Two Case Studies of the Transport of Dust Storm Aerosol and the Potential for Incorporation into Precipitation

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ABSTRACT

To investigate the hypothesis that dust storms enhanced the calcium concentrations in precipitation in the mid-1950s, two case studies were performed for major dust events in the southern Plains of the United States during March and April of 1981. Forward trajectories were calculated from source areas of blowing dust and then compared with hourly radar summaries to see if the advected dust cloud intercepted precipitation over sites of the National Atmospheric Deposition Program. Four sites met these criteria between the two case studies and exhibited extremely high calcium concentration and deposition values for the study period.

1. Introduction

Stensland and Semonin (1982) reevaluated the available precipitation chemistry data of the mid-1950s and found median concentrations of calcium and magnesium several times greater than more current levels, as determined from the National Atmospheric Deposition Program (NADP) at sites in the Midwest and East (NADP, 1984). Stensland and Semonin (1982) hypothesized that the source of the alkaline materials was soil related, since large parts of the Great Plains and Southeast experienced significant drought in the mid-1950s with numerous reports of dust storm events. This study will focus on the NADP sampling periods of 17–24 March 1981 and 31 March–7 April 1981, when several significant dust events occurred in the southern Plains. By looking at meteorological and chemical data, our goal was to seek evidence for the impact of soil aerosol from distant sources on the inorganic chemistry of precipitation.

2. Crustal sources of alkaline materials

The major inorganic ions measured in current precipitation chemistry networks (along with calculated HCO_3^-) provide a reasonable ionic charge balance. Therefore, the free acidity in precipitation as described by the hydrogen ion concentration can be expressed to a large degree as a function of a net ions term, where an equilibrium relationship between gaseous CO_2 and liquid water is assumed (Stensland, 1983). The net ions term is the difference between the measured equivalent concentrations of anions (SO_4^{2-}, NO_3^-, and Cl^-) and cations (NH_4^+, Ca^{2+}, Mg^{2+}, Na^+, and K^+).

This formulation does not include the effects of weak organic acids. As the major precipitation chemistry networks do not routinely measure organic constituents, quantitative measurements of their spatial and temporal importance are limited at the present time. Chapman and Sklarew (1986) analyzed springtime precipitation chemistry samples for two sites in Wisconsin and showed that formate and acetate could have contributed up to an average of 18.6% of the total free acidity for samples with pH $\leq$ 5.0. Keene and Galloway (1984) derived a comparable value for 16 precipitation events of 16.0% at a site near Charlottesville, Virginia.

Throughout the rest of this paper, ionic signs will be omitted for simplicity. For inland sites in the eastern United States, SO_4 and NO_3 typically have the highest anionic concentrations (in μeq/L), while H, NH_4, and Ca (in that order, respectively), have the highest cationic concentrations. Calcium, Mg, and K are usually related to crustal sources. Evans and Cooper (1980) estimated open sources of suspended particulate matter across the United States and found unpaved road dust and wind erosion of soil to be the two largest sources of particulate material, respectively, on a national basis. Evidence seems to indicate that unpaved roads are a major source for the Ca and Mg content of atmospheric particulate material and precipitation as compared to soil sources across the United States (Barnard et al., 1986). Barnard et al. concluded that the primary reason for this dominance was the high concentrations of Ca and Mg in road materials, although their calculations have considerable uncertainty given the paucity of certain needed data. The role of soil derived aerosol may be enhanced during the spring season for certain parts of the United States, as will be described in section 4. An example of the role of dust storm aerosol in precipitation chemistry is given by Gitlin (1978), who examined the inorganic composition of hailstones as part of Project DUSTORM conducted by the National Center for Atmospheric Research (NCAR). X-ray

analyses of Oklahoma hailstones revealed Ca/Si ratios which were similar to the same ratios in soil aerosol collected at a height of 2 km over Texas during a dust storm. The latter dust storm was not the same as the one which preceded the convective activity leading to the hailstones, but both dust storms had similar source regions in terms of areal coverage of blowing dust. The high calcium content of the aerosol and hailstones was related to Portales loamy fine sand, one of the major soil types involved in wind erosion over western Texas and northeastern New Mexico.

Apart from other evidence, distinguishing between sources such as unpaved roads and wind erosion of soil by observing the levels of Ca, Mg, and K in precipitation creates substantial challenges. The problem of chemical fractionation between the bulk source composition and the generated aerosol, the problem of differing solubility of various source constituents, and the question of local versus distant sources make the establishment of source-receptor relationships difficult. Resolution of these issues will help substantiate the evidence provided in this study.

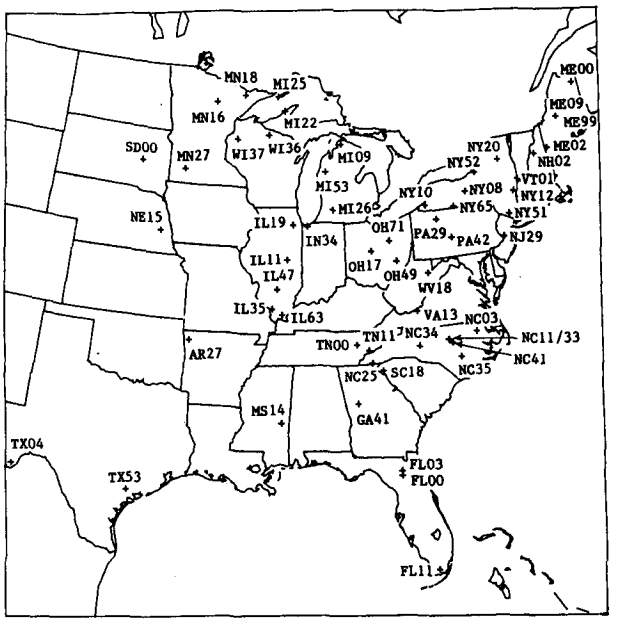

FIG. 1. National Atmospheric Deposition Program (NADP) site locations and codes for March 1981.

