochemical and meteorological indicators of sediment provenance, and to examine the relative importance of each of the potential source regions in the contribution of dust in samples collected from a ship in the Arabian Sea during 1995. To understand the significance of source areas, local environments which could contribute to the regions dust input are discussed, including Somalia, the southern and interior Arabian Peninsula, and parts of Iran, Pakistan, and India. Terrestrial samples were collected from the Wahiba Sands area of Oman to develop a geochemical reference for dust sources from deserts surrounding the Arabian Sea. Regional climate patterns suggest that Oman holds the potential for significant contributions to the annual dust levels in the region during different times of the year (Middleton, 1986*a*; Sirocko & Sarnthein, 1989). An overview of aerosol collection and details on atmospheric dynamics and chemistry during 1995 has been presented by Tindale & Pease (in review).

Regional wind patterns can be considered only a first order indicator of dust sources. Dust production is also a function of terrestrial surface conditions, which must be suitable for deflation in order for significant dust to be entrained. Therefore, in addition to regional climatic patterns, the geomorphic setting of potential dust-generating areas from arid environments surrounding the Arabian Sea was examined.

Regional setting

The continental areas surrounding the Arabian Sea constitute one of the world's major source areas of dust production (Middleton *et al*., 1986). The most important sub-regions for dust production are described below.

The alluvial plains of southern Iraq and Kuwait

The areas along the lower Mesopotamia plain of the Tigris and Euphrates Rivers, along with the coastal plains of Kuwait and north-eastern Saudi Arabia, are significant sources for sediment deflation (Middleton, 1986*b*). This source region is characterized by fine-grained, fluvial and deltaic sediments as well as significant aeolian dune sands. The disruption of Kuwait's desert surface during the 1991 Gulf War has led to increased aeolian activity and deflation, as well as the reactivation of stabilized dunes (Al-Dabi *et al*., 1997).

The southern Arabian Peninsula

The primary dust producing regions in this area include Oman, Yemen, and the Rub-Al-Khali (Empty Quarter) sand sea, and, to a lesser degree, the sabkha complexes along the south-eastern Arabian Peninsula's coastline (Fig. 1).

Oman

The major dust-producing areas include the alluvial/fluvial complexes at the foot of the Hajar Mountains in northern Oman, the Wahiba Sand Sea and the Coastal Lowlands. The Hajar massif is primarily composed of a late Mesozoic ophiolitic complex

(Lippard *et al.*, 1986; Glennie, 1988; Hanna, 1995). The unique mineral constituents of this assemblage (e.g. chromite) are present in the weathered alluvial/fluvial material and serve as an indicator for provenance. Although much of the overall alluvial fan surfaces are presently inactive (as indicated by thick rock varnish coatings and armoured surfaces), many individual wadis are still intermittently active (Maizels, 1988) and most likely contribute to the regional dust flux, especially when disturbed by automobile travel (*cf*. Wilshire, 1980; O'Hara, 1997).

The Wahiba Sand Sea is an active dune field located on the eastern coast of Oman (Fig. 1). The sand sea is bordered on the west by a large wadi/fan complex which drains ophiolitic mountains to the north (Warren & Kay, 1987; Jones *et al.*, 1988; Warren, 1988). Most of the sediment throughout the Wahiba area consists primarily of quartz, carbonate, and notable amounts of ultramafic mineralogies originating from an ophiolite sequence (Goudie *et al.*, 1987; Allison, 1988). The Coastal Lowlands are composed largely of distal alluvial materials as well as sabkha deposits (evaporites) and carbonate cemented aeolianites. Chemical signatures related to Wahiba mineralogies

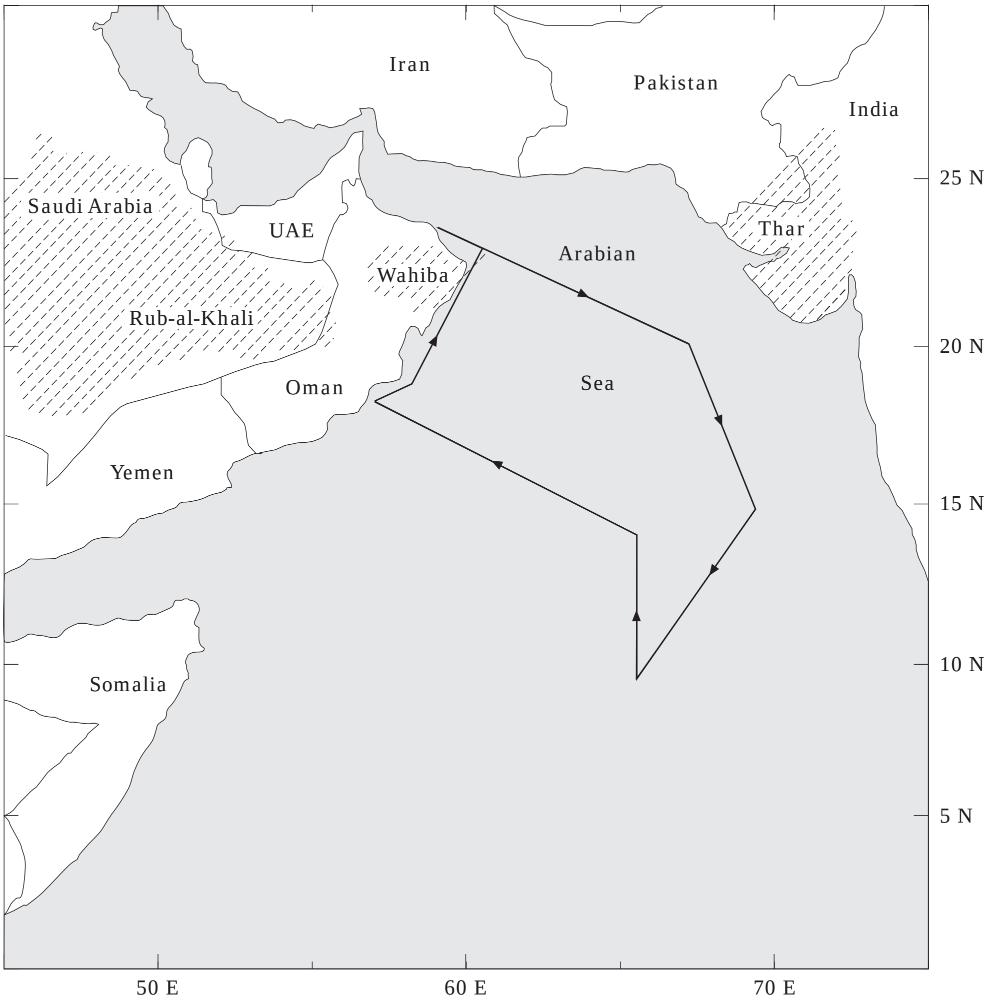

Figure 1. Regional map showing the land areas thought to be potential contributors to dust collected over the Arabian Sea. The arrow/line in the Arabian Sea shows an average month-long cruise track during which dust samples were collected.

(primarily the mafic, ophiolite minerals) are useful as an indication of dust from this region.

