



A LARGE SILICON-ALUMINUM AEROSOL PLUME IN CENTRAL ILLINOIS: NORTH AFRICAN DESERT DUST?

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Abstract—During a summer atmospheric chemistry field project in central Illinois in 1979, unusually high concentrations of Si, Al, and other earth's crust elements were observed simultaneously in two series of 2-h aerosol samples collected at sites separated by about 20 km. The Si–Al “event” persisted for about 32 h, and was accompanied by winds shifting from east through north as a weak low pressure area moved eastward across southern Illinois, and a nearly stationary front moved back and forth across the study area. Comparison of aerosol Si/Al and Ca/Al ratios during the event with those in possible sources showed that local soils, coal flyash, and Al smelter emissions were unlikely sources of the observed plume, and focused the investigation on distant dust sources. Climatology favors north Africa over the western United States as a source of desert dust in summer. Forty-eight hour back-trajectories from Illinois show flow from the Gulf of Mexico. Temperature and humidity soundings at Key West, Florida, three days before the onset of the dust plume in Illinois, showed a typical “Sahara air” profile, and simultaneous mineral dust measurements at Miami indicated a strong influx of North African dust at the same time. The evidence indicates that North African dust is the most likely source of the observed high concentrations of Si and Al in central Illinois in July 1979, and illustrates that long range transport can influence air quality at great distances from source areas. Copyright © 1996 Elsevier Science Ltd

Key word index: Desert dust, long-range transport, clay minerals, African dust, mineral aerosols.

INTRODUCTION

There is considerable interest in the relationship between aerosols and precipitation acidity. The major focus of such aerosol studies has been sulfate and nitrate because of their role in producing low pH values in precipitation. However, there is also an interest in neutralizing species such as soil dust. Past studies have shown that the presence of alkaline dust in precipitation samples can lead to higher (more basic) pH values (Stensland and Semonin, 1982; Thasan and Steele, 1987). In our program we have made aerosol measurements concurrently with precipitation studies since the early 1970s (Gatz, 1974, 1975). On many occasions relatively high concentrations of base cations from mineral dust have been observed in precipitation (Doty and Semonin, 1987), and we have shown how trends in cation concentrations in precipitation affect trends in acidity (Stensland and Semonin, 1982; Bowersox *et al.*, 1995; Lynch *et al.*, 1995). In this paper we present observations and analyses of a 32-h aerosol event in central Illinois

during which we measured remarkably high concentrations of Si and Al, which we attribute to soil dust. In a series of 2-h mean concentrations of multiple elements in airborne dust, large Si and Al peaks were observed almost simultaneously at two locations separated by 21 km, indicating that the source was not local. The composition of the aerosol was unlike that previously measured at the site. We present various lines of evidence that show that the soil dust was most likely transported from sources in North Africa.

METHODS

Aerosol samples were collected at 1 m above the ground surface using Florida State University linear “streaker” samplers (Nelson, 1977). The sampling locations (Fig. 1) were (1) the Illinois State Water Survey's atmospheric chemistry site near Bondville, Illinois, and (2) a second site about 21 km to the WNW, near Weldon, Illinois. During sampling, a 2 mm by 4 mm vacuum orifice seals against a strip of 0.4 μm pore diameter Nuclepore filter exposed face down, and is moved along the length of the filter by a DC motor at a rate of

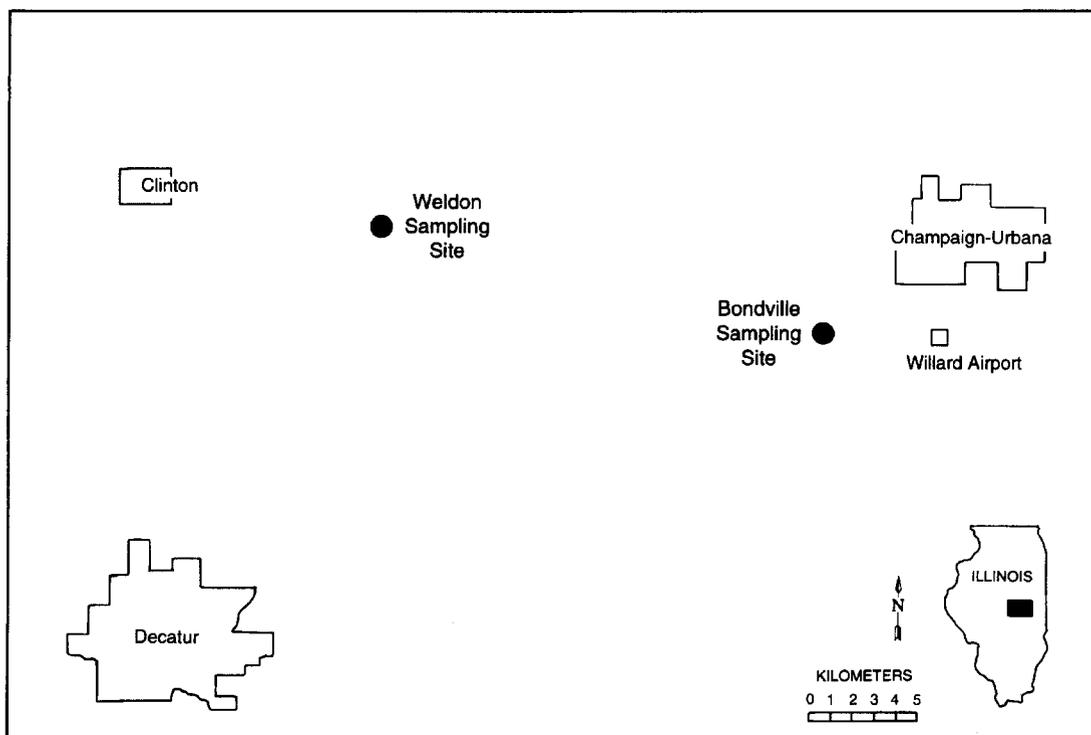


Fig. 1. Map of the study area, showing the Bondville and Weldon sites and Willard Airport.

1 mm h^{-1} , so that a continuous "streak" of sample 168 mm long is collected in one week. The flow rate through the filter is limited to 0.8 l min^{-1} by the size and density of the pores. These samples were analyzed in 2-h increments using proton-induced X-ray emission (PIXE) (Johansson *et al.*, 1975) at Florida State University.

Weather data used in this investigation were the hourly airways observations made at the University of Illinois' Willard Airport, located as shown in Fig. 1. Trajectories were calculated using National Weather Service upper air data and an objective trajectory model described by Scott and Achtemeier (1987).

