7. STUDY PERIOD REPRESENTATIVENESS

When considering BRAVO Study findings, it is important to understand how conditions during the BRAVO period compared with those during the rest of the year and during the same months in other years. The study took place over only the four months of July through October 1999, and thus could not provide information concerning the visibility and aerosol at Big Bend during the entire year. Furthermore, conditions during those four months in 1999 could have been different from those in the same four months in other nearby years. Several investigators performed analyses investigating how BRAVO study conditions compared with those during the rest of 1999 and as to how representative the four months in 1999 were of the same periods in other years. These evaluations provide a point of perspective for assessing whether the findings of the BRAVO study might also provide insight concerning the mechanisms of air pollution impacts on Big Bend visibility throughout the year and during other years.

7.1 Meteorology

To investigate if BRAVO weather conditions were characteristic of those during the same months in other years, temperature, relative humidity (RH) and surface wind measurements at Big Bend National Park during the BRAVO Study period in 1999 were compared with the same measurements during the corresponding months in the five years from 1994 through 1998. The historical data for temperature and RH were obtained from the IMPROVE database for the BIBE1 transmissometer site (http://vista.cira.colostate.edu/improve, accessed 17 October 2001) and for wind from the CASTNet (Clean Air Status and Trends Network) database (http://www.epa.gov/castnet/metdata.html, accessed 25 October 2001). For temperature and RH, only those hours in which RH was less than 90% were considered. This threshold, which is intended to result in comparisons for only those periods when fog or rain are not likely to be contributors to haze, did not affect many days. Average values of temperature and RH were then calculated for each day, and monthly averages were calculated in turn. Details of the data screening, processing and analyses are described by Georgoulias (2003), which is enclosed in the Appendix.

Table 7-1 shows monthly averages of daily mean temperature and relative humidity. Also shown are values of the corresponding monthly average relative humidity scaling factor, *f*(RH), for sulfate and nitrate light scattering, based on the *f*(RH) curve published by the USEPA (2001). Statistically significant differences, as established by the non-parametric Kruskal-Wallis test, are denoted by shaded cells.

Table 7-1. Monthly average temperature, RH, and *f*(RH) at Big Bend for hours with RH < 90%. Standard deviations are in parentheses.

	July		August		September		October	
	'94-'98	*'99*	*'94-'98*	*'99*	*'94-'98*	*'99*	*'94-'98*	*'99*
Temperature	29 °C (2)	27 °C (2)	28 °C (2)	29 °C (2)	25 °C (3)	26 °C (3)	21 °C (4)	21 °C (4)
RH	45% (13)	54% (10)	50% (13)	40% (10)	51% (12)	47% (11)	45% (15)	36% (10)
f(RH)	1.2	1.5	1.3	1.1	1.4	1.3	1.3	1.1

The 1999 average temperatures in July and August were statistically different (at the 0.05 level) from temperatures during the same months in previous years, but are still within 2 °C. We also conclude that the mean relative humidities in July, August, and October 1999 were statistically different (at the 0.05 level) than during the same months in the previous five years; however, the standard deviation in the five-year data set indicates considerable variability from year to year. The 1999 values were not consistently higher or lower than the averages during the historical period.

Wind data from 1995 through 1999 were also examined, though only qualitatively. Wind roses in Figures 7-1 through 7-4 (again grouped by month) illustrate monthly distributions of wind speed and direction for 1995-98 versus 1999. (The numerals in the centers indicate the percentages of time that the wind was calm.) There are some differences, such as a stronger SE component in July 1999 and a varying NW component in October 1999 (less frequent NW winds, but more frequent high speeds from the NNW than the historical period). However, the roses are generally similar enough to indicate that wind patterns at Big Bend during the BRAVO Study were generally characteristic of those in the previous years.