Yemen

The Hadramawt region of eastern Yemen includes several limestone plateaus which are incised by major wadi systems, some as deep as 150 m. Most of the wadi floors are covered by extensive sand and gravel deposits. Some of the deepest incised wadis seem to have been active during late Pleistocene time. The wadi systems provide large sediment inputs to the coastal zone. In the south-western region of Yemen, volcanic tablelands cover the landscape, with smaller wadi systems crossing them and bringing sediment to the coastal regions.

Rub-Al-Khali

The world's largest sand sea (erg) covers an area of about 600,000 km^2 (Fig. 1). The main part of the sand sea is comprised of linear dunes, some extending for over 100 km. Given its hyperarid climate, the Rub-al-Khali is almost devoid of vegetation and considered a primary source for aeolian deflation (McClure, 1978). Along the south-eastern coastline of the Arabian Peninsula, sabkha complexes stretching for over 250 km (mostly along the coast of the United Arab Emirates) contain mostly muddy carbonates along with significant concentrations of siliclastic sands (Viles & Spencer, 1995).

The Somali Coast

Dust deflation from the Somali region is primarily confined to the coastal zone (Orme, 1996). For 1500 km, from the Kenyan border in the south to near Gifle on the central coast of Somalia, a low lying coastal plain backed by massive Quaternary dunes and fronted by coral reefs and small fields of active coastal dunes is present (Orme, 1985). The vegetated Quaternary coastal dunes (mostly palaeodunes) have been destabilized by overgrazing and are subject to gullying and aeolian deflation (Orme, 1996).

India/Pakistan/Iran

The primary potential dust source in this region is the Thar Desert centered in eastern Pakistan and western India, including the arid regions of the Indian Rajasthan Desert (Allchin *et al.*, 1978) (Fig. 1). To the east of the Rajasthan Desert is the Aravalli Range, composed primarily of granite, quartzite and other igneous and metamorphic rocks. Numerous wadis drain these mountains, although most of the water in the wadis never reaches the Arabian Sea, owing to high infiltration and evaporation in the sands of the Rajasthan Desert. Other significant dust sources include the coastline of the Arabian Sea (with sabkha and calcareous aeolianite deposits), the alluvial plain of the Indus River, the weathering of sandstone and granite inselbergs near the coastal plains, and the very extensive parabolic and linear dune systems in the Thar Desert (Hegde & Sychantharong, 1982). The Thar Desert also contains a number of closed basins with extensive evaporite deposits (Cooke *et al.*, 1993). Further west in Iran, the Makran Mountains and the adjoining Seistan Basin could also be considered potential source regions, the latter averaging over 80 dust storm days per year, one of the highest recorded averages in the world (Middleton, 1986*a*).

Climate and meteorology

Most areas surrounding the Arabian Sea can be characterized as arid climates (Köppen's type BWh climate). The segments bordering the Arabian Sea in Saudi Arabia, Oman, Yemen, Iran, Pakistan and India can be classified as hyperarid to arid, with average annual precipitation values between 30 to 100 mm. Some of the mountains, such as the Hajar Range in Oman and the higher plateau regions in Yemen, can receive increased amounts of precipitation owing to the effects of orographic lifting (Pedgley, 1970). The majority of areas surrounding the study region are primarily under the influence of the semi-permanent belts of sub-tropical high pressure cells including most of the Arabian and Thar Deserts. The only region that is an exception to the above is Somalia. In this coastal desert region, annual precipitation is between 100 and 300 mm, with increasing amounts southward from Mogadishu to the Kenyan border (Orme, 1996). The Southwest Monsoon in July and August is the primary harbinger of moisture in the Somali region (Hance, 1975; Orme, 1996). The major meteorological systems are the Northeast Monsoon, Southwest Monsoon, and, from a more local perspective, the Shamal.

Northeast Monsoon

During the winter months, development of a hemispheric scale high pressure system over central Asia sends winds from the interior across the Indian subcontinent and out over the Arabian Sea. This creates the basic north-easterly pattern of the Northeast Monsoon from November to early February. A regional wind field model (Fig. 2) and similar wind patterns described by Findlater (1971) suggest the normal development of two jet streaks which merge over the central Arabian Sea. One jet blows down from over the Thar Desert owing to steep atmospheric pressure gradients (Middleton, 1997). The other jet moves out of south-west India, south of the Käthiawar Peninsula. Deflation of sediments from playa, sabkha, wadi, dune and alluvial plains is a substantial source of input into the region's dust budget (Cooke *et al.*, 1993; O'Hara, 1997). Depending on the position of the main jet merging point, Omani and Yemeni coastal lands are also susceptible to aeolian deflation as the Thar jet skims along the coastline.

Southwest Monsoon

The most pronounced synoptic meteorological phenomenon in the study area is the Southwest Monsoon. During the summer months, continental low pressure develops over the land masses surrounding the Arabian Sea with a corresponding high pressure cell over the cool ocean waters. This well-developed system stretches from Somalia northward across the Arabian Peninsula to the Indian subcontinent where the principal low pressure cell is developed (Miller & Keshavamurthy, 1968; Olson, 1990). The result is a strong wind originating over the Indian Ocean which curves to a south-westerly wind blowing over the Somali coast across the Arabian Sea and onto India (Findlater, 1971). The main core of this monsoon flow is termed the Findlater Jet (Findlater, 1971). In the Somali/Yemen region, this synoptic wind flow pattern is augmented by the development of regional mesoscale land/sea breezes and mountain/valley winds that 'join' the south-west winds, owing to the pressure gradients produced by temperature differences across the coastal zone and the presence of mountain ranges surrounding the Gulf of Aden (Hsu, 1988). These regional winds, especially with mountain/valley outflow, could provide additional inputs of dust from the Somali and Yemeni inland regions to the main Southwest Monsoon winds.