Dust storm samples were collected during the course of a routine daily filter sampling program at a rural sampling site near Bondville, Illinois, about 10 km southwest of Champaign, Illinois. Samples were collected on preweighed 37 mm diameter, $1 \mu\text{m}$ pore size, Teflon filters. The filters were exposed in open-face plastic cartridges face down under an inverted funnel rain shield, about 1.5 m over grass. Although not experimentally verified, this arrangement probably collects particles mostly $< 10 \mu\text{m}$ diameter.

Surface soil samples were collected along a northeast-southwest transect from near Watseka, in Iroquois County, Illinois, through our Bondville site, to near Assumption, in Christian County, Illinois. Each sample was collected from 3–5 sampling spots in a local area, either varying drainage conditions along a slope, or along a 0.5–0.8 km line in level locations. At each sampling spot, 5–10 trowels-full of surface soil material from an area about 6 m in diameter were collected in a plastic bucket. Each sample was mixed in the bucket, transferred to a plastic bag, and brought to the laboratory, where it was air-dried, crushed, and passed first through a 2 mm sieve and then through a $53 \mu\text{m}$ sieve. Samples of $< 53 \mu\text{m}$ material were resuspended in a jet of filtered air by NEA, Inc., and collected in a dichotomous virtual impactor on Teflon filters in two size ranges: fine ($< 2.5 \mu\text{m}$) and coarse (2.5– $10 \mu\text{m}$). The samples were analyzed by NEA, Inc., using X-ray fluorescence methods. Full

details on soil sampling and sample handling were given by Gatz *et al.* (1984).

RESULTS

Time patterns of element concentrations

The key observations for this unusual event are shown in Fig. 2. Al and Si concentrations increased suddenly from near detection limit levels to several thousand ng m^{-3} . The increases occurred first at the Bondville sampling site at 0400 CDT† on 28 July 1979, and about 4 h later at the Weldon site. The maximum error in timing at each site is 1 h (half the duration of one 2-h time step). Thus, it is very unlikely that the 4-h time lag between plume onset at the two sites was the result of timing uncertainties. At each site there was a primary peak in both Al and Si (which occurred at 1000 at Bondville and 1600 at Weldon), followed by a decrease in concentrations and then by a secondary peak (which occurred first at Weldon, at 2200, and then at Bondville, at 2400). By noon on 29 July, concentrations at both sites were back to detection limit levels. At each site, the shapes of the Al and Si plots are virtually identical, even down to small fluctuations. Thus two sites 21 km apart observed unusually high concentrations of and very similar variations in Al and Si over a

† Midpoint of a 2-h sampling interval.

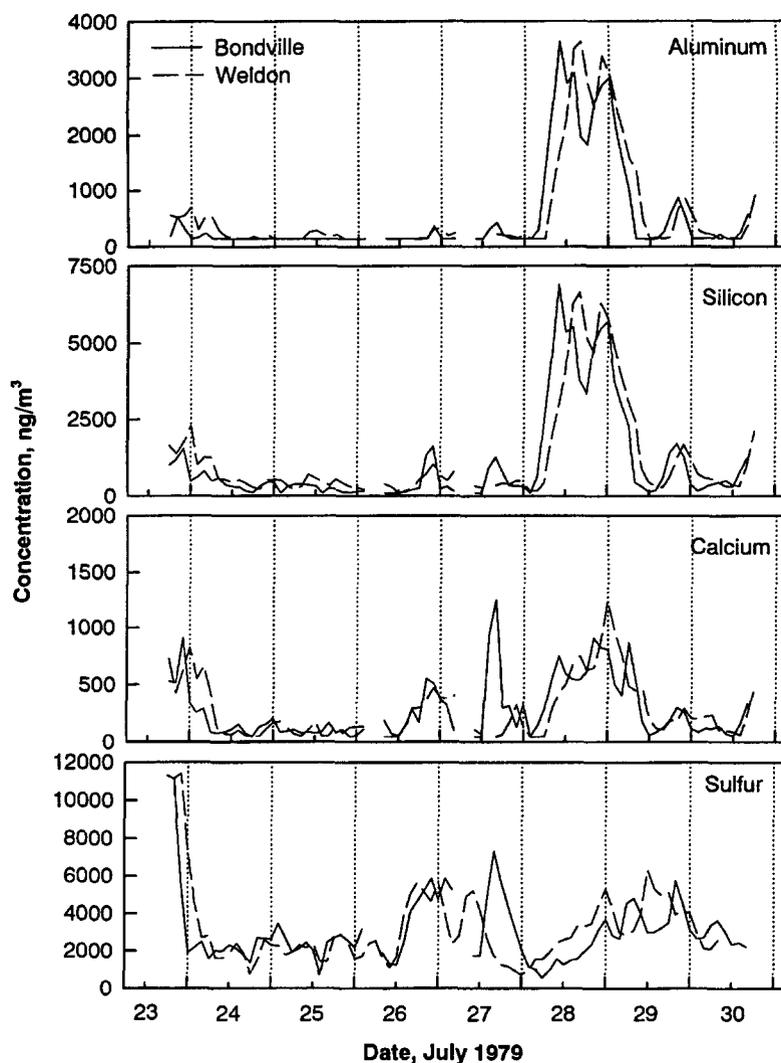


Fig. 2. Element concentrations at Bondville and Weldon vs time, for 23–30 July 1979.

32-h period. This indicates a significant non-local source of these elements, but what might it be? Some clues may be developed by examining the concentration–time patterns of other elements measured simultaneously.

The trace for Ca (Fig. 2) shows a similar broad increase at both sites during the same period. While Ca also showed two peaks at both sites, for Ca the second peak was higher. As with Si and Al, the initial sudden increase in Ca occurred first at Bondville. Other elements (not shown) exhibiting similar, but less spectacular, concentration peaks at both sites include Mg, K, Ti, and Fe, all abundant in the earth's crust.

Figure 2 also shows the time pattern of S concentrations at Bondville and Weldon. Both sites show gradually increasing concentrations during the Al–Si “plume” period, with the increase occurring first at Weldon; overall this is a very different pattern than was seen in the earth's crust elements.

The concentration patterns of Zn and Pb (not shown) were also very dissimilar from those of the earth elements.

Local weather observations

Wind direction is an important key to establishing possible sources of the high Si and Al concentrations. During the late evening of 27 July, winds were from the SSW. Then during the first hours of 28 July, the wind direction gradually shifted to the S, then SE, and then became easterly (about 90°) at 0400, when Si and Al concentrations suddenly increased. As dust concentrations increased, the wind direction continued to shift toward NE and then N. During the hours beginning at 2100 and 2200, roughly the period of the lower-concentration “gap” between the Si and Al peaks in Fig. 2, winds were temporarily from the SW. They then returned to approximately northerly at 2300, and after that gradually shifted through E, reaching S by noon on 29 July. Wind speed increased

from about 5 to 15 knots ($3\text{--}8\text{ m s}^{-1}$) during the first peak in Si and Al concentrations, gradually dropped off to about 4 knots (2 m s^{-1}) at the time of the shift to SW winds, and then varied between 5 and 10 knots ($3\text{--}5\text{ m s}^{-1}$) through noon on 29 July.