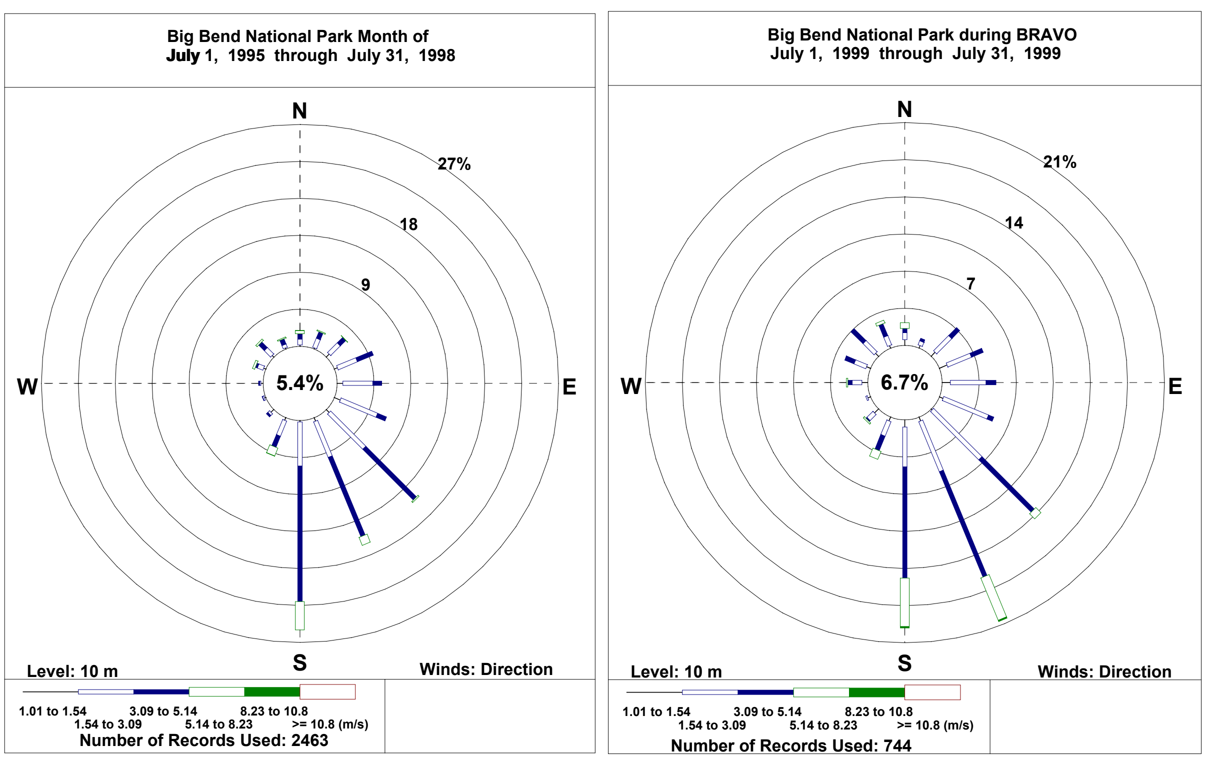

Figure 7-1. *Comparison of wind roses for July 1995-1998 (left) and 1999 (right).*