3. Datasets utilized

National Atmospheric Deposition Program data (NADP, 1984 and Bowersox, 1985) were used to determine the chemical characteristics of the soluble portions of the major inorganic constituents in precipitation over the eastern half of the United States. Constituents which are measured routinely include pH, SO_4, NO_3, Cl, NH_4, Ca, Mg, Na, K, PO_4, and conductivity. Standard sampling periods end Tuesday mornings at each site when the wet-side buckets are changed. The sample comments recorded by the field and laboratory personnel for each NADP sample were also valuable. They provided a description of the color and nature of any insoluble material in the sample and any possible contamination, as well as providing the days on which precipitation occurred and the amount. Figure 1 shows the locations and site codes for NADP sites in the eastern half of the United States for March 1981.

The meteorological data used in this analysis included 3-h surface maps and hourly radar summaries from the National Climatic Center (NCC) of the National Oceanic and Atmospheric Administration (NOAA). Input for the trajectory analyses was the North American wind–temperature dataset (NAMER-WINDTEMP) provided by NCC. The NCC publication *Climatological Data* (1981) was used in determining the weekly precipitation across the eastern United States. Since NADP samples are collected on Tuesday mornings, the normal Monday–Sunday precipitation summaries were not sufficient. For a better approximation, the daily precipitation data for National Weather Service Offices and Federal Aviation Administration sites were summed, with midnight on Monday as the weekly cutoff. The NADP raingage data were then incorporated with the latter analysis to produce the weekly precipitation analyses.

4. Meteorology of dust storms

Orgill and Sehmel (1976) developed a climatology of dust storms across the United States as based on surface hourly observations from the National Weather Service and from the military for the approximate period 1940–70. Huschke (1969) defines a dust storm as a situation where blowing dust reduces the visibility below ⅝ of a mile. However, Orgill and Sehmel (1976) used the term "dust storm" in a more liberal sense, including all situations where blowing dust reduced the visibility below seven miles. The latter distance is according to standard weather observing procedures (NOAA, 1970). Orgill and Sehmel's analysis indicated a maximum over the southern Plains, with the highest average value of about 223 dust hours per year at Lubbock, Texas. A rather large area across eastern portions of Colorado and New Mexico, western portions of Kansas and Oklahoma, and much of the northern half of Texas had, on the average, 80 h or more per year of dust observations. A secondary maximum was located over the northern Plains. Seasonal variations showed a distinct maximum for the months of March, April, and May. Orgill and Sehmel (1976) related this seasonal effect to spring storms with high surface winds, which occur in conjunction with soil surfaces in an erodible state because of agricultural practices or other factors.

5. Trajectory model

The Heffter (1980) Air Resources Laboratories-Atmospheric Transport and Dispersion (ARL-ATAD)

trajectory model was used in this study to calculate forward trajectories from the dust storm area in the southern Plains. These trajectories were then compared with hourly radar summaries to determine whether they intercepted any precipitation areas over NADP sites. In the model, two options exist for defining the transport layer. The model can define the top of the transport layer by searching for a potential temperature inversion meeting specified criteria, or the top and bottom of the transport layer can be manually set to a certain fixed distance above the station elevation. The latter method was used in this study to model the upper regions of the mixed layer which could be affected by the upper-level jet. Determining the depth of the mixed layer was difficult as the most intense areas of blowing dust rarely coincided with rawinsonde stations. Even the closest station may not have given a good indication of the mixed layer structure for a given storm. Benkley and Schulman (1979) give a method of determining the depth of the mixed layer using observed surface and upper-air data which chooses between the maximum of either a mechanical or thermal layer. Their estimate of the mechanically mixed layer was based on the work of Plate (1971), whereas their estimate of the convectively mixed layer was based on the height at which the adiabat of the current surface temperature intersects the morning 1200 UTC sounding (Miller, 1967). The latter technique for estimating the convective layer depth is standard, but Benkley and Schulman (1979) added several refinements, one of which was the adjustment of the surface temperature to reflect temperature advection within the boundary layer by using the 12 h temperature change at 500 or 700 mb, depending on the altitude of the station. Using their method with the latter refinement, estimates were made of the height of the mixed layer for rawinsonde stations in or close to areas with blowing dust. To the extent that nearby stations reflected the actual conditions within the blowing dust areas, typical mixing depths were 1 to 3 km above the surface. The upper portion of this mixing depth was then used as the transport layer for trajectory calculations.

Once a transport layer had been determined, 3 h surface weather maps were used to locate areas with observations of blowing dust for the case studies to be considered. Points were then chosen which created a simple geometric shape (such as a rectangle) which enclosed the primary area of blowing dust. Forward trajectories were then calculated from these points using the prescribed transport layer. Locations of these trajectories in time gave an estimate of the dust cloud volume. In subsequent discussion this "volume" may also be referred to as the advected "area", given its two-dimensional representation on a map.

No provision was made for synoptic-scale vertical motion in the calculation of trajectories with the Heffter (1980) model. This could be a serious deficiency for intense cyclonic systems. Air parcels rising through a region of warm air advection ahead of the upper-level trough may experience the influence of veering winds. Also, no provision was made for mesoscale dispersion during transport. Given these factors, it is likely that the trajectory volume advected downwind will not undergo the degree of shear that an actual volume would experience. Future work could benefit from a technique such as isentropic trajectories to account for vertical motion. Artz, Pielke, and Galloway (1985) have compared trajectories of the ARL-ATAD model with those of the NCAR isentropic model and found that differences can be substantial for certain situations.

Tetroon trajectories or tracer data are often used as a means of comparison with calculated trajectories [e.g., Peterson (1966), Pack et al. (1978), and Reisinger and Mueller (1983)]. Either of these methods can have their difficulties in providing a means of establishing the accuracy of calculated trajectories. Another approach is given by Kuo et al. (1985), who gave the results of a set of observing system simulation experiments (OSSE) which were carried out on a 3-day period of the Oxidation and Scavenging Characteristics of April Rains (OSCAR) experiment. A mesoscale numerical weather prediction model (Anthes and Warner, 1978) was used to create a three-dimensional wind field with considerable temporal and spatial detail. This dataset was considered as the "real" atmosphere. Three-dimensional trajectories were calculated with this dataset from a grid of 88 origins across the United States. The original dataset was then degraded in various ways; spatially, temporally, and trajectories calculated with each of these new datasets were then compared to those calculated with the "real" atmosphere. The comparison in which the original dataset had been interpolated to actual rawinsonde station locations (at 12 h intervals with appropriate random measurement errors included, and trajectories calculated at a constant altitude above the surface within the boundary layer) was the closest to the Heffter (1980) model used here. After 25 h of travel, the average horizontal transport error across all 88 trajectories for this comparison was approximately 200 km. Kuo et al. (1985) state that these errors are probably lower limits given the fact that the mesoscale model was run on a 80 km grid and therefore circulations below that size could not be represented. Although the simulation was based on one synoptic event, Kuo et al. (1985) state that the results should be applicable given that the system was representative of those found in winter and spring for much of the United States. It was not discussed how the errors varied according to the origin of the trajectories across the United States.