Visibility decreased markedly within 2 h after dust plume onset during a period of light rain showers and fog, which occurred between 0500 and 0800. After the rain ended, visibility improved to about 10 miles (16 km), and remained constant until about the time of the SW winds, when 20 mile (32 km) visibilities were recorded. As the winds returned to northeasterly, visibility dropped to about 7 miles (11 km), and remained in the range of 6–10 miles (10–16 km) for the rest of the period.

With a few minor exceptions, sky cover was 100% until about 3 h after the rain ended, after which it gradually improved to about 10% coverage by 2300 on 28 July. Coverage during the first half of 29 July was quite variable, but mostly between 20 and 30%.

Temperatures were in the upper 60s ($^{\circ}\text{F}$) (about 20°C) during the nighttime hours of 28 July, reaching a low of 65°F (18°C) from 0600–0700. Temperatures climbed gradually during the day on the 28th to a high of 83°F (28°C) at 1700, and then gradually dropped to a low of 64°F (18°C) the next morning.

Dew points stayed relatively constant in the range of $62\text{--}66^{\circ}\text{F}$ ($17\text{--}19^{\circ}\text{C}$) during all of 28 July, dropped off to

about 55°F (13°C) at 0600 on the 29th, and increased again, reaching 69°F (21°C) at 1300 on the 29th.

Surface weather map

The surface weather map for 0700 CDT on 28 July is shown in Fig. 3, as redrawn from the series of daily weather maps published by the National Oceanic and Atmospheric Administration (NOAA, 1979). The map shows a (slow-moving) cold front across northern Illinois, a bit to the north of the study area, and a weak low pressure center in southern Illinois, moving to the ENE. These two features explain some of the local observations. The passage of the low pressure center, with its counterclockwise circulation, to the south of the study area explains the wind shift from S around through E to N. Apparently during the course of this wind shift the front moved across the study area, perhaps during the period of precipitation, so that by the time the surface winds were out of the north, the front had moved to the south of the study area. Then, from the brief period of SW winds and higher (20 mile) visibility late in the day on 28 July, it appears that the front meandered north across the study area for 2–3 h. The peaks of the Si and Al concentrations thus occurred behind (north of) the front, and the period of somewhat lower concentrations between the peaks coincided with the brief period when the front had meandered back to the north of

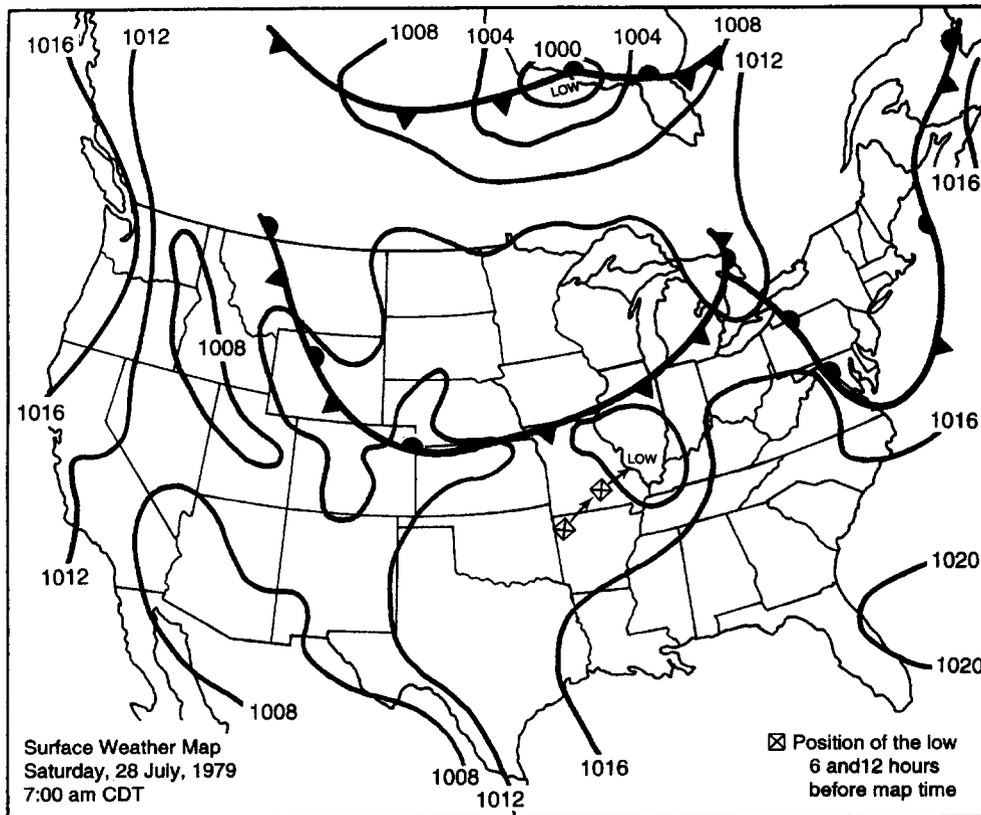


Fig. 3. Surface weather map for 0700 CDT on 28 July 1979, at onset of dust plume in central Illinois. Isobars are labeled in mb.

the study area. Mixing in the frontal zone associated with the light rain showers is likely to have brought the dust plume to the surface.

Sometimes the dew point is useful in delineating frontal positions, but in this case the plotted station data on the original NOAA weather map (NOAA, 1979) show that dew points were about the same on both sides of the front. Likewise, there are no clues to frontal passage in the temperature trace, since temperatures also were similar on both sides of the front. Sky cover gradually improved from 100% right after the morning rain showers to just 10% coverage by late evening on 28 July, and showed no evidence of frontal passages either before or after the brief period of SW winds. After the rain showers, visibility was very constant at 10 miles (16 km) until the brief period of 20 miles (32 km) visibilities during the SW winds, after which visibility was constant again at 7 miles (11 km). It is possible, but difficult to prove, that these limited visibilities were caused by the dust plume responsible for the high concentrations of Si and Al.

DISCUSSION AND ANALYSIS

The peak Si and Al concentrations observed during this event (see Fig. 2) were very unusual. Previous observations (Gatz *et al.*, 1981) showed that Si concentrations at the Bondville site were typically less than 2000 ng m^{-3} , and Al less than 500 ng m^{-3} .