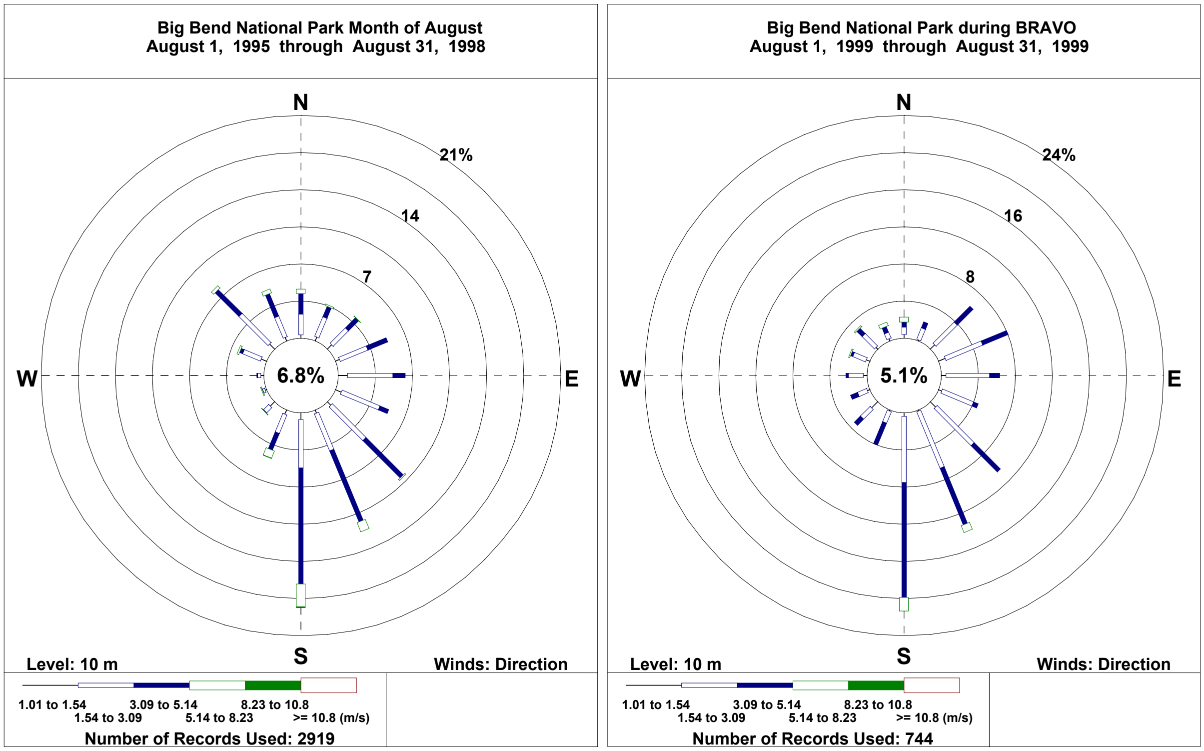

Figure 7-2. *Comparison of wind roses for August 1995-1998 (left) and 1999 (right).*