6. The 17–24 March 1981 case

a. Meteorology

The NADP sampling period of 17–24 March 1981 was characterized by three dust events of varying mag-

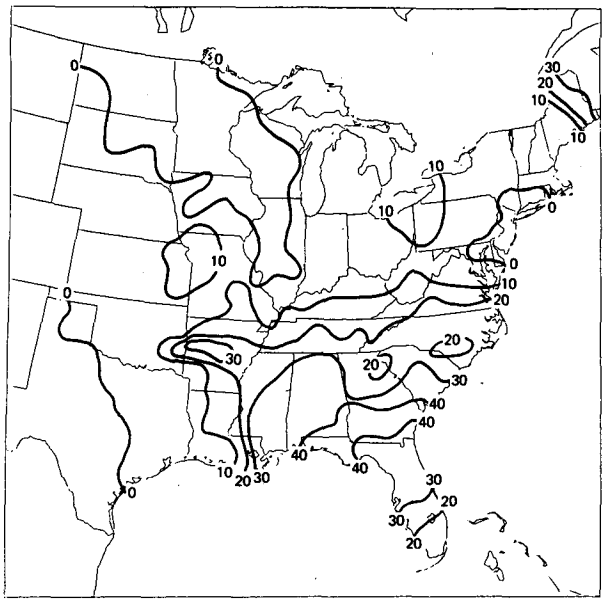

FIG. 2. Precipitation (mm) for the period 17–23 March 1981.

nitude on 17, 20, and 21 March in Texas and New Mexico. Figure 2 shows the precipitation for the period 17–23 March. The week was characterized by several storm systems, but with the major storm track across the southern States as continental polar air dominated much of the week in the Midwest and Northeast. Precipitation was generally light across the country except for the Southeast. Trajectory calculations for the dust events on 17, 20, and 21 March and the intensity of the system on 17 March indicated that it was the most important event, and will be the only one discussed for this period.

Figure 3 shows the frontal positions and sea level pressure analysis at 2100 UTC 17 March 1981. An intense low pressure center of 986 mb was located over the Kansas–Oklahoma border. Another very intense storm off the coast of Maine was the other main synoptic feature. Surface observations of blowing dust (up to the severe dust storm level) were observed from 1800 UTC 17 March until 0000 UTC 18 March in north central Texas. Average surface winds ranged from 15 to 20 m s^{-1} with gusts to over 50 m s^{-1}, while temperatures ranged from 15–21°C. The NCC publication *Storm Data* (1981a) described the major wind damage and poor visibilities with this storm. A large area had surface dewpoints less than or equal to −9°C from Lubbock, Texas westward across much of New Mexico, reflecting the dry adiabatic descent of air from higher altitudes.

Using the procedure described earlier, the mixing depths during the peak of this storm were estimated to be at least 3 km above the surface. Whereas the lower

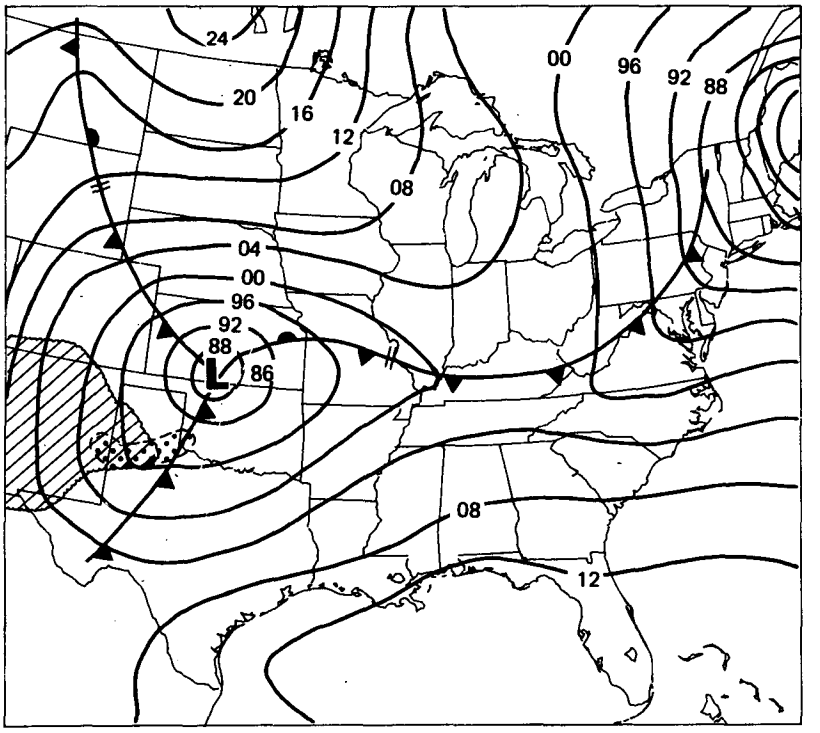

FIG. 3. Surface analysis for 2100 UTC 17 March 1981. Isobaric analysis is incomplete off the coast of Maine. Stippled area over Texas indicates the area of blowing dust. The area with diagonal lines has surface dewpoints less than or equal to −9°C.

portions of this mixed layer would be influenced by surface synoptic features, the upper portions would be dominated by the free atmosphere as it became decoupled from the lower portions at night. Subsequent evolution of the boundary layer would determine whether this elevated layer was mixed back to the surface downwind from the source region. The assumption in this study was that transport was dominated by the upper-level jet and hence a transport layer of 2–3 km above the surface was chosen for the trajectory calculations for this event.