The main question that arises from the observation of a major plume of Si, Al, and other earth's crust elements is, "What is the source of this material?" Several possibilities come to mind, including coal-fired power plants, aluminum smelters, and soil dust, either from local soils (mobilized by tilling or wind erosion) or from a distant desert. Comparison of Si/Al, Ca/Al, and Fe/Ca ratios during the dust event with those in emissions from possible sources provides important clues to the origin of the aerosol.

Figure 4 shows a time history of these three ratios at the two sites during the dust event along with Al concentrations at both sites. Compared to the normal variations in both ratios *outside* the dust plume, it is

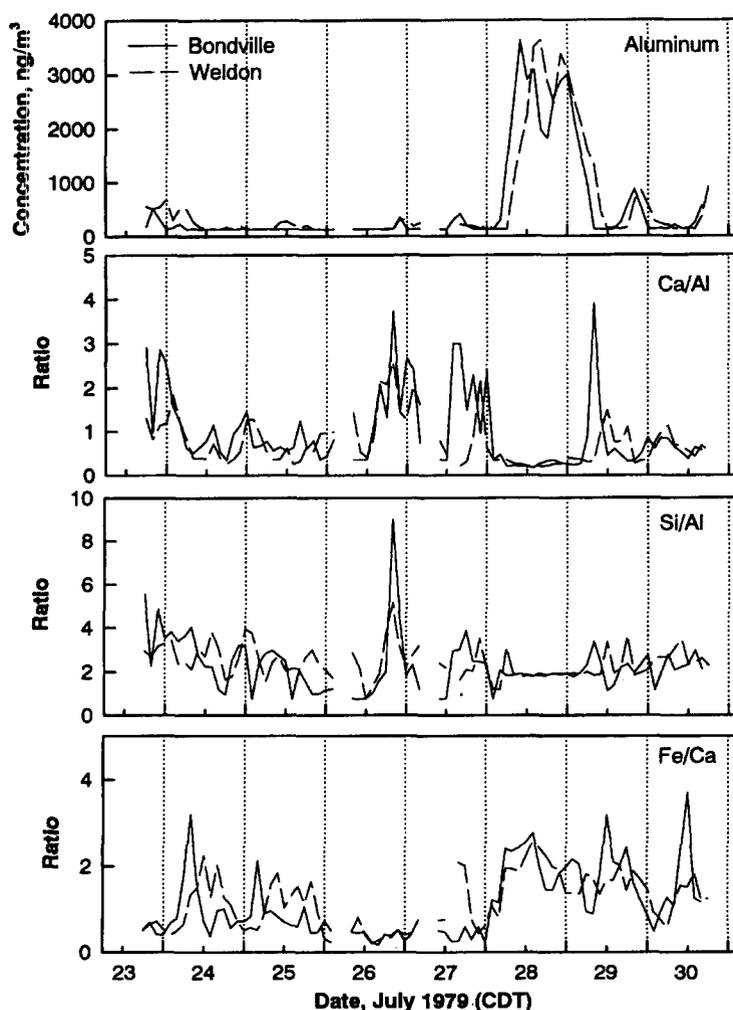


Fig. 4. Time variations of Al and the ratios Ca/Al, Si/Al, and Fe/Ca at the Bondville and Weldon sampling sites. Note especially the constant Ca/Al and Si/Al ratios during the Al plume.

striking how constant the Si/Al and Ca/Al ratios were in the dust plume, even as concentrations varied by a factor of two. In the plume, the Si/Al ratio was very close to 2.0 and Ca/Al was about 0.3. The Fe/Ca ratio was more variable during the plume, but showed good agreement between sampling sites.

Although coal fly ash is similar in elemental composition to the earth's crust (Gatz, 1978), it is unlikely that coal combustion is the source of the observed plume, because the time trace for S (Fig. 2), a widespread trace element in eastern U.S. coals, behaved independently of those of the crustal elements. In addition, the prolonged (32-h) duration of the plume, despite a surface wind variation of more than 90°, argues for a much more extensive plume than would be expected from a regional point source.

The same argument against regional point sources makes an Al smelter an unlikely source, but in addition, the few available elemental signatures do not appear to fit. Source sample compositions listed by Watson (1979) for various operations associated with aluminum manufacturing all showed a large excess of Al over Si, whereas Al/Si in the plume was about 0.5. Further, Olmez *et al.* (1988) measured Cl/Al ratios of 12.0 and 4.4 and K/Al ratios of 6.6 and 1.3 in fine and coarse particles, respectively, in emissions from a secondary aluminum smelter in Philadelphia. The Cl/Al and K/Al ratios (computed from mean element concentrations) observed in the central Illinois plume were much different, at 0.044 and 0.18, respectively.

Figure 5 presents a graphical comparison of mean ratios measured during this event, during the

non-plume portions of the same streaker samples, and in soil-derived aerosols from various locations around the world. The mean Si/Al and Ca/Al ratios computed from 14 separate 2-h samples in the dust plume are shown at the top of the figure, just above those for the rest of the one-week streaker run (excluding samples where either element was not detected). The error bars shown are the standard errors of the mean ratios. (In many cases the standard errors are so small that the error bars do not extend outside the solid plotting symbol.) For both Si/Al and Ca/Al, the in-plume values at the two sites were in excellent agreement. In addition, they were considerably smaller than those in the ambient aerosol present during the rest of the week, signifying a singular event.

Comparison of the Si/Al ratio in the plume (Fig. 5) with those measured in two local dust storms (plotted individually with different symbols) shows that the in-plume ratio is significantly less than the ratios in aerosols derived from local soils. The same is true for regional soils, based on a comparison of the Si/Al ratio in the plume with those in resuspended dust from a set of 20 varied Illinois soils (Gatz *et al.*, 1984).

Comparison of the Ca/Al ratios is also useful. Ca/Al in the dust plume was about 0.3, which is greater than that in local dust storms and in both fine and coarse resuspended aerosols from local soils.