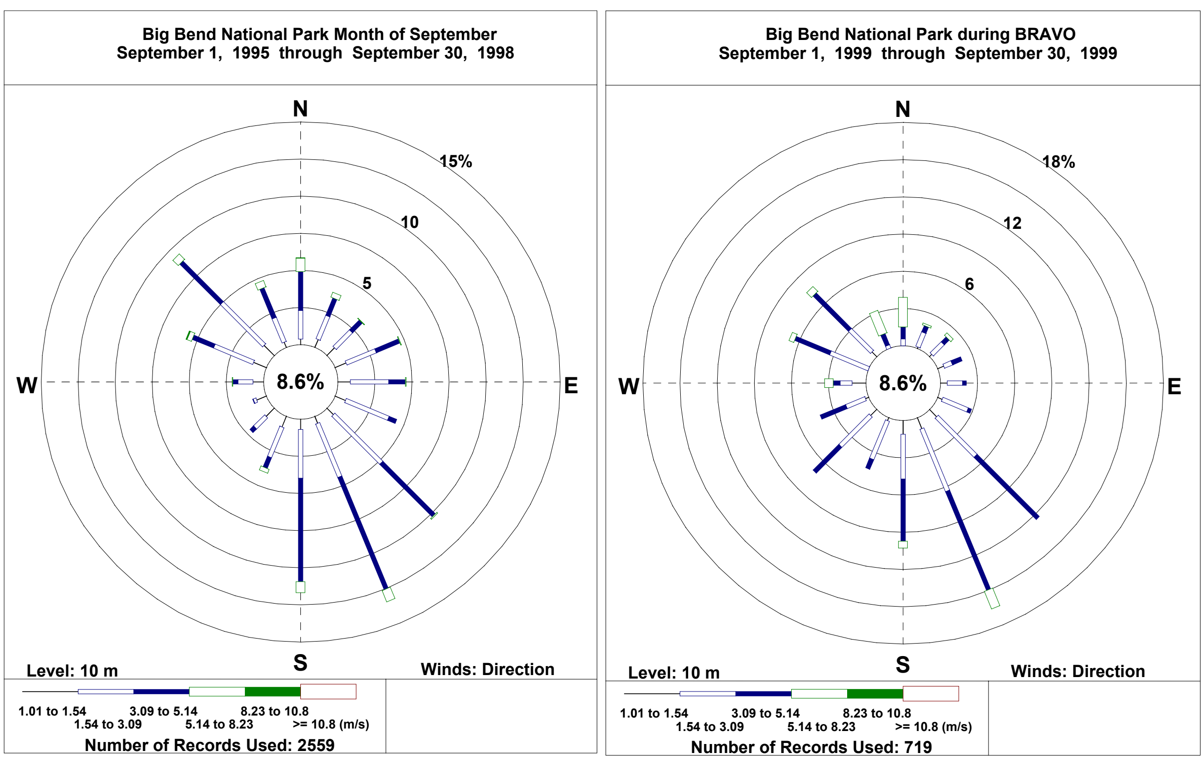

Figure 7-3. *Comparison of wind roses for September 1995-1998 (left) and 1999 (right).*

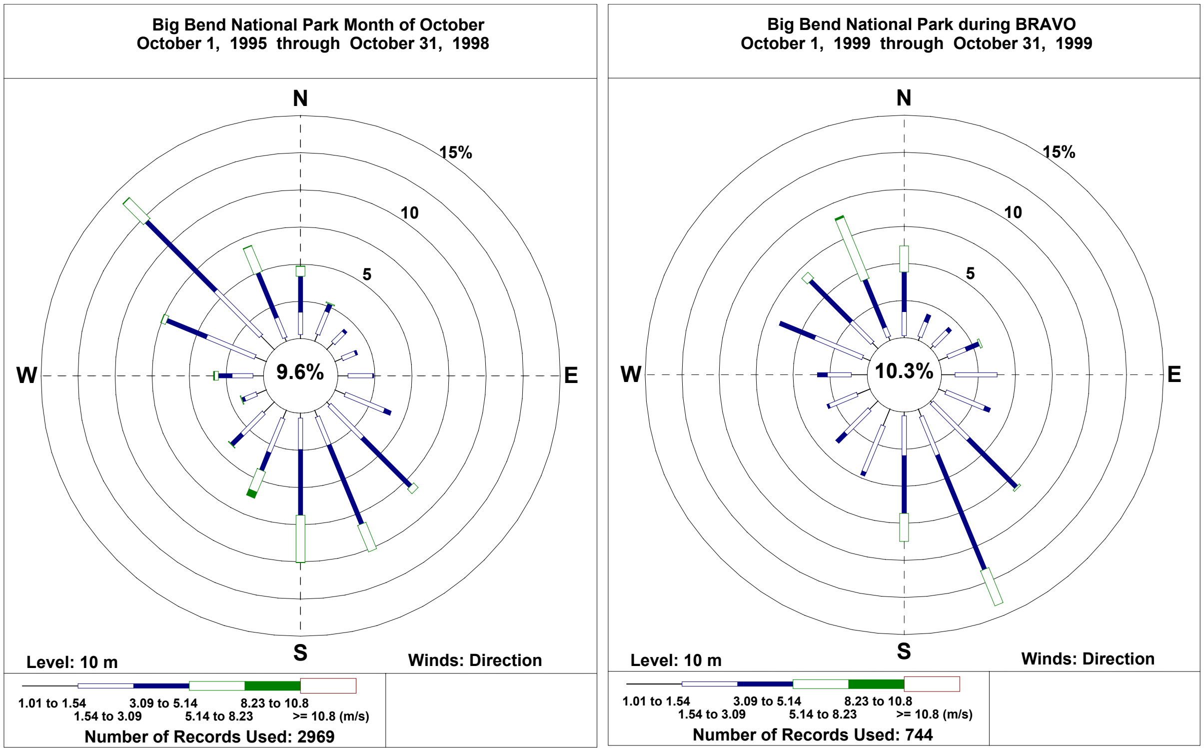

Figure 7-4. *Comparison of wind roses for October 1995-1998 (left) and 1999 (right).*