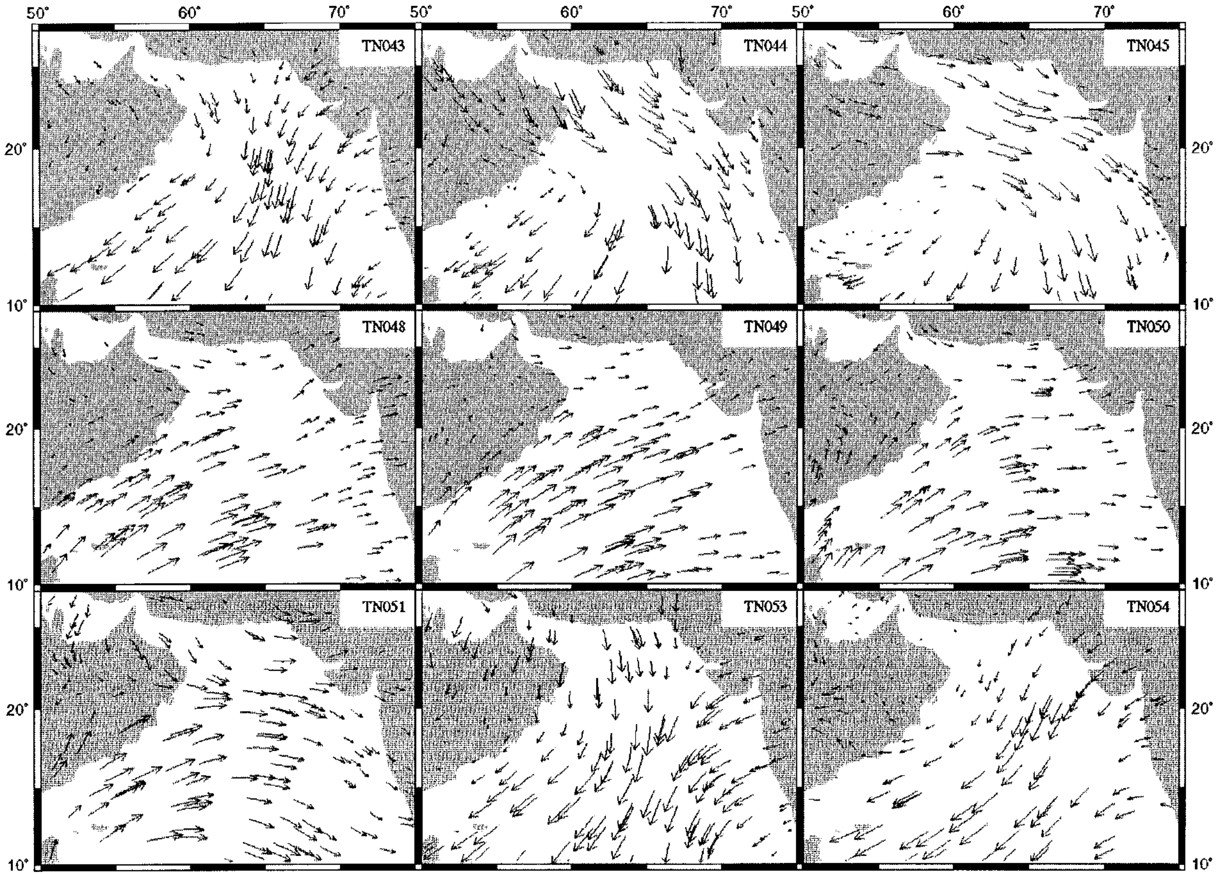

Figure 2. Wind field maps generated from an NCEP 2·5 × 2·5 degree data grid. Each map represents an average wind field for a cruise period (approximately 30 days each). The vector orientation shows the wind direction and the length represents the wind intensity. Dates for the cruise numbers are given in Table 1.

Shamal

Potentially, one of the most important synoptic meteorological systems capable of entraining large quantities of dust is the movement of low pressure cells with steep atmospheric pressure gradients that are accompanied with very high velocity winds (Pye, 1987). Such a situation develops over the northern Arabian peninsula in early summer and is locally refereed to as the Shamal (Middleton *et al.*, 1986). The presence of two well-developed low pressure troughs over Pakistan and Afghanistan and the Zagros Mountains in Iran, accompanied by the development of a monsoonal low over the north-west Indian subcontinent, leads to the formation of these north-westerly Shamal wind systems in late May to early July (Membery, 1983; Pye, 1987; Ali, 1992). The Shamal winds blow over the arid Mesopotamia Plain and into the tip of the Arabian Peninsula, passing over Oman and the Arabian Sea. It is very possible that the Shamal winds also pick up dust and aerosols over the sandy Nafud Desert (with an area $>117{,}000\,\mathrm{km}^2$) of north-eastern Saudi Arabia as well as from the south-eastern segments of the Rub-Al-Khali sand sea (Pye, 1987).

Methods

To determine the relative importance of dust source areas in the Arabian Sea region, dust samples were collected onboard a ship during most of 1995. The Arabian Sea provided a central sampling location for all potential sources. In addition, sediment samples were collected from the Wahiba Sand Sea area in the Sultanate of Oman to be used as a geochemical reference for environments adjacent to the Arabian Sea and as an indicator of the relative importance of one local environment to the annual dust load.

Aerosol sampling

Aerosol samples were collected from a tower erected on the bow of the research ship R.V. Thomas G. Thompson along a cruise track covering a range of approximately 55·5° E to 65·5° E and 10° N to 22° N (Fig. 1). Samples were collected by vacuum-pumping air through cellulose matrix filters mounted about 10 m above the water surface. Samples were collected only while winds were blowing over the bow of the ship to prevent contamination of samples with ship exhaust. Thirty-two of the samples collected during the year were selected for both short and long irradiation analysis and used in this study. Chemical analysis of the filter samples was done by instrumental neutron activation analysis at the Texas A&M University Nuclear Science Center. Aerosol samples were collected on nine U.S. JGOFS cruises. Cruise identification numbers and corresponding dates are given in Table 1.

Aerosols collected from over an ocean can include sea salt, organic material, and mineral dust. This study is concerned only with the mineral dust component. Aluminum is typically used as an indicator of mineral dust in the atmosphere (Duce *et al.*, 1991; Measures & Brown, 1996). Usually estimates of the dust load are made assuming the aluminum content of the dust roughly equals that of the upper crustal average (approximately 8%, Taylor & McLennen, 1985). However, it is common for surface sample ratios not to match those of the average upper crust, which is roughly the composition of a granodiorite (Taylor & McLennan, 1985). For example, in the terrestrial samples collected from the Wahiba Sands area in Oman, aluminum is depleted relative to the granodiorite mean. The average aluminum concentration for fine grained ($<63\,\mu\mathrm{m}$) surface sediment samples collected in Oman is only 2·8%.

Therefore, a 2·8% Al/dust ratio was used for dust estimations in this study because it represents the ratio from one of the potential source areas.

Another way to study dust source signatures is by the use of geochemical enrichment factors. Enrichment plots are ratios of sample concentration to a reference chemistry, generally using aluminum as a normalizing element (Lawson & Winchester, 1979). Elemental ratios higher than the geochemical average (a ratio value of 1) often indicate the impact of a specific source or process and thus can be used as a diagnostic tool (Buat-Menard & Chesselet, 1979). The plots are generated using the typical equation:

$$EF = \frac{(C_{xs}/C_{Als})}{(C_{xc}/C_{Alc})}$$

where EF is the enrichment factor, C_{xs} and C_{xc} are the element in question in the aerosol sample and the reference average, respectively, and C_{Als} and C_{Alc} are the aluminum content of the element in question in the sample and of the reference average, respectively (*cf*. Lawson & Winchester, 1979; Buat-Menard and Chesselet, 1979; Arimoto *et al*., 1989).

Terrestrial samples

Surface sediment samples were collected from the Wahiba Sand Sea and surrounding environments, including wadis, sabkhas, and beaches. Traverses in the sand sea were made in a north–south direction along interdune corridors and sediment samples were collected approximately every 10 km in all areas which were accessible with 4-wheel drive vehicles. Sample sites were prepared by brushing away surface lag and debris then plunging a 10 dram plastic vial into the sand perpendicular to the strike plane. Samples were also collected intermittently throughout the northern and western wadi complexes, and sabkhas near the coast. Wadi sites where the surface armouring was disturbed were of prime interest as potential dust-generating environments.