If the plume is unlikely to be either coal fly ash, smelter emissions, or local soil dust, distant soil or desert dust would appear to be the most likely source. Indeed, the low Si/Al ratios observed in the plume suggest that the plume was composed primarily of the

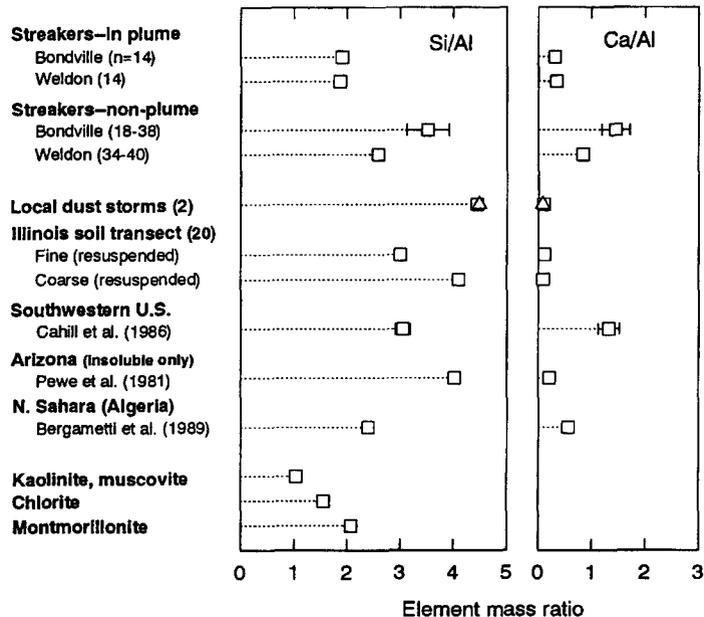


Fig. 5. Element ratios in the 28–29 July 1979 plume, compared to non-plume ratios and ratios in potential dust sources. Error bars are standard errors. Error bars for the in-plume streaker samples, the Weldon non-plume streaker samples, and the Illinois soil transect samples do not extend beyond the plotting symbol.

clay minerals (see Fig. 5) that still remained airborne after many days of travel, during which the larger minerals had been removed by deposition (Rahn, 1976; Pye, 1987). Figure 2 shows Al concentrations of about $3 \mu\text{g m}^{-3}$ in the center of the dust plume. Typical soil materials are 6–8% Al, so the Al concentrations are equivalent to 35–50 $\mu\text{g m}^{-3}$ of mineral dust. The same calculation using 6 $\mu\text{g m}^{-3}$ of Si in the plume and a soil Si abundance of 20% gives a mineral dust concentration of 30 $\mu\text{g m}^{-3}$. A very large source is required to produce such concentrations of Si, Al, and mineral dust. Arid areas of the western United States and northern Africa are the most likely locations of such a source.

Desert areas of the western United States are known to have dust storms in which aerosols are transported for long distances (McCauley *et al.*, 1981). These storms occur primarily in the spring, and rather infrequently in summer (Orgill and Schmel, 1976). Si/Al and Ca/Al ratios measured in aerosols from the western United States are plotted in Fig. 5. Both ratios measured by Cahill *et al.* (1986) are significantly higher than those measured in the plume of 28–29 July. The same is true for the Si/Al ratio reported for soil-derived insoluble aerosols in Arizona by Péwé *et al.* (1981). These ratios would be expected to decrease to some extent with time of travel away from source areas as larger particles such as quartz are removed from the plume. The Ca/Al ratio reported by Péwé *et al.* (1981) is rather similar to that of the central Illinois plume; however, the agreement may be fortuitous if a substantial fraction of the Ca was in one of the soluble minerals such as calcite or gypsum. In any case, the substantial mismatch in the Si/Al ratio and the occurrence of the Illinois plume during summer, when western U.S. sources are at a minimum, argue against the western U.S. as a potential source. We must therefore examine the possibility of a north African source.

It is well known that during the summer months large quantities of North African dust are carried across the Atlantic into the Caribbean (Prospero and Nees, 1986) and into South Florida (Prospero *et al.*, 1993), often causing “muddy” rains (Prospero *et al.*, 1987). The incursion of North African air masses can usually be identified on meteorological soundings by the presence of a deep layer of relatively hot, dry air which normally extends to altitudes of 400–500 mb (Carlson and Prospero, 1972). During such events, a well-defined marine boundary layer (MBL) is usually (but not necessarily) present, capped by a strong inversion caused by the overlying hot Saharan air.

In order to check for the possible advection of North African air into central Illinois, we calculated back-trajectories for the period of high dust concentrations (Fig. 6). The figure shows back-trajectories ending in east-central Illinois at 1200 GMT (0700 CDT) on 28 July, and at 0000 GMT (1900 CDT on 28 July) and 1200 GMT (0700 CDT) on 29 July. These end points correspond roughly to the beginning,

middle, and end of the observed Si–Al plume. In each case, the air arriving over east-central Illinois at pressures between about 800 and 925 mb had been over the Gulf of Mexico two to three days earlier.

We then obtained meteorological soundings from Key West, Florida for the period 0000 GMT on 24 July to 1200 GMT on 29 July. The two successive soundings on 1200 GMT on 25 July and 0000 GMT on 26 July [Fig. 7(a),(b)] show the well-defined characteristics of a Saharan air incursion—i.e. an MBL capped by an inversion; hot, dry air above the inversion, extending to 400–500 mb. The sounding on 1200 GMT on 26 July [Fig. 7(c)] does not show a strong inversion but it does show the presence of a very deep dry layer similar to that observed in the previous two soundings. On the basis of these soundings we conclude that the North African air mass entered the southeastern U.S. about 2.5 d before the dust event that we observed in central Illinois.

Note from Fig. 7 that on the 0000 GMT sounding on 26 July, the Saharan air occupied the layer between about 700 and 850 mb with a potential temperature of 37–39°C. That is somewhat lower and slightly cooler than in the typical eastern Caribbean sounding, but as pointed out by Carlson and Prospero (1972) and Prospero and Carlson (1981), Saharan air typically sinks and cools as it moves westward. Although it is not readily apparent from Fig. 7, it was verified from a hand plotted sounding that the mixing ratio in the Saharan air layer was between 2.5 and 3.5 g kg^{-1} , which agrees with the typical value of 2–4 g kg^{-1} given by Carlson and Prospero (1972). Also note that airflow in that layer is generally easterly on 26 July. Continued easterly flow would have carried the Saharan air to the western Gulf of Mexico within 24 h, and the trajectories shown in Fig. 6 would have carried it northward from there to the midwestern United States.

The conclusions drawn from the meteorological data are supported by measurements of mineral dust concentrations (Fig. 8) made at coastal sites in Miami (Prospero *et al.*, 1987) and Barbados (Prospero and Nees, 1986) during the summer of 1979. The dust concentrations were obtained by extracting water-soluble material from the filter (Whatman-41) and ashing the filter. Thus, the indicated dust concentrations are conservative. The loss of volatile material is about 25%. In late July, a very large dust event lasting more than a week appears to have occurred at Miami. Note especially the high dust concentrations (about 30 $\mu\text{g m}^{-3}$) on 23–25 July; the last day of this period corresponds to the soundings that show Sahara air aloft in Fig. 7. The high dust concentrations at Miami are remarkably consistent with the central Illinois measurements, which suggest concentrations of 35–50 $\mu\text{g m}^{-3}$.