From these analyses, we conclude that there were some differences between historical (1994-98) and BRAVO-period temperature and RH monthly averages. However, historically RH has had a high degree of variability. During those months when temperature differences were statistically significant, the mean differences were small (within 2 ^{o}C). Also, wind roses showed patterns during BRAVO months that were generally similar to those during 1995 through 1998. Thus, overall, meteorological conditions during the study seemed fairly typical of those in the previous five years and are likely to have minimal impacts on the applicability of the study findings to the same months in other years. The degree to which the differences identified in this analysis might play a role in interpreting BRAVO Study findings would need to be evaluated for each particular application, however.

7.2 Transport Climatology

As another measure of representativeness, the frequency of transport from different areas to Big Bend National Park during July through October for each of the years 1998 through 2002 was compared. This metric is an important indicator of whether the same source areas could potentially impact the park at corresponding times each year.

The HYSPLIT back trajectory model was used with default conditions (e.g., model vertical velocity) and using the FNL meteorological archive (ftp://www.arl.noaa.gov/pub/archives/fnl). The FNL meteorological fields were used because they provide a more complete data set for the period than the EDAS fields (which are missing for the last month of the BRAVO period and for some time thereafter because of a fire in a NOAA computer), although the grid spacing of about 190 km is coarse compared to the EDAS spacing of 80 km. The FNL archive is described in detail at http://www.arl.noaa.gov/ready-bin/fnl.pl.

Eight-day (192-hour) back trajectories were started at one-hour intervals for the four-month period in all five years. The eight-day period was selected to allow for possible transport from distant areas, such as the eastern United States, during relatively light wind conditions to be identified, although it should be recognized that uncertainties increase as the length of the back trajectory is increased. Three starting heights were used: 10 m, 500 m, and 1,500 m above ground level (i.e., the actual forward trajectories are assumed to arrive at Big Bend at these elevations). Typical afternoon mixing heights in south Texas (Del Rio soundings) during summer are about 2,500 m, so these heights represent lower to middle-upper daytime mixed layer locations.

Residence time was calculated by counting the number of back trajectory endpoints (hourly locations) in each one-degree-latitude-by-one-degree-longitude area and dividing by the total number of endpoints. The gridded residence times were then contoured. Maps of residence time were generated for each year (1998 through 2002) for each starting height (10, 500, 1,500 m AGL). The differences between residence times for each year and the five-year average residence time at each height were also computed to illustrate differences of each year from the five-year mean.

To illustrate the results, Figure 7-5 compares the residence times for July-October 1999 to the 1998-2002 July-October five-year average residence time for the 10 and 1,500 meters AGL starting heights. Figure 7-5 shows that the mean transport direction at both elevations is roughly from the southeast along the U.S./Mexico border, that transport distances are longer for the higher starting elevation (higher wind speeds with height), and there is more variability in wind direction at the higher elevation.

Figure 7-6 shows the differences between July-October 1999 and the July-October five-year averages at each of the three heights. The general flow patterns for 1999 and the five-year average are similar, but some differences can be noted. At all three heights during 1999, there was less long-range transport from the eastern U.S. as compared to the five-year average for July-October. At 10 meters starting height, 1999 shows less flow over most of Texas (except the Panhandle and far southern Texas) than the five-year average, and more flow over the border area and far northeastern Mexico. At 1,500 meters back-trajectory starting height, 1999 had more frequent flow over southeastern Texas, northern Mexico, and Louisiana.

To complete the picture, Figure 7-7 shows the differences from the five-year mean for July-October 1998, 2000, 2001, and 2002 residence times. Compared to the five-year average, in 1998, there was more frequent flow from the Ohio River Valley, 2001 had less frequent flow from the eastern U.S., and 2002 had a higher frequency of flow from the southeastern U.S..