Sediment samples were dry sieved at 0·25-phi intervals. Since finer grained sediment is more likely to be deflated as aerosol dust, the fine fraction ($< 63\,\mu$m) was separated from samples and used to define the geochemical characterization of the Wahiba environments. Twenty-seven of the samples contained a significant volume of fine fraction and were used in this study. Because significant percentages of the sands consisted of non-silicate minerals, such as carbonates (Goudie *et al*., 1987; Allison, 1988), pre-sieve preparation of samples with acid washing was not undertaken. After the fine fraction was separated, 100 mg were weighed out for instrumental neutron

Table 1. *Cruise identification numbers and dates*

Number	Date (1995)
TN43	1 Jan–4 Feb
TN44	8 Feb–25 Feb
TN45	14 Mar–10 Apr
TN48	21 Jun–13 Jul
TN49	17 Jul–15 Aug
TN50	17 Aug–15 Sep
TN51	18 Sep–11 Oct
TN53	28 Oct–26 Nov
TN54	29 Nov–24 Dec

activation analysis, and analysed following the same methods as the aerosol samples.

Meteorology models

To examine mean wind patterns during sampling periods, wind field maps were generated for each of the cruise periods in which aerosol material was collected (Fig. 2). The wind field maps represent mean wind vector data (direction and magnitude) at the surface level (1000 mb) for the period of each cruise. The wind fields were generated using data from the medium range weather forecast model of the U.S. National Center for Environmental Prediction (NCEP). The wind field maps provide only the average wind vector data for each cruise, and therefore lack details about specific airmass pathways. To improve interpretation of the transport of individual airmass dust plumes, airmass back trajectories were calculated for individual dust samples. The trajectories were calculated back in time and space for 5 days from a nominal ship position for each individual sample collection period. Back trajectories represent the path of air movement in the regional scale circulation, not the actual movement of any particular parcel of air, and therefore some uncertainties are inherent (*cf.* Merrill *et al.*, 1985; Harris, 1992; Kahl, 1993). Despite such limitations, the trajectory models provide more detailed predictions of air movement for particular aerosol samples than do the mean wind fields.

While back trajectory models are three-dimensional, taking both vertical and horizontal movement, Fig. 3 shows only the average two-dimensional direction of airmass trajectories during a sampling period for each season. The circle indicates the nominal ship location during sampling, and the vector angle points to the average direction the wind came from. The length of the line indicates the relative concentration of dust in the air measured in $\mu g\,m^{-3}$.

Discussion and analysis

The primary atmospheric phenomena in the Arabian Sea are the Southwest and Northeast Monsoons, with secondary influences by the transitional intermonsoon seasons and the Shamal winds. Regional wind patterns are a function of seasonal conditions, and it is most useful to discuss atmospheric dust in terms of season signals. Based on atmospheric conditions and our aerosol chemistry data, we delineated the four seasons as follows: winter, 1 Jan–10 Feb and 1 Nov– 31 Dec; spring, 11 Feb–31 May; summer, 1 Jun–24 Aug; autumn, 25 Aug–31 Oct. The actual transition from one season to another is gradual, taking several days to complete, so these dates should be considered approximate.

Winter

Although the winter data were collected over two winters, they are treated here as one season. Dust samples taken during November and December (cruises TN53 and TN54) represent early winter. The winter season experienced the second highest dust levels of the year with an average air concentration of $40\,\mu g\,m^{-3}$. Actual dust levels varied with individual samples ranging between $7\,\mu g\,m^{-3}$ and $178\,\mu g\,m^{-3}$. Samples indicate dust levels were higher over the northern and eastern Arabian Sea than the southern Arabian Sea (Fig. 4).

The geochemical enrichment plot of aerosols relative to Oman surface silts (Fig. 5) can be used to examine relative abundance of elements between different seasons. The

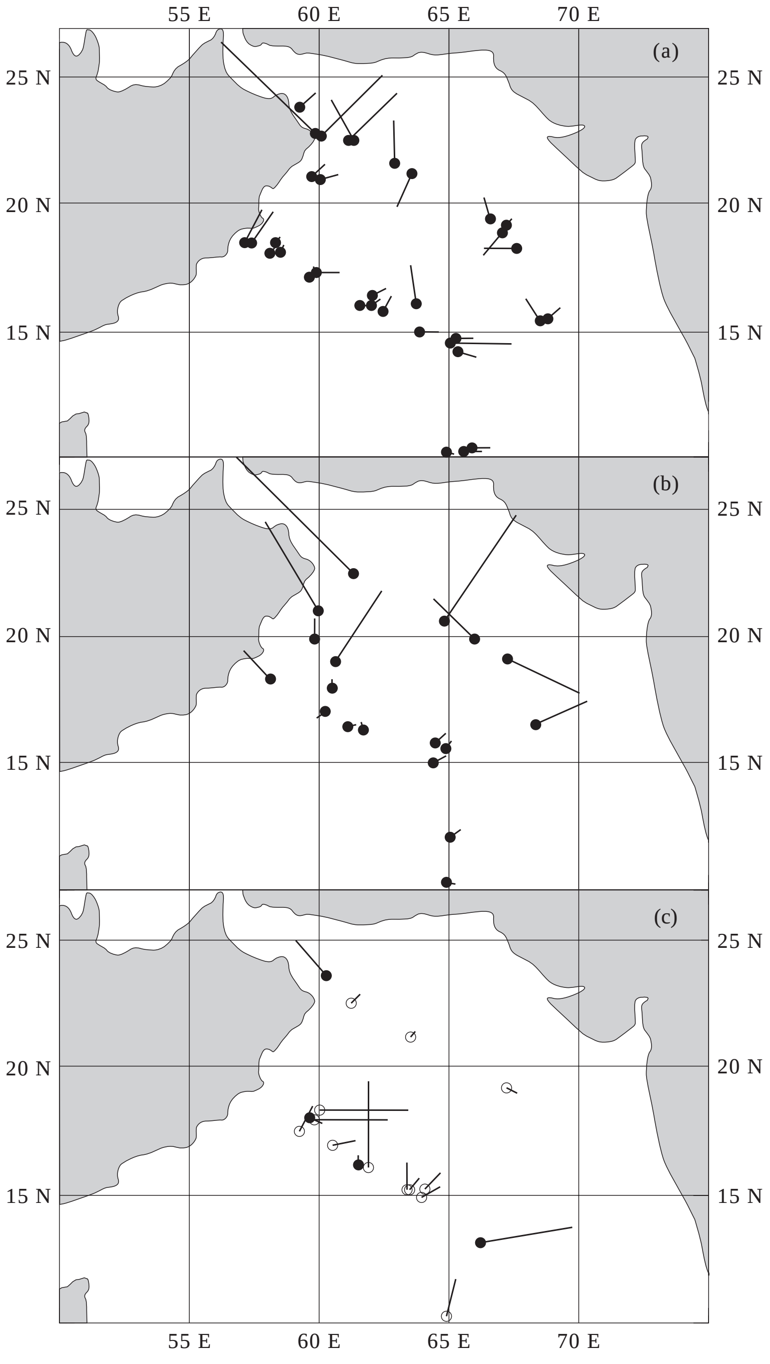

Figure 3. Averaged airmass back trajectory directions for each sample collected during (a) winter (Northeast Monsoon), (b) summer (Southeast Monsoon), and (c) spring/autumn intermonsoons. The dots show the nominal ship position when the sample was collected. The vector orientation gives the average direction, or origin, of the airmasses which were encountered during the individual sample periods, and the vector length gives the relative concentration of dust in the air sampled in micrograms of dust per cubic meter of air. In (c) (summer) dust concentrations (vector lengths) are exaggerated 10 times relative the plots (a) and (b). In plot (c), the spring intermonsoon is represented by open dots and closed dots represent the autumn intermonsoon.