Figure 4 shows the location of an area originally over the primary dust area (dashed lines) after 12 h of travel with a start time of 1800 UTC 17 March. The advected box (solid lines) and precipitation coincide over the AR27 site at the approximate time of 0600 UTC 18 March. This confirms the information provided by the site observer that wet deposition of reddish Texas soil had occurred with this event. Wagner and Steele (1985) have reported the chemical composition of the insoluble component of an event sample for this storm at the AR27 site and attributed the reddish color to hematite. The wind shear across the upper-level jet has rotated the original area cyclonically so that the western edge of the original area now leads the original eastern edge on the advected area. Whereas the northern portions of the advected area in Fig. 4 appear to be within precipitation, the southern section remained in precipitation-free air until it reached the Georgia–Alabama area.

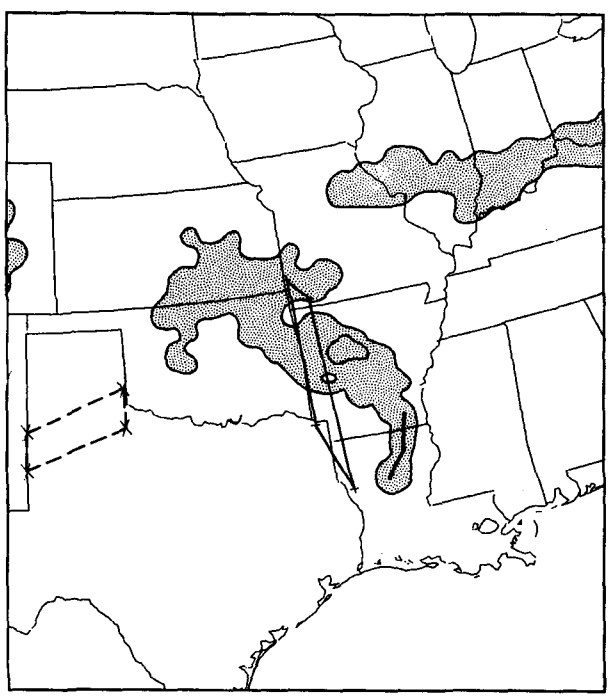

FIG. 4. Forward trajectories were calculated with the origins being the vertices of the dashed area over Texas. The area with solid lines is the location of the advected points after 12 h of travel with a start time of 1800 UTC 17 March 1981 and a transport layer of 2–3 km above the surface. Shaded areas are radar echoes for 0635 UTC 18 March. Radar echoes adapted from radar summary charts on microfilm from NCC.

Figure 5 shows the situation at 2100 UTC 18 March after 27 h of transport. The western edge of the original area has raced eastward and is within a rapidly developing area of convection across the Southeast. The advected area has deformed into an approximate straight line 100 km north of the GA41 site, where laboratory comments noted a large amount of reddish soil in the sample. Interpretation of this visual evidence is complicated by the severe convective activity in parts of Georgia, which could have produced locally high surface winds and generation of local aerosol. However, the severe weather was primarily limited to areas south and east of the GA41 site, which suggests that the origin of the red material was not local. While the dust cloud aloft apparently traveled over the MS14 site, it was not in conjunction with any precipitation as demonstrated by the hourly radar summaries.

b. Chemistry

In comparison with all the other ions, the striking feature of the 17–24 March 1981 NADP sampling period was the extremely high concentrations of Ca, Mg, and K for certain sites. Since the patterns for these three ions were similar, only Ca concentrations will be discussed. Figure 6 shows the Ca concentrations in precipitation for the sampling period of 17–24 March. The five sites with highest concentrations in μeq/L are AR27, 98; WV18, 85; GA41, 55; IL35, 54; and OH49, 52. Trajectory calculations were in agreement with the visual evidence of transport at AR27, and suggested transport as well to GA41. In both cases there were high concentrations observed at those sites. To determine the distinctive nature of these concentrations, it is necessary to compare them against the climatology of other concentrations of similar sample volume for a given site. Table 1 gives the information needed to make such a comparison. The statistics in Table 1 are based on the initial screened (Bowersox, 1985) NADP (1984) data through December 1984 for samples having volumes greater than or equal to 35 mL and having sampling periods of 6–8 days. For the sites AR27, GA41, OH49, WV18, and IL35, the sample volume ranges were determined by taking the observed sample volume for the period 17–24 March plus or minus 175 mL. Samples within these volume ranges were then used to calculate the maximum and volume-weighted average Ca concentrations for the five sites. As seen in Table 1, the observed Ca concentrations for AR27 and GA41 for the 17–24 March period are the maximum for the given sample volume ranges and are four to six times the volume-weighted averages. The observed concentrations at OH49, WV18, and IL35 are at or above the volume-weighted averages, but not to the

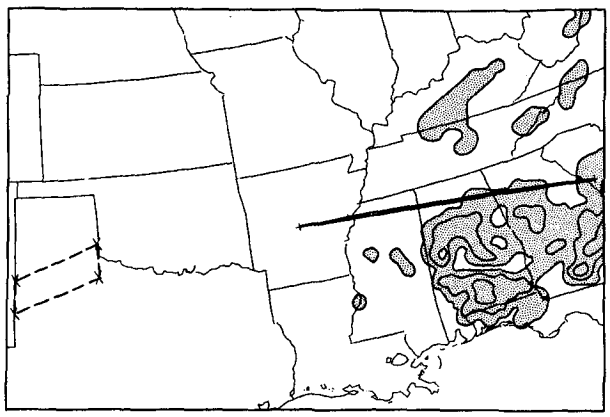

FIG. 5. Forward trajectories were calculated with the origins being the vertices of the dashed area over Texas. The area with solid lines is the location of the advected points after 27 h of travel with a start time of 1800 UTC 17 March 1981 and a transport layer of 2–3 km above the surface. Shaded areas are radar echoes for 2035 UTC 18 March. Radar echoes adapted from radar summary charts on microfilm from NCC.

degree of those at AR27 and GA41. Sampler problems at WV18 make that concentration suspicious.

It is also of interest to look at the observed depositions climatologically for this week as well. Using the same initial dataset as described above through December 1984, the weekly Ca depositions were ranked from the largest to the smallest. The top 20 NADP weekly Ca depositions, divided by the site median deposition, are plotted against sample volume for AR27 in Fig. 7 and for GA41 in Fig. 8. In Fig. 7 it is seen that the 17–24 March 1981 sampling period had the third largest Ca deposition with respect to the data period considered, being about six times the site median deposition. In Fig. 8, the 17–24 March 1981 sampling period demonstrated the largest Ca deposition for the GA41 site, being about 15 times the site median value.