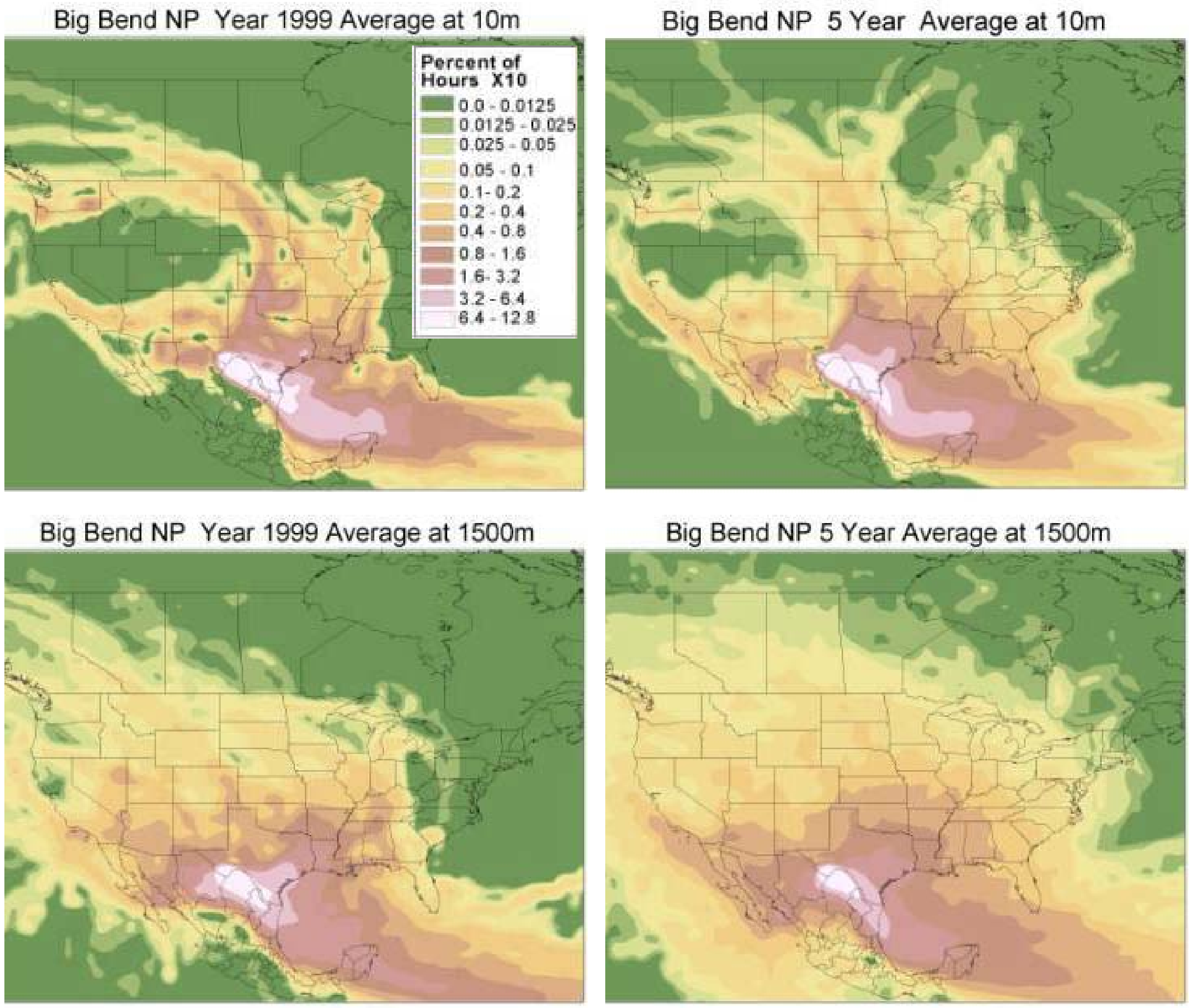

Figure 7-5. *Residence times for July-October 1999 (left) and the five-year July-October average (right), for 10 and 1,500 meter back-trajectory starting heights at Big Bend.*