average winter composition is distinct from the other seasonal patterns. Geochemically, much of the dust during the Northeast Monsoon is unique and can be identified by a marked enrichment of zinc relative to samples collected during the rest of the year (Fig. 6). Figure 6 shows winter samples compared to samples from the rest of the year. The winter samples are broken into two groups; those collected from east of 63° and those collected from west of 63°. Figure 2 suggests that this division roughly corresponds to air flow out of Iran/Pakistan for samples collected from the west side of the study area, and a possible air/dust source of India for samples collected on the east side. The exact source of this zinc is not presently known, but it is commonly considered an indication of anthropogenic pollution (Chester *et al.*, 1984). The spatial pattern of high zinc levels can be used to suggest a regional source for the aerosol associated with it. Samples with the highest zinc levels were those collected in the eastern Arabian Sea. If the atmospheric low-level jet development suggested by our model (Fig. 2, TN53, 54, 43), and by Findlater (1971) is correct, it implies that the

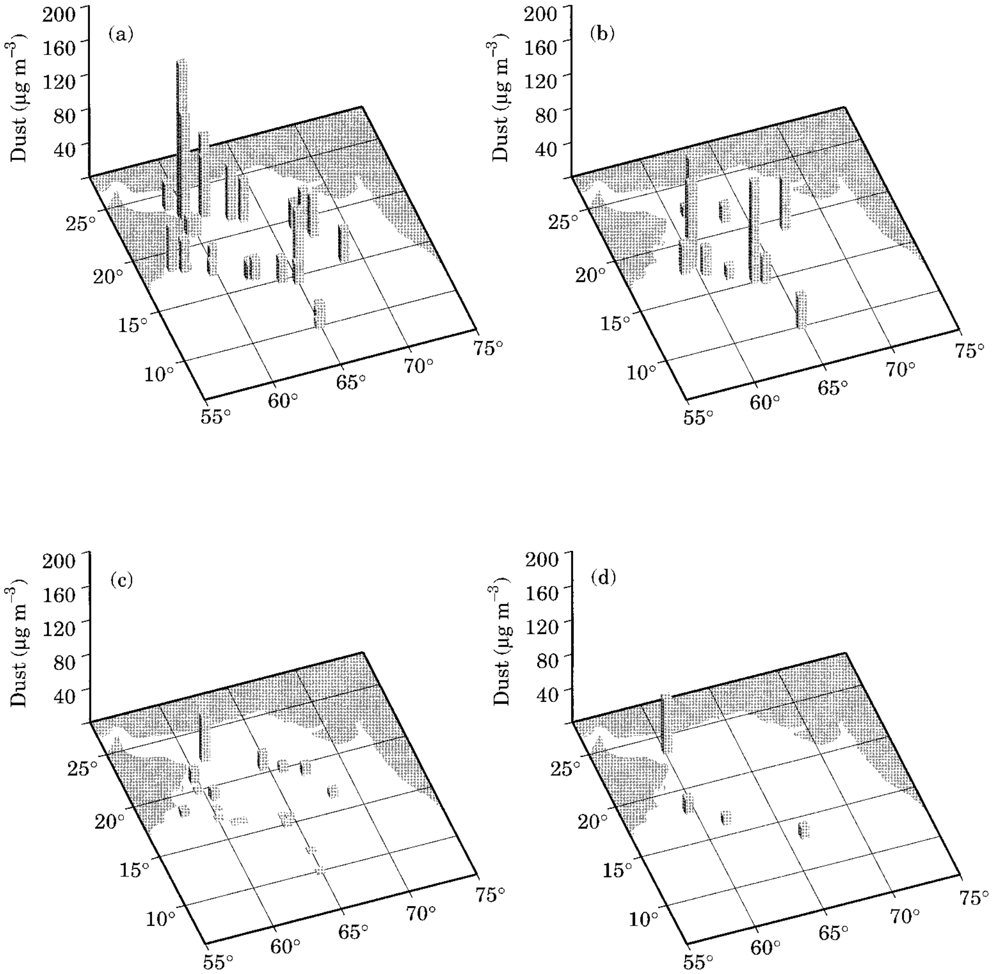

Figure 4. Plots of the spatial distribution of dust concentrations for (a) winter, (b) spring, (c) summer and (d) autumn. Bars represent individual samples and are situated at the nominal ship position when the sample was collected. The exact seasonal dates are given in the text.

samples collected over the eastern Arabian Sea derived much of their airmass, and thus aerosol dust load, from India where the Rajasthan Desert represents a possible local source. If the concentration of zinc in the eastern Arabian Sea can be linked to India, it follows that dust collected from over the western Arabian Sea may have originated from a different source, possibly the Thar Desert.

The general pattern of dust concentration during the winter is shown in Fig. 4(a). The highest levels were seen over the north and east Arabian Sea with the peak over the Gulf of Oman. The lowest levels were seen over the southern Arabian Sea. This pattern is supported by the wind field maps (Fig. 2) and airmass back trajectories (Fig. 3(a)) which indicate air flow out of India, Pakistan, and Iran. The higher dust values in east and north-eastern Arabian Sea suggest high dust concentrations in the jet streak which passed over the Käthiawar Peninsula, perhaps gathering dust from the Rajasthan Desert as discussed above. Samples from the north-west portion of the Arabian Sea, which show the highest dust concentrations of the season (Fig. 6(a)), probably reflect some flow out of Iran which moved over the Gulf of Oman. High dust concentrations over the Gulf of Oman imply that local dust-producing winds are suppling sediment from Iran and perhaps Oman. This is supported by Pye (1987) who noted the lower Mesopotamia area and the coast of Oman as areas of high annual dust production. Farther from the source, in the southern Arabian Sea, lower dust levels were found. Such a downwind decrease in concentration is to be expected, supported both by the decrease in dust levels with increasing distance off shore and by ocean sediment data (Stewart *et al.*, 1965; Kolla *et al.*, 1981).