These concentration and deposition statistics illustrate that the Ca loading in the samples at AR27 and GA41 were very atypical. While this evidence does not exclude the impact of local sources, when considered along with the trajectory calculations it seems very likely that dust storm aerosol played a key role in enhancing the mass of calcium in the samples. Both AR27 and GA41 had two days of rainfall, so event statistics related to the dust event on 17 March are not possible to determine with NADP data.

7. The 31 March–7 April 1981 case

a. Meteorology

Figure 9 shows the precipitation for the period 31 March–6 April 1981. Three areas of heavy precipitation existed: one along the East coast, one from Ohio to the Gulf coast, and another in the northern Plains and Great Lakes area. Two weather systems dominated the synoptic pattern for the eastern United States during the week. The first system moved across the Midwest on 1 April. By 1800 UTC 1 April, a cold front extended southward along the Appalachians from a deep low pressure center over southern Ontario. The cold front produced shower activity along it, with the heaviest precipitation in the East and Southeast. Strong winds to the rear of the front produced blowing dust in northern Indiana. This was symptomatic of the condition of much of the cropland in the Midwest as a result of a dry spring, strong winds, and extensive field work. Figure 10 shows the second major system of the week with a very intense low pressure center of 983 mb over the Nebraska–Kansas border at 0000 UTC 4 April. This system produced the precipitation maximums over the northern Plains and from Ohio southward to the Gulf. Many severe thunderstorms and tornadoes were reported ahead of this system (*Storm Data*, 1981b). The system weakened as it moved northeastward, with decreasing surface wind speeds and less intense convection. This system will be the focus of discussion in regard to precipitation chemistry, as it was the only or dominant producer of precipitation for many of the NADP sites in Ohio, Indiana, Illinois, Nebraska, and Arkansas. At 0000 UTC 4 April, blowing dust was reported over central Kansas and Oklahoma, northern Texas, and southeastern New Mexico. Other areas of blowing dust were observed over southeastern Arkansas and northwestern Illinois. By 0300 UTC 4 April, the latter area had moved eastward, with

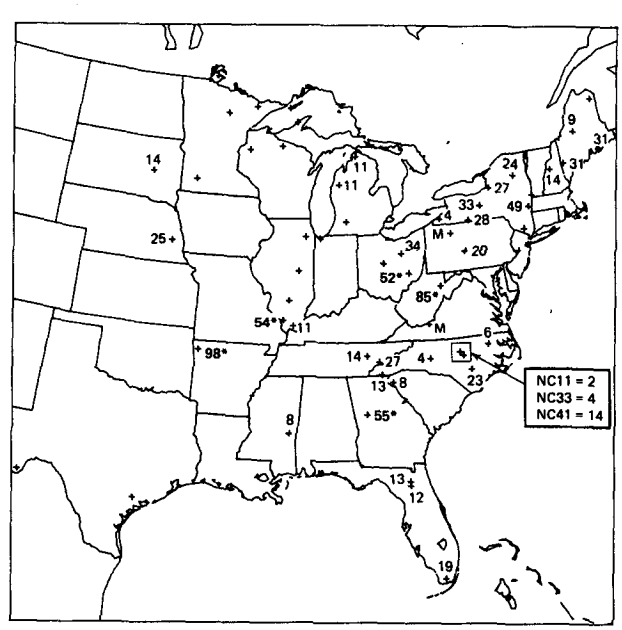

FIG. 6. Calcium concentrations (μeq/L) in precipitation for the NADP sampling period 17–24 March 1981. Starred values are discussed in the text. Sites marked "M" had samples with field or laboratory problems.

TABLE 1. Comparison of maximum and volume-weighted average Ca concentrations for specified sample volume ranges against observed Ca concentrations for specified sites for the NADP sampling period of 17–24 March 1981. Initial dataset described in text.

Site	Sample volume range (mL)*	Maximum concentration (μeq/L)†	Volume-weighted average (μeq/L)‡	Observed concentration (μeq/L)¶	Number of samples#
AR27	732–1082	98	23	98	22
GA41	1728–2078	55	9	55	18
OH49	35–236	329	52	52	38
WV18	179–529	124	30	85@	51
IL35	144–494	79	27	54	47

* Sample volume ranges determined by taking volume of 17–24 March 1981 sample plus or minus 175 mL. Minimum lower bound of range is 35 mL.

† Maximum Ca concentration for the given sample volume range and site.

‡ Volume-weighted mean Ca concentration for given sample volume range and site.

¶ Observed concentration for given site for NADP sampling period 17–24 March 1981.

Number of samples from initial, screened dataset within the sample volume range for the given site.

@ The sampler at WV18 for the period 17–24 March may have been open during times without precipitation and therefore concentration may be bulk in nature.

Chicago, Illinois and South Bend, Indiana reporting blowing dust. Based on the surface maps, available every 3 h, the dust storm over the southern Plains began at 1800 UTC 3 April and lasted approximately 6 h. However, a tongue of blowing and suspended dust could be traced northeastward for an additional 12 h behind the cold front and ahead of a secondary surface trough. This lingering dust cloud during the last 6 h was composed mainly of suspended dust that was transported from the original source region and not produced locally. At 1200 UTC 4 April, surface observations indicated suspended dust from St. Louis, Missouri southwestward to McAlester, Oklahoma.

For this storm, trajectories were calculated for a layer 1–2 km above the surface, using the methods described in section 5. Since the area of dust production changed with time, different source areas were used for the 1800 UTC 3 April and 0000 UTC 4 April starting times. Figure 11 shows an area (solid lines) after 6 h of transport from the vicinity of northern Texas which was

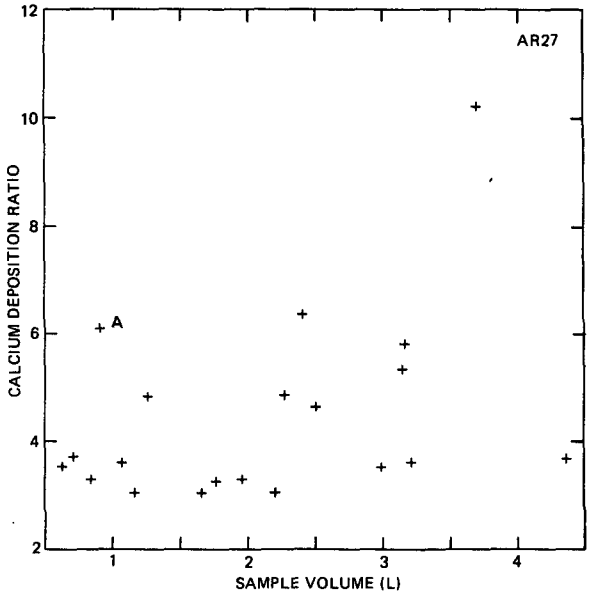

FIG. 7. The top 20 weekly NADP Ca deposition ratios versus sample volume (L) for AR27. Ratios are derived by taking the weekly values and dividing by the site median Ca deposition as based on data through 1984. Value marked with "A" corresponds to the sampling period 17–24 March 1981.