It is also of interest to compare the Si/Al and Fe/Ca ratios in the plume with those given by Bergametti *et al.* (1995) as indicative of specific dust source regions in North Africa, based on observations in the

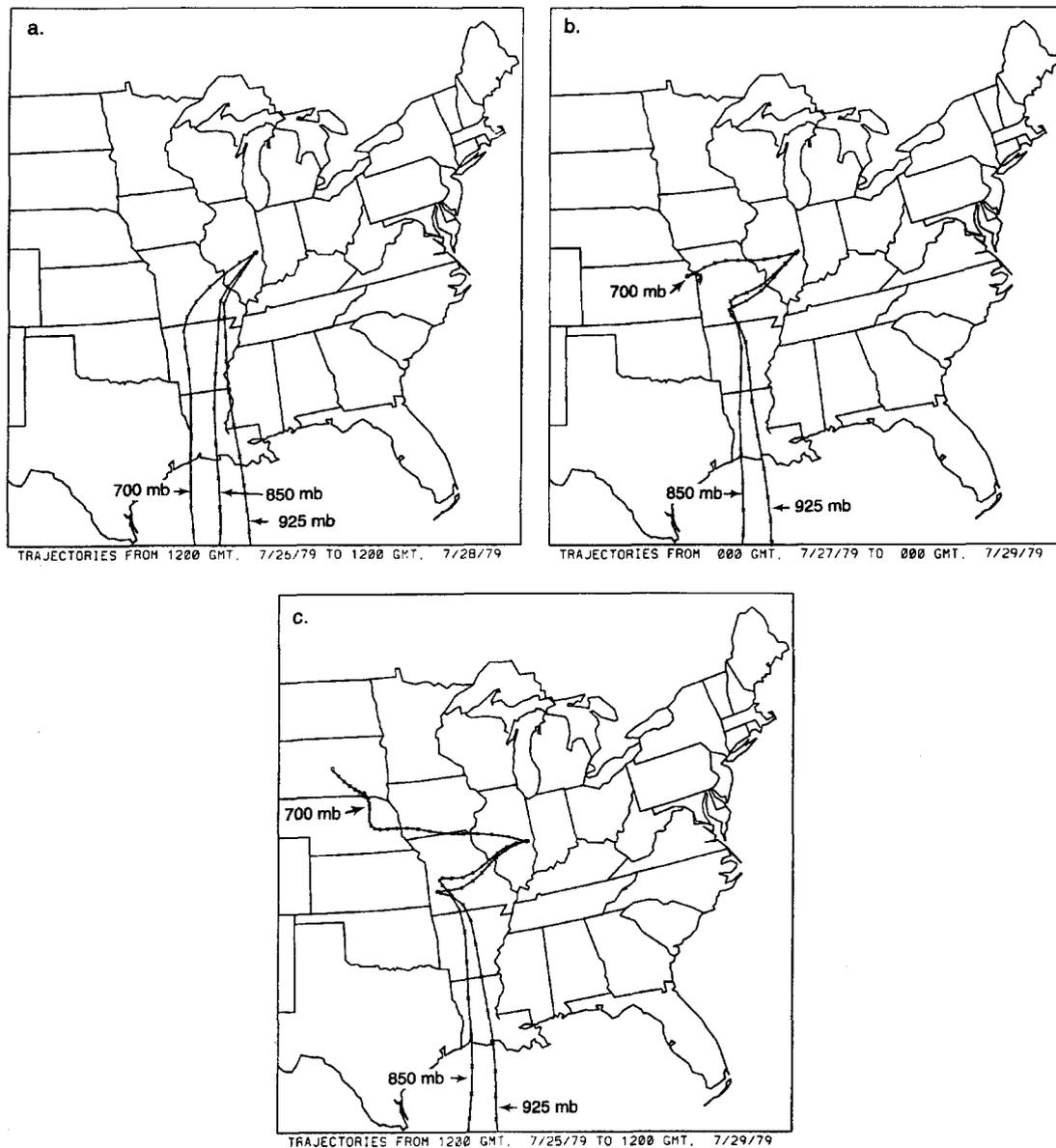


Fig. 6. Isobaric back-trajectories from east-central Illinois for air parcels arriving at (a) 1200 GMT (0700 CDT) on 28 July, (b) 0000 GMT on 29 July (1900 CDT on 28 July) and (c) 1200 GMT (0700 CDT) on 29 July. Trajectories were calculated using the model of Scott and Achtemeier (1987). Each asterisk is the endpoint of a 3-h trajectory segment. The data show that lower tropospheric flow arriving at the sampling sites during the period when the plume was observed was predominantly from the Gulf of Mexico.

western Mediterranean and the Cape Verde Islands. Figure 4 shows that Si/Al was very constant in the plume with a value of about 1.9 at both sampling sites, which corresponds well to the Bergametti *et al.* mean value of 2.03 ± 0.09 (S.D.) for the Sahel. Figure 4 shows that Fe/Ca was more variable in the plume. At Bondville the range for Fe/Ca during the plume was 1.45–2.76, with a mean of 2.03. At Weldon the range was 1.36–2.56 with a mean of 1.91. These values suggest possible sources in the Sahel (2.71 ± 0.59) and the northwest Sahara (1.43 ± 0.32). These comparisons are interesting, and seem to suggest that the dust may have come from the Sahel, but the applicability

of ratios measured relatively close to the sources to dust observations made at a much greater distance from the sources is uncertain at this point.

Evidence from the U.S. strongly suggests that in July 1979 a vast belt of dust was transported across the tropical North Atlantic and across the Caribbean Sea, to the southeastern and Gulf coasts of the U.S., and inland at least as far as central Illinois. The direct distance from the west coast of Africa to South Florida is about 6500 km and thence to central Illinois an additional 1800 km, so the total distance is over 7000 km. This demonstrates once again that winds can transport materials great distances from