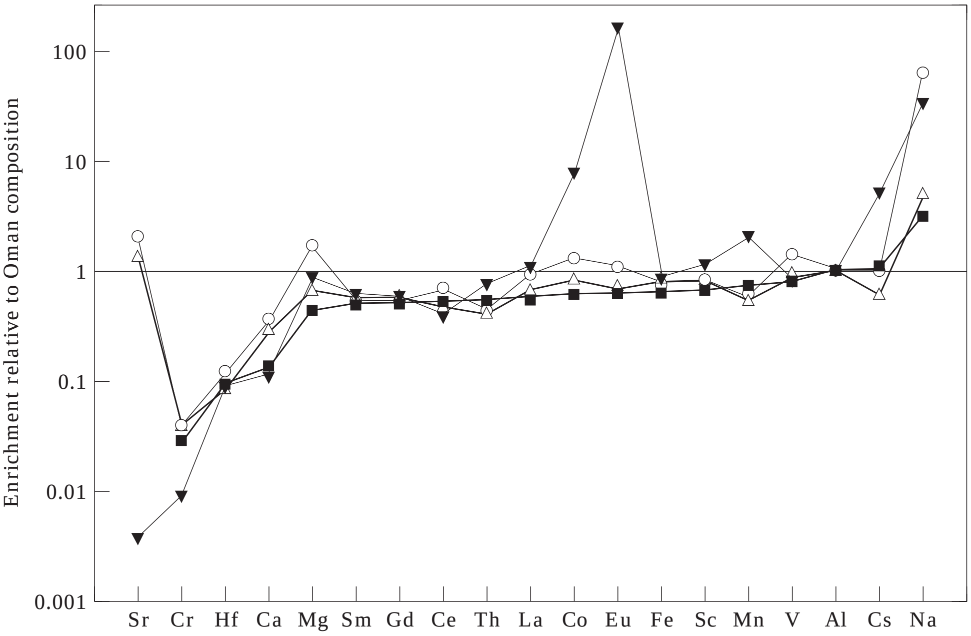

Figure 5. Mean geochemical enrichment factors for winter (■), spring (△), summer (○), and autumn (▼). Elements on the x-axis are not arranged in any particular order. The line at 1 on the y-axis represents the value of the Oman sample used as a standard in this study. The importance of the plot is the relative position of the symbols on each curve, which represents the depletion or enrichment of an element relative to the Oman sample. The lines connecting the symbols are present only to aid in the reading of the graph and do not represent a continuum from one element to the next within a season.

Spring

During the spring intermonsoon, the average wind pattern is predominantly northwesterly, with winds passing directly over Oman and the Wahiba Sand Sea area before passing over the Arabian Sea (Fig. 2) (Findlater, 1971). Samples collected during this period showed the highest dust concentration of the year, averaging 50 μg m^{-3} and ranging from 12 to 117 μg m^{-3}. The highest levels were in samples collected closest to the coast. This is the expected pattern if a local area, such as the Omani region, were the prominent source. The enrichment factors for the spring season (Fig. 5) are distinguishable from other seasons, indicating the spring intermonsoon dust load originated from a seasonally unique source or process. The spatial distribution of dust concentration during the spring intermonsoon is highly variable (Fig. 4(b)). This probably reflects the generation of individual dust events moving out of the southern Arabian Peninsula and Mesopotamia.

Geochemical evidence indicates Oman is a likely source for much of the dust load during the spring intermonsoon. In fine grained terrestrial sediments collected throughout the Wahiba region of Oman, there is an average chromium enrichment of 58 times the mean crustal ratio. Therefore, chromium can be used as an indicator for the presence of material from Oman. Samples collected from over the Arabian Sea

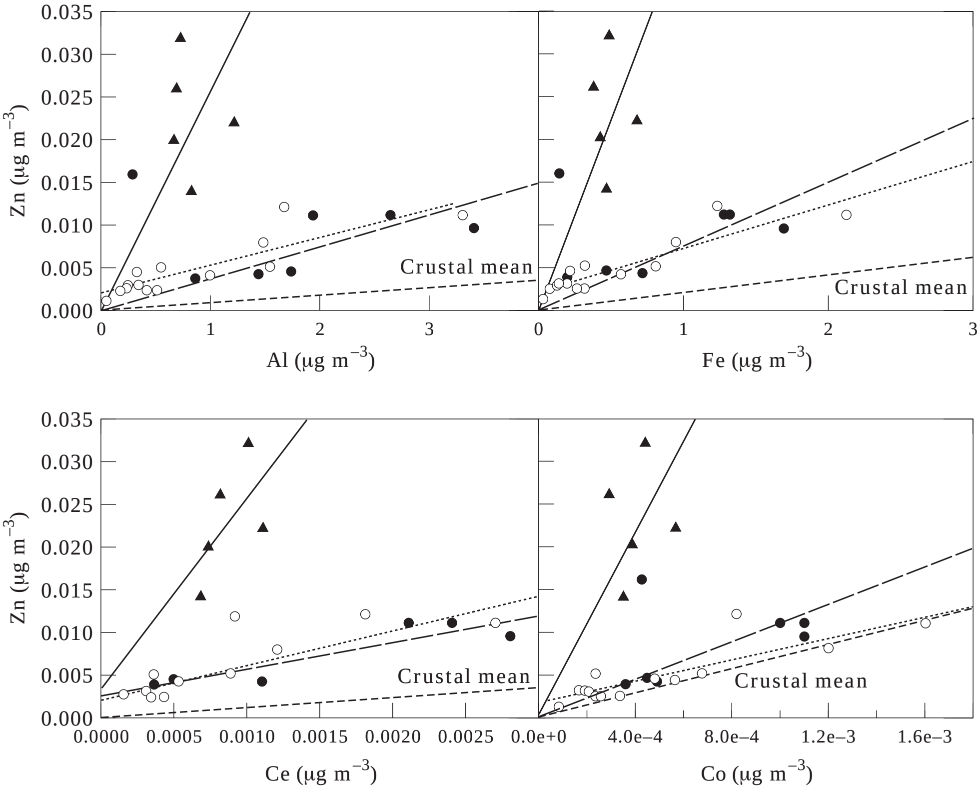

Figure 6. Plots of Al, Fe, Ce, and Co against zinc levels in dust samples. Open circles represent samples collected from spring, summer, and autumn. Closed symbols represent samples collected during winter: closed circles are winter samples collected from the western side of the sample cruise track (west of 63°); closed triangles are winter samples collected from the eastern side of the cruise track (east of 63°). Regression lines are given to show trends; solid line for triangles, dashed for closed circles, and dotted for open circles. The labeled dashed line is the regression for the mean upper crustal ratio and is shown for enrichment comparison.

during the spring intermonsoon showed a measurable increase in chromium relative to elements which show a degree of correlation to chromium in terrestrial samples (Fig. 7). The increase in chromium ratios to Al, Co, Eu, and Ce in the spring intermonsoon samples are 12%, 20%, 30%, and 30% higher, respectively, than those samples collected during other seasons.