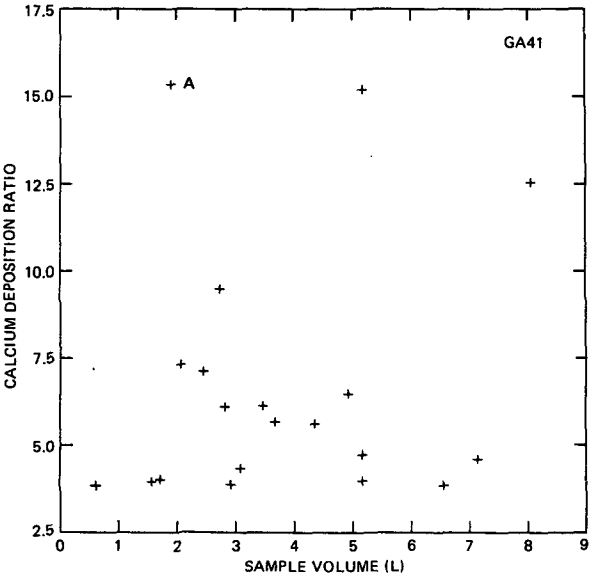

FIG. 8. The top 20 weekly NADP Ca deposition ratios versus sample volume (L) for GA41. Ratios are derived by taking the weekly values and dividing by the site median Ca deposition as based on data through 1984. Value marked with "A" corresponds to the sampling period 17–24 March 1981.

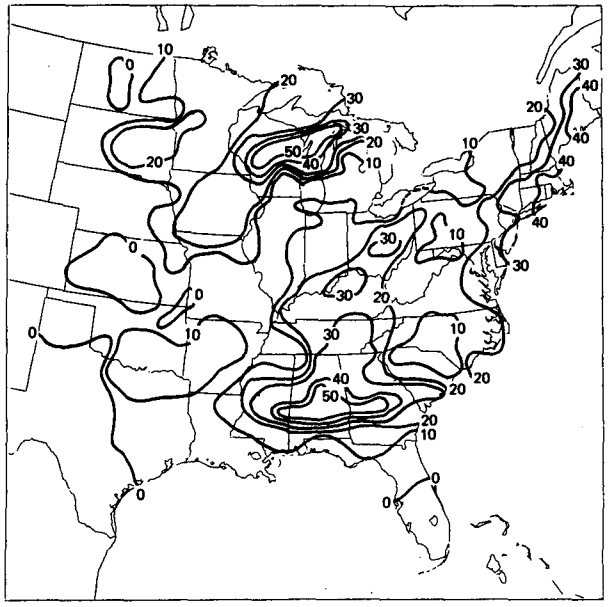

FIG. 9. Precipitation (mm) for the period 31 March–6 April 1981.

the source area (dashed lines) at a start time of 1800 UTC 3 April. The northern edge of the advected area coincides with convection over the NE15 site. By 0600 UTC 4 April, intense convection was occurring across Illinois (not shown). High winds associated with these severe thunderstorms (*Storm Data,* 1981b) could have produced local aerosol before the onset of precipitation. This makes differentiation between local and distant sources more difficult for NADP sites in Illinois. Figure 12 shows the advected area (solid lines) after 18 h of travel with a source area (dashed lines) further south as compared to Fig. 11 and with a start time of 0000 UTC 4 April. The southern edge of the advected box comes very close to site IL35. Laboratory personnel noted large amounts of reddish soil in the sample, and no known local sources of such material exist (J. Fralish, personal communication, 1983). This strongly suggests that long-range transport did occur.

b. Chemistry

Figure 13 shows the Ca concentrations in precipitation for the NADP sampling period 31 March–7 April 1981. The six sites with the highest concentrations (in μeq/L) are IL35, 144; NE15, 131; IN34, 105; AR27, 95; MI26, 65; and OH49, 50. Trajectory calculations indicated possible incorporation of the advected dust cloud with precipitation over sites IL35 and NE15, which is in agreement with the high values observed. Table 2 gives a comparison of the observed values for

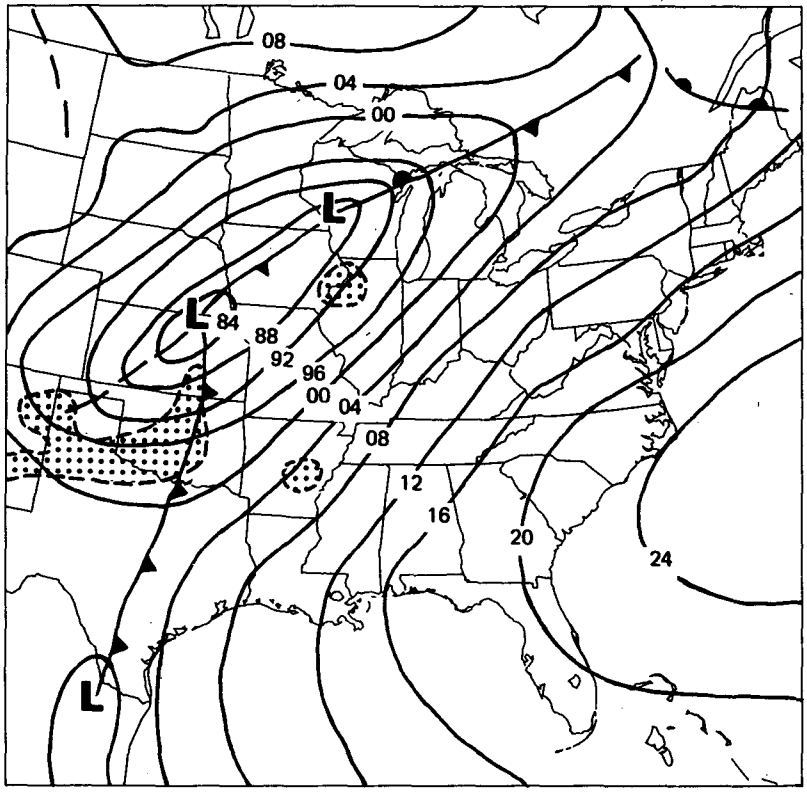

FIG. 10. Surface analysis for 0000 UTC 4 April 1981. Areas with blowing or suspended dust are stippled.