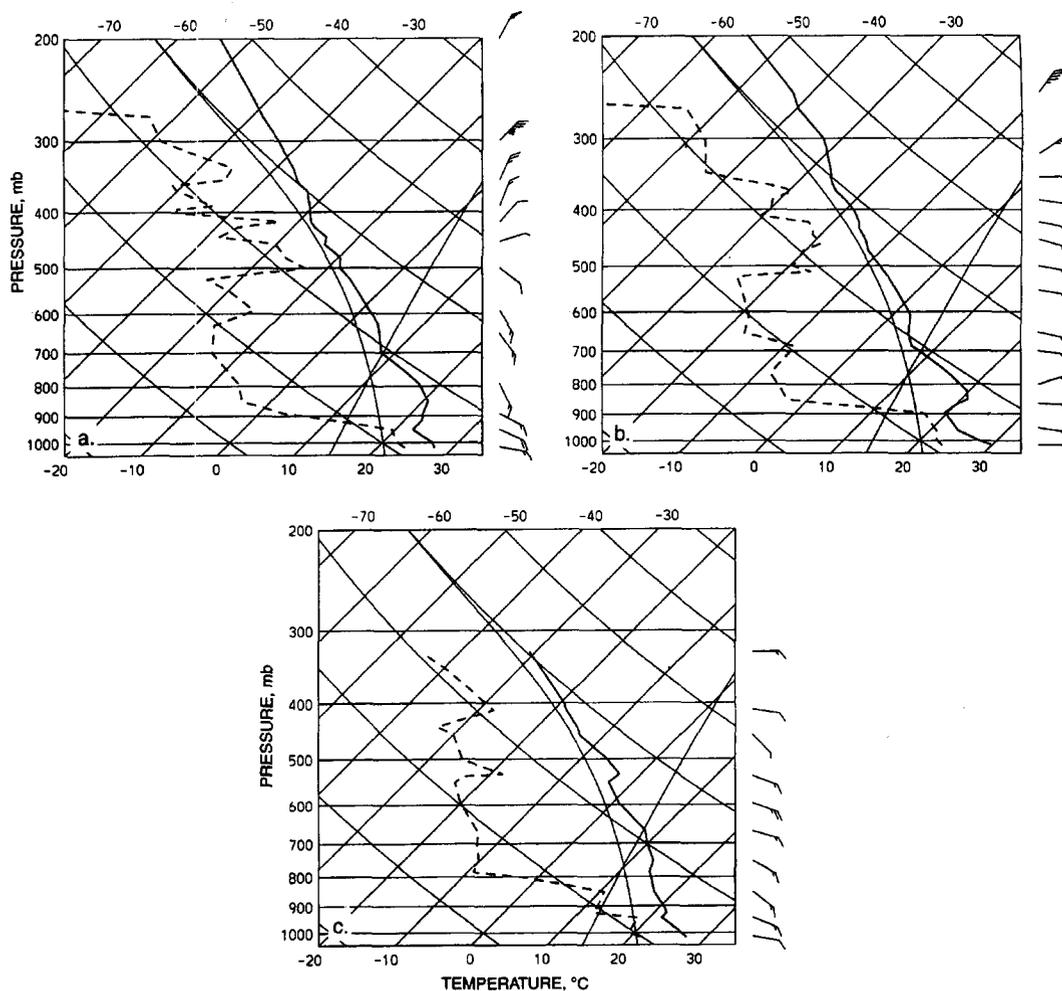


Fig. 7. Temperature (solid line) and dew point (dashed line) soundings from Key West, Florida, compared to the classic Saharan air layer sounding (panel a) typical in the eastern Caribbean (modified from Prospero and Carlson, 1981). The soundings for (b) 1200 GMT on 25 July and (c) 0000 GMT on 26 July show the temperature and dewpoint profiles characteristic of the Saharan air layer, while that for (d) 1200 GMT on 26 July does not.

their sources. It should serve as an example to atmospheric chemists that they should always be alert to the possibility of materials from distant locations impacting on their region of study.

Although we report on only one dust episode here, there is considerable evidence that dust transport from North Africa to the east coast of the U.S. is a relatively frequent phenomenon that has occurred for many years. As previously stated, dust measurements made continuously since 1974 in Miami show that African dust is by far the dominant source of mineral aerosol in the region (Prospero *et al.*, 1987).

SUMMARY AND CONCLUSIONS

A series of 2-h measurements of Si, Al, and other elements in particles smaller than about $4 \mu\text{m}$ showed high concentrations of earth's crust elements at two

central Illinois locations separated by 21 km over a 32-h period in July 1979. This unusual aerosol event occurred as winds shifted from E to N in response to the passage of a weak surface low pressure area across southern Illinois, and light rain fell briefly as a stationary front advanced and retreated over the study area. Examination of Si/Al and Ca/Al ratios and specific trace elements showed that local soil, coal fly ash, and aluminum smelter emissions were unlikely sources of the observed plume, focusing the investigation on distant dust sources. Climatology favors North Africa over the western United States as a source of desert dust in summer. Temperature and humidity soundings at Key West three days before the onset of the dust plume in Illinois showed a typical "Sahara air" profile, and 48-h back-trajectories from Illinois show flow from the Gulf of Mexico. Mineral dust measurements from Miami showed a strong influx of dust to the southeastern and Gulf coasts of the U.S. at the

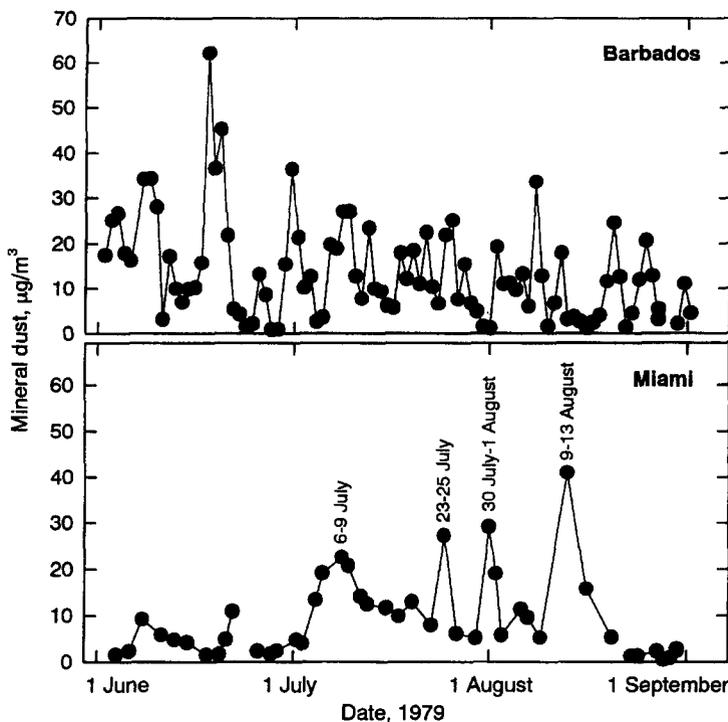


Fig. 8. Mineral dust concentrations measured at Barbados and Miami during summer, 1979.

appropriate time as well. Thus, the evidence indicates that North African dust is the most likely source of the observed high concentrations of Si and Al in central Illinois in July 1979. This event appears to be the first case where North African desert dust was observed in the central U.S. It illustrates that atmospheric transport truly can extend to a very long range, and can have far-reaching impacts on atmospheric properties.