In times other than the spring, Oman is believed to be a source of dust found close to the Omani coast. Therefore, we subdivided our dataset into two groups based on the time of sample collection and the location in which it was collected. The first group (Group 1) is made up of samples from all seasons except the spring and excluding samples collected from near the Omani coast. The second (Group 2) is comprised of samples from cruises TN44 and TN45 during the spring intermonsoon, and individual samples from other cruises which are close to the Omani shore, and for which local offshore wind patterns and individual back trajectories suggest the airmasses passed over Oman. These include samples from the early part of cruise TN48 which represents the end of the Shamal winds. Figure 7 reflects these groups. Regression lines for the datasets are provided to suggest different trends for sample groups. Also included in Fig. 7 are the regression lines for the average element ratios of the mean crustal composition and the mean Oman terrestrial silt composition. Although the enrichment is modest, given the complications of fractionation during deflation and

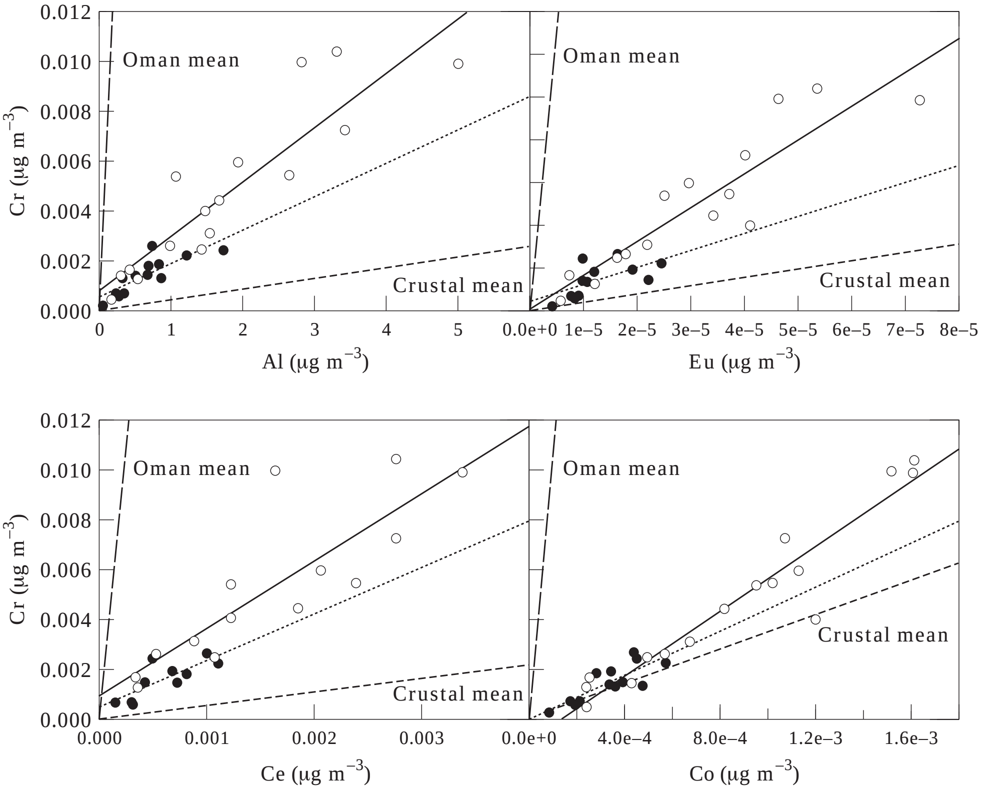

Figure 7. Plots of Al, Eu, Ce, and Co against chromium levels in dust samples. Open circles represent Group 2 samples (likely partial contribution from Oman), closed circles represent Group 1 samples (no likely contribution from Oman). The generation of the Groups 1 and 2 sub-sets is discussed in the text. Dotted lines are regression lines for Group 1 samples, solid lines are regression results for Group 2 samples. Short dashed lines represent the ratio regressions for the average upper crustal composition and long dashed lines represent the average Oman terrestrial sediment composition.

settling, and the mixing of atmospheric airmasses, it is encouraging to see the chromium enrichment in samples downwind of the Wahiba region where it is expected.

Summer

Cruises TN48, TN49, and TN50 comprise mostly the summer, Southwest Monsoon season. During the Southwest Monsoon, strong south-westerly winds flow off Somalia with the development of the Findlater Jet, situated roughly parallel with the Omani coast (Fig. 2) (Miller & Keshavamurthy, 1968; Findlater, 1971, 1974). In addition, the Shamal develops out of the Persian Gulf and usually joins the Findlater Jet across the Wahiba Sand Sea during the early part of the summer (Findlater, 1971; Membury, 1983; Ali, 1992) which is represented by the early summer samples in our study.

Satellite data have previously been used to suggest that the highest annual dust levels in the region are associated with the Southwest Monsoon (Sirocko & Sarnthein, 1989). Our data show that during 1995 the surface level air in the Southwest Monsoon had the lowest dust concentration of the year (Fig. 4(c)). The average dust level for the Southwest Monsoon season was $8\,\mu g\,m^{-3}$, a third that of the next lowest seasonal concentration and six times lower than the spring season.

The average elemental enrichment pattern for the summer season differ from those of other seasons, indicating unique dust sources during the summer. While the details vary, the summer pattern follows a similar shape to that of the spring season (Fig. 5). This suggests that the two seasons perhaps receive a portion of their dust loads from the same source. The average chromium enrichment during the summer season is also similar (but slightly lower) to that of the spring season (Fig. 5). This suggests that the possible shared dust source between the summer and spring seasons is likely the Oman area. The reason for the higher average chromium enrichment during the summer is a high chromium level in samples located near the Omani coast, which raises the seasonal average. Those samples are believed to have received dust from Oman during the Southwest Monsoon owing to offshore winds from the Shamal and other local winds which blow off the Omani coast to join the Findlater Jet throughout the Southwest Monsoon. The Shamal winds have previously been proposed as an important source of dust, based on marine sediment deposits (Kolla & Biscaye, 1977; Sirocko & Sarnthein, 1989).

It has previously been assumed that the Findlater Jet deflates and carries dust from Somalia over the Arabian Sea (Sirocko & Sarnthein, 1989). Our data indicate that this was not the case, or if it was, that the dust was not transported far enough to the north-east to reach our sample area during the 1995 Southwest Monsoon. The hypothesis of low dust transport out of Somalia is supported by the spatial distribution of dust levels. Dust samples collected from the southern Arabian sea during the Southwest Monsoon had a lower concentration than those collected from near the Omani coast and those collected from the northern Arabian Sea (Fig. 4(c)). The higher dust levels near the Omani shore, as mentioned above, can be explained by the development of the Shamal moving dust out of Oman on a local scale and possibly entraining sediments from the Wahiba region. Samples near the Omani shore and along the northern Arabian Sea were collected during the early part of the summer, when the Shamal was still active. The Shamal winds are known for producing dust storms in Kuwait and Iraq (Membery, 1983) and are believed to be responsible for high dust levels off the coast of Oman (Sirocko & Sarnthein, 1989). Higher dust levels in samples from the north-eastern Arabian Sea might be explained by the position of the Shamal flow relative to the Southwest Monsoon. Figure 2 and Findlater (1971) suggest the Southwest Monsoon curves eastward before reaching the sample area in the northern Arabian Sea. Therefore, the flow in the northern leg of the cruise path, which was sampled in the early summer, was influenced by flow off the eastern Arabian Peninsula, moving to join with the Findlater Jet. This argument suggests the airmasses with low dust concentrations sampled in the southern portion of the study area were derived from the Findlater Jet originating in the Indian Ocean. Furthermore, dust was not carried from the Somalia area to the study site in the Arabian Sea. In addition, airmasses sampled along the northern cruise leg of the study area, sampled during early summer while the Shamal was likely still active, originated from over the Wahiba Region and, prior to that, Iran.