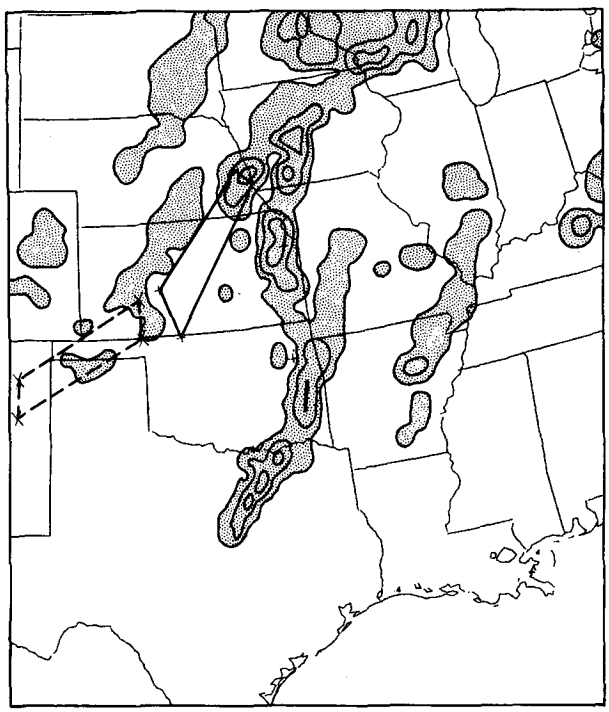

FIG. 11. Forward trajectories were calculated with the origins being the vertices of the dashed area over Texas. The area with solid lines is the location of the advected points after 6 h of travel with a start time of 1800 UTC 3 April 1981 and a transport layer of 1–2 km above the surface. Shaded areas are radar echoes for 0035 UTC 4 April 1981. Radar echoes adapted from radar summary charts on microfilm from NCC.

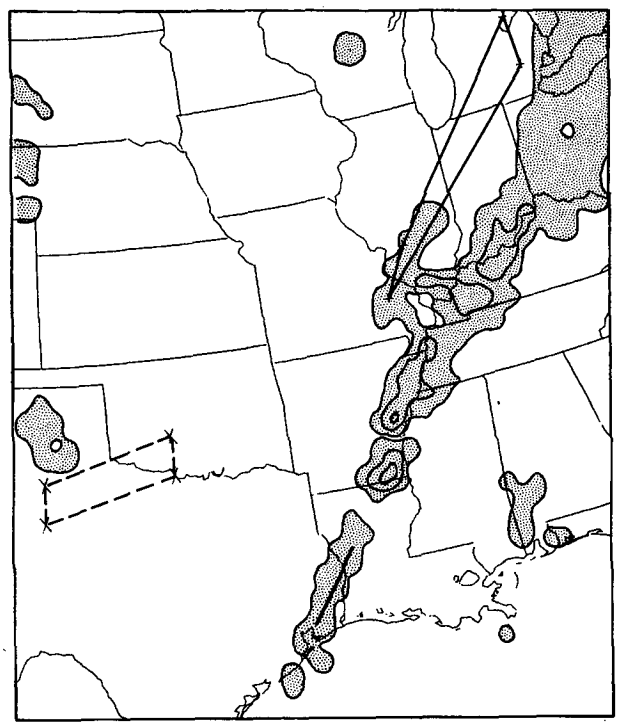

FIG. 12. Forward trajectories were calculated with the origins being the vertices of the dashed area over Texas. The area with solid lines is the location of the advected points after 18 h of travel with a start time of 0000 UTC 4 April 1981 and a transport layer of 1–2 km above the surface. Shaded areas are radar echoes for 1835 UTC 4 April 1981. Radar echoes adapted from radar summary charts on microfilm from NCC.

this week with the respective site climatologies for similar sample volumes. The initial dataset for the statistics in Table 2 is the same as that described for Table 1. The observed Ca concentrations for IL35 and NE15 are seen to be the maximum for the given sample volume ranges and between four and five times the volume weighted average. Concentrations for IN34, AR27, and MI26 are high but not to the same degree as for the first two sites. The observed Ca concentration for OH49 was the maximum for the given sample volume range. Trajectories did not seem to indicate any incorporation of the Texas dust that far east. Possible causes are the first synoptic system of the week which created blowing dust over parts of Indiana, or more local sources.

Figures 14 and 15 are analogous to Figs. 7 and 8 in showing the top 20 Ca deposition events plotted against sample volume for the two sites and with the depositions scaled by the site median Ca deposition. The deposition for the NADP sampling period 1–7 April 1981 (one day off from the standard sampling time of 31 March) at IL35 was third with respect to data through 1984, being about seven times the site median value. The Ca deposition for the week under consideration at NE15 was the largest, with respect to the same initial dataset, being about ten times the site median value.

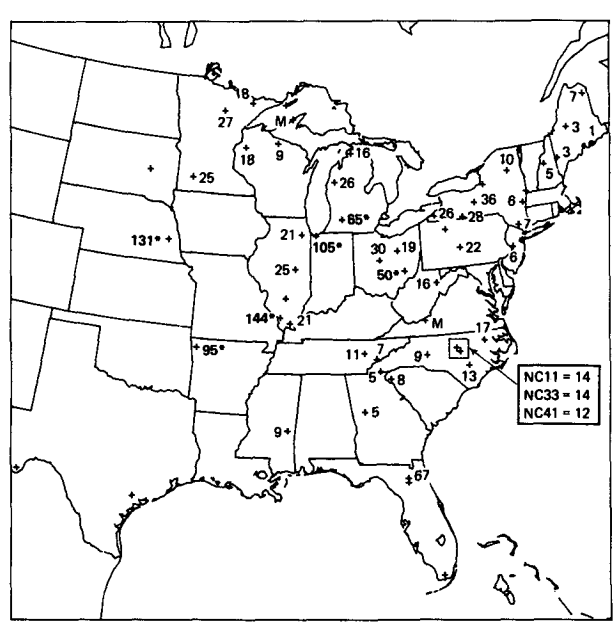

FIG. 13. Calcium concentrations (μeq/L) in precipitation for the NADP sampling period 31 March–7 April 1981. Starred values are discussed in the text. Sites marked "M" had samples with field or laboratory problems.