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REFERENCES

- Bergametti G., Marticorena B. and Chatenet B. (1995) An assessment of source-regions and transport patterns of Saharan dust by combining geochemical data, air-mass trajectories, and modeling of dust emissions. Paper presented at the Fall 1995 Meeting of the American Geophysical Union, San Francisco, CA, 11–15 December; Abstract, *Eos Trans. AGU* 76(46).
- Bowersox V. C., Lynch J. A. and Grimm W. (1995) Trends in precipitation chemistry measured at U.S. National Atmospheric Deposition Program/National Trends Network sites, 1980–1993. In Proc. A&WMA Annual Meeting, Paper 95-TP58.02, Air and Waste Management Association, Pittsburgh, PA.
- Cahill T., Eldred R. and Feeney P. (1986) Particulate monitoring and data analysis for the National Park Service, 1982–1985. National Park Service Contract Number USDICX-0001-3-0056, William Malm, Project Manager.
- Carlson T. N. and Prospero J. M. (1972) The large-scale movement of Saharan air outbreaks over the northern Equatorial Atlantic. *J. appl. Met.* 11, 283–297.
- Doty K. G. and Semonin R. G. (1987) Two case studies of the transport of dust storm aerosol and the potential for incorporation into precipitation. *J. Clim. appl. Met.* 26, 763–773.
- Gatz D. F. (1974) METROMEX: air and rain chemistry analyses. *Bull. Am. Met. Soc.* 55, 92–93.
- Gatz D. F. (1975) Wet deposition estimation using scavenging ratios. *J. Great Lakes Res.* 2 (Suppl. 1), 21–29.
- Gatz D. F. (1978) Identification of aerosol sources in the St. Louis area using factor analysis. *J. appl. Met.* 17(5), 600–608.
- Gatz D. F., Stensland G. J., Miller M. V. and Leslie A. C. D. (1981) Sources of airborne calcium in rural central Illinois. In *Atmospheric Aerosol: Source/Air Quality Relationships* (edited by Macias E. S. and Hopke P. K.), ACS Symposium Series, No. 167. American Chemical Society, Washington, DC.
- Gatz D. F., Stensland G. J., Miller M. V. and Chu L.-C. (1984) Alkaline aerosols: an initial investigation of their role in determining precipitation acidity. Final report to the National Science Foundation, Grant ATM 77-24294, Illinois State Water Survey Contract Report 343, Champaign, Illinois.

- Johansson T. B., Var Grieken R. E., Nelson J. W. and Winchester J. W. (1975) Elemental trace analysis of small samples by proton-induced X-ray emission. *Anal. Chem.* **47**, 855–860.
- Lynch J. A., Grimm W. and Bowersox V. C. (1995) Trends in precipitation chemistry in the United States: a national perspective, 1980–1992. *Atmospheric Environment* **29**(11), 1231–1246.
- McCaughey J. F., Breed C. S., Grolier M. J. and MacKinnon D. J. (1981) The U.S. dust storm of February 1977. In *Desert Dust: Origin, Characteristics, and Effect on Man* (edited by P  w   T. L.), Special Paper 186, pp. 123–147. The Geological Society of America, Boulder, Colorado.
- Nelson J. W. (1977) Proton-induced aerosol analysis: methods and samplers. In *X-ray Fluorescence of Environmental Samples* (edited by Dzubay T. G.), pp. 19–32. Ann Arbor Science Publishers, Ann Arbor, Michigan.
- NOAA (1979) Daily Weather Maps, Weekly Series for July 23–29, 1979. U.S. Dept. of Commerce, NOAA, Environmental Data and Information Service, Government Printing Office, Division of Public Documents, Washington, D.C., 20,402.
- Olmez I., Sheffield A. E., Gordon G. E., Houck J. E., Pritchett L. C., Cooper J. A., Dzubay T. G. and Bennett R. L. (1988) Compositions of particles from selected sources in Philadelphia for receptor modeling applications. *J. Air Pollut. Control Ass.* **38**, 1392–1402.
- Orgill M. M. and Sehmel G. A. (1976) Frequency and diurnal variation of dust storms in the contiguous U.S. *Atmospheric Environment* **10**, 813–825.
- P  w   T. L., P  w   E. A., P  w   R. H., Journaux A. and Slatt R. M. (1981) Desert dust: characteristics and rates of deposition in central Arizona, U.S.A. *Geol. Soc. Am.* **186**, 169–190.
- Prospero J. M. and Carlson T. N. (1981) Saharan air outbreaks over the tropical North Atlantic. *Pure Appl. Geophys.* **119**, 677–691.
- Prospero J. M. and Nees R. T. (1986) Impact of the North African drought and El Ni  o on mineral dust in the Barbados trade wind. *Nature* **320**, 735–738.
- Prospero J. M., Nees R. T., and Uematsu M. (1987) Deposition rate of particulate and dissolved aluminum derived from Saharan dust in precipitation at Miami, Florida. *J. geophys. Res.* **92**, 14,723–14,731.
- Prospero J. M., Savoie D. L., Arimoto R. and Huang F. (1993) Long-term trends in African mineral dust concentrations over the western North Atlantic: relationship to North African rainfall. *Eos Trans. AGU* **74**(43), 146; Fall Meeting of the American Geophysical Union, San Francisco, CA, 6–10 December 1993.
- Pye K. (1987) *Aeolian Dust and Dust Deposits*, p. 137. Academic Press, New York.
- Rahn K. A. (1976) Silicon and aluminum in atmospheric aerosols: crust-air fractionation? *Atmospheric Environment* **10**, 597–601.
- Scott R. W. and Achtemeier G. L. (1987) Estimating pathways of migrating insects carried in atmospheric winds. *Environmental Entomology* **16**(6), 1244–1254.
- Stensland G. J. (1981) Summary of sulfate and pH for SCORE-79. In *Study of Air Pollution Scavenging*, 19th Progress Report, Prepared for U.S. Department of Energy, Pollutant Characterization and Safety Research Division, Office of Health and Environmental Research (edited by Semonin R. G., Bowersox V. C., Gatz D. F., Peden M. E. and Stensland G. J.), pp. 1–6. Illinois State Water Survey Contract Report 252, Champaign, Illinois.
- Stensland G. J. and Semonin R. G. (1982) Another interpretation of pH trend in the United States. *Bull. Am. Met. Soc.* **63**(11), 1277–1283.
- Thasan P. and Steele K. F. (1987) Chemical and mineralogical characterization of rain particulate matter at a mid-continent site, U.S.A. In *Acid Rain: Scientific and Technical Advances*, pp. 213–218. Selper Ltd., London.
- Watson J. G. (1979) Chemical element balance receptor model methodology for assessing the sources of fine and total suspended particulate matter in Portland, Oregon. Doctoral Dissertation, Oregon Graduate Center, Portland, Oregon.