Autumn

The autumn intermonsoon is represented in our study by cruise TN51 as well as by samples from the end and beginning of cruises TN50 and TN53, during the period of late August through early November. This season marks the second lowest dust levels averaging about 26 $\mu g\,m^{-3}$. The wind field maps (Fig. 2) suggest that the average wind pattern of this season was an eastward rotation of the Findlater Jet from its summer position (Findlater, 1971). This orientation implies Somalia, Yemen, and Oman as likely source areas for dust (Fig. 2). Conversely, back trajectory models suggest the airmasses from upper level flow during this period originate from the north-east and east and descend over the Arabian Sea to join the south-west flow. This suggests the possibility of airmass mixing from both south-west and north-east directions, if significant dust is carried in the upper level air.

Geochemically, the autumn intermonsoon is the most distinct season of the year. The autumn curve on the enrichment factor plot (Fig. 5) shows a highly variable chemical signature relative to other seasons. The dissimilarity of the curve compared to other seasons suggests the probability of a greater degree of multiple source mixing or production of dust from regions which were not active any other time of the year. The eastward rotation of the main jet axis observed by the wind field model, and by Findlater (1971), strongly suggests the possibility of air originating from Somalia and Yemen. Examination of the average seasonal wind patterns indicate this to be the only time Yemen is a likely contributor of dust to the sample area, an observation supported by the unique geochemical signal (Fig. 2).

Although not many samples were collected during the autumn intermonsoon, only the sample off the north Omani coast shows an anomalously high dust concentration (Fig. 4(d)). Given the suggested average wind field data for cruise TN 51(Fig. 2) and the back trajectory model for the sample (Fig. 3(c)), the concentration in this area is likely the result of dust movement out of the lower Mesopotamia, where Iran is an obvious local source of deflated material.

Spatial distribution of dust

On average, the highest dust levels during 1995 were associated with samples collected near the Gulf of Oman and the Omani coast (Fig. 4(a–c)). Geochemical data, dust concentrations, and model wind data all indicate this area to have high dust-producing potential throughout the year. Furthermore, seasonal evidence has been presented which suggests most dust in these areas originates from Oman and perhaps the plains of Iran. This observation is supported by previous research examining the input of aeolian dust to basins in the Arabian Sea. A number of authors, based on spatial patterns of ocean basin sediments, have suggested the Arabian Peninsula to be a major source of sediments (Stewart *et al.*, 1965; Kolla & Biscaye, 1977; Kolla *et al.*, 1981; Sirocko & Sarnthein, 1989). Stewart *et al.* (1965) and Kolla *et al.* (1981) invoked frosted quartz grains as evidence of aeolian input to the Arabian Sea near Oman. They noted that frosted grains were found only off the coast of Oman (in the Owen basin) and off the Pakistan coast near the Iran border. Other areas of the Arabian Sea showed considerably less influence from aeolian input. Kolla *et al.* (1981) and Sirocko & Sarnthein (1989) also noted high quantities of rounded dolomite grains extending away from the Oman region. Sirocko & Sarnthein (1989) also found a similar enrichment in lithogenic carbonate grains extending out from the Omani coast. The enrichment of these continental, aeolian inputs occurs downwind of the Shamal wind path, to which Sirocko & Sarnthein (1989) attribute much of the aeolian transport in the area. This suggests Oman as a significant dust source because the Wahiba sediments are known for their high carbonate content (Goudie *et al.*, 1987; Allison, 1988).

Stewart *et al.* (1965) also noted that in samples off the coast of Oman there was a significant increase in amphibole varieties and olivine relative to other basins in the Arabian Sea. They presented the mineral abundances relative to the percentage of heavy minerals (instead of as a percentage of the total sample) so it is difficult to determine their absolute importance. Despite this, the relative enrichment of these minerals, which occur in abundance in the ophiolite derived sediments in the Wahiba Sand Sea area, suggest a local Wahiba source.

Conclusions

Given the uncertainties associated with deflation and settling fractionation of dust and airmass mixing, the results from this study are encouraging. On a broad scale, the source of dust over the Arabian Sea is controlled primarily by the regional scale wind patterns (monsoons) and also by local winds which merge into the monsoon, such as the Shamal. However, because of the orientation of the main air flow and the generation of local winds, source areas cannot be inferred only from the origin of the monsoon. Therefore, sampling location is as important to the interpretation of dust concentrations and sources as the season in which the sample was collected. The summary of these factors is presented.

Dust concentration

(1) The highest dust concentrations were seen during the winter and spring, and the lowest during the summer and autumn. The variation in seasonal dust levels is an indication of changes in source areas with changing seasonal wind patterns. The highest wind speeds were observed during the summer months when dust levels were lowest, suggesting the dust level variations are controlled more by source area than by wind strength.

(2) The concentration and geochemistry of the dust samples and the prevailing wind patterns imply that during the winter and spring the India/Pakistan/Iran area and the Arabian Peninsula (including the Rub-al-Khali and Wahiba area) are the prominent sources for aeolian dust. Because of the permanence of offshore winds during the Southwest Monsoon, much of the sample area received dust from the Arabian Peninsula during the summer months.

(3) Collection of aerosols from a moving ship did not allow us to distinguish between stable dust-bearing winds and individual, isolated airmasses that passed through the sampling area. Therefore, the distribution of concentrations may be the result of individual dust-bearing airmasses, or controlled by the position of major jet flow at the time the ship passed through them.

(4) The spatial location is as important to the concentration of dust as the major seasonal wind systems. For example, air over the Gulf of Oman was dusty during the

entire year. This pattern is reflected in marine sediments (Sirocko & Sarnthein, 1989) which suggests the Gulf of Oman consistently receives high dust levels and has done so for long periods of time. This suggests local offshore winds, such as the Shamal, supply much of the annual dust load to the region and are possibly more important than the monsoon jets.

Dust geochemistry

(1) Each seasonal elemental enrichment plot is unique from the others. This, like the seasonal dust concentrations, suggests that the source areas of dust do change with the changing seasonal wind patterns. While source areas cannot be accurately determined from enrichment factors, they do indicate general trends in the seasonal patterns, such as the overall similarities between the summer and spring patterns, indicating partial similarities in the dust sources for those seasons.

(2) Analysis of dust geochemical data indicated that discrimination of individual source areas was possible despite atmospheric mixing and sediment fractionation. This was particularly true when source areas possessed unique geochemical tracers, such as the high chromium levels in silt samples from Oman.

(3) Dust geochemistry was used to identify individual sources of dust. Chromium enrichments in samples collected during the spring, downwind of the Wahiba area in Oman, strongly suggest this area to be a prominent dust source for the Arabian Sea and a significant local source during other seasons.

(4) Zinc enrichments during the winter months, identified in samples along the eastern half of the sample area, suggest that the eastern portions of the Arabian Sea received dust from west India, whereas dust over the western Arabian Sea probably originated from the Thar region or farther inland from Pakistan and Iran. While zinc is not considered a mineral dust constituent at such high levels, the spatial and temporal distribution of zinc-enriched samples was a useful indicator of source.

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