TABLE 2. Comparison of maximum and volume-weighted average Ca concentrations for specified sample volume ranges against observed Ca concentrations for specified sites for the NADP sampling period of 31 March–7 April 1981. Initial dataset described in text.

Site	Sample volume range (mL)*	Maximum concentration (μeq/L)†	Volume-weighted average (μeq/L)‡	Observed concentration (μeq/L)¶	Number of samples#
IL35	376–726	144	30	144	37
NE15	1094–1444	131	31	131	13
IN34	35–318	248	56	105	45
AR27	35–295	290	45	95	32
MI26	349–699	93	22	65	35
OH49	1726–2076	50	12	50	21

* Sample volume ranges determined by taking volume of 17–24 March 1981 sample plus or minus 175 mL. Minimum lower bound of range is 35 mL.

† Maximum Ca concentration for the given sample volume range and site.

‡ Volume-weight mean Ca concentration for given sample volume range and site.

¶ Observed concentration for given site for NADP sampling period 17–24 March 1981.

Number of samples from initial, screened dataset within the sample volume range for the given site.

The Ca concentrations and depositions at IL35 and NE15 are seen to be very high when compared to their respective site climatologies. As in the case of the 17 March event, the evidence strongly suggests an enhancement of Ca loadings at these two sites because of the impact of dust storm aerosol advected from the southern Plains. However, unlike the 17 March event, IL35 and NE15 each had only 1 day of precipitation, so these statistics are "event" oriented.

8. Conclusions

Trajectory calculations, Ca concentrations, and visual observations of the respective samples confirm that the 17 March 1981 dust event affected the sample at AR27 and strongly suggest an impact on the GA41 site as well. The same type of evidence points towards an influence from the 3 April 1981 storm on sites NE15 and IL35. The observed Ca concentrations at these sites for the respective weeks were the maximum observed for similar sample volumes for data through 1984. The Ca depositions for the same sites and periods were in the top three compared to the same site histories.

Apportioning the contribution of local versus distant sources toward these unusually high Ca loadings is not possible with the information available. However, the combination of all the evidence indicates that the Ca

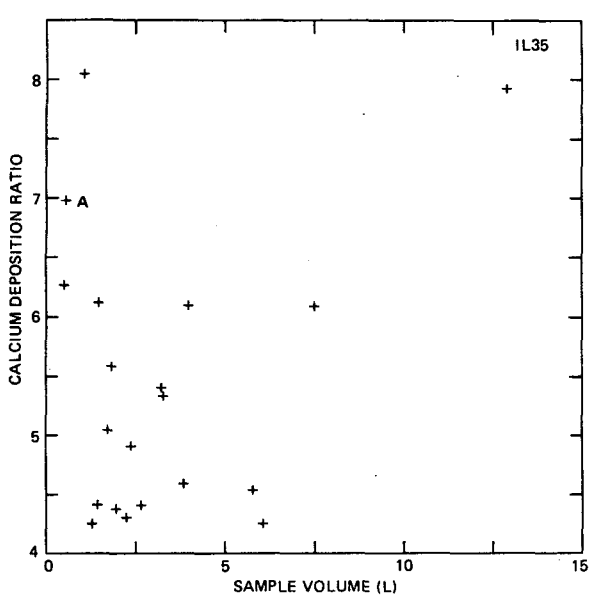

FIG. 14. The top 20 weekly NADP Ca deposition ratios versus sample volume (L) for IL35. Ratios are derived by taking the weekly values and dividing by the site median Ca deposition as based on data through 1984. Value marked with "A" corresponds to the sampling period 1–7 April 1981.

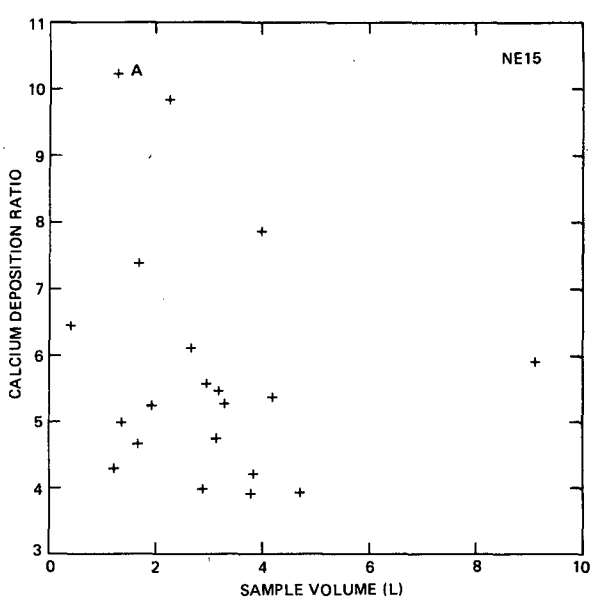

FIG. 15. The top 20 weekly NADP Ca deposition ratios versus sample volume (L) for NE15. Ratios are derived by taking the weekly values and dividing by the site median Ca deposition as based on data through 1984. Value marked with "A" corresponds to the sampling period 31 March–7 April 1981.

loadings were higher than that which could have been provided by local sources alone, at least in terms of the impact of local sources thus far, as indicated by the site climatologies. Although Ca concentrations were elevated at several sites in these two case studies, it is difficult to extrapolate these results to the situation which may have existed in the mid-1950s as described in the beginning of this paper. If these results are typical, dust events of sufficient magnitude to produce a dust cloud with a major impact on precipitation chemistry at several NADP sites in any given week are uncommon. Whether the intensity and frequency of dust storms in the mid-1950s was sufficient to alter the Ca concentration of precipitation over longer periods of time would require investigation of the specific events involved.

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