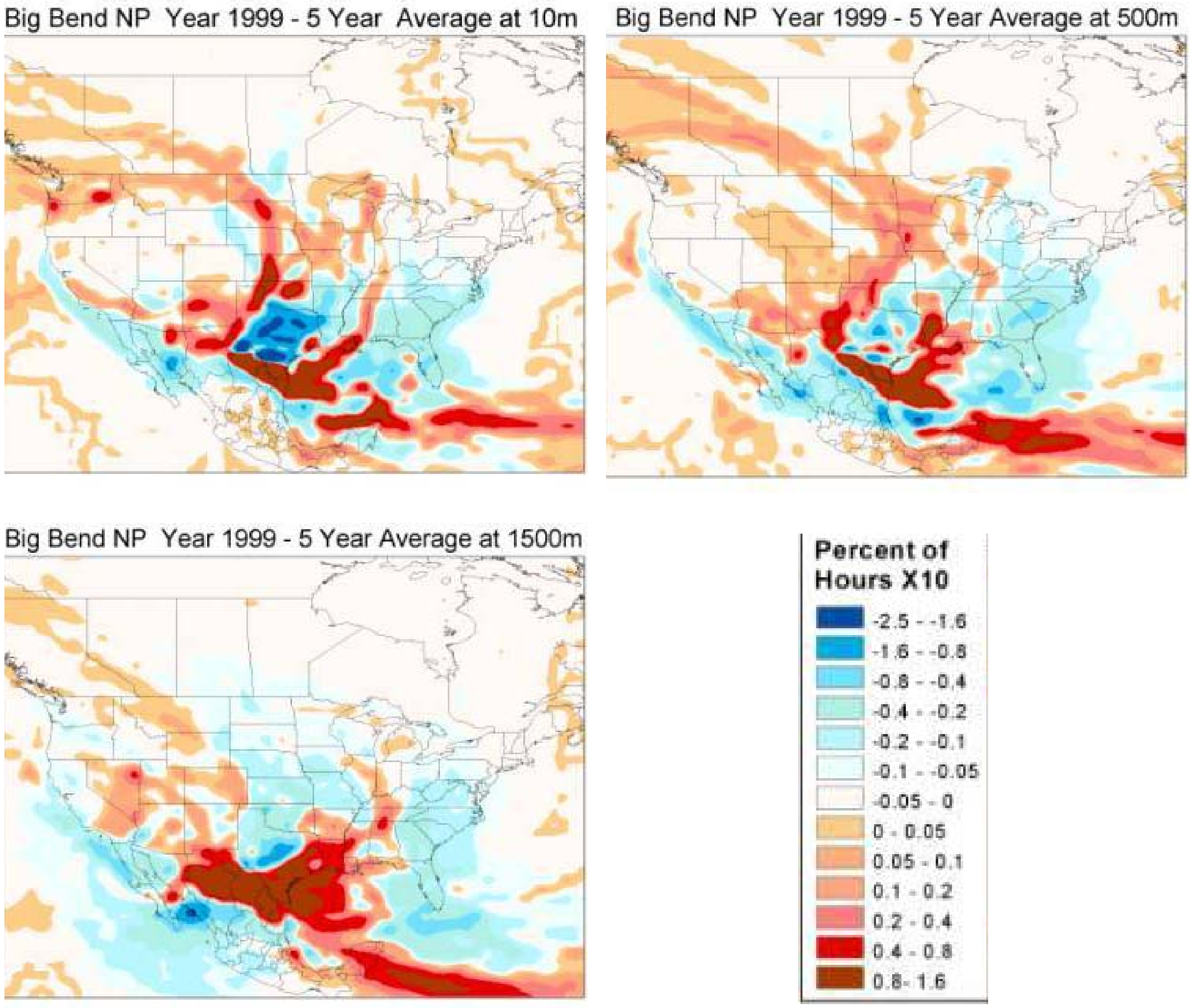

Figure 7-6. *Differences in residence times between July-October 1999 and the five-year (1998-2002) July-October average for all three back trajectory starting elevations. Blue colors denote greater back trajectory residence times in 1998-2002, and red colors denote greater residence times in 1999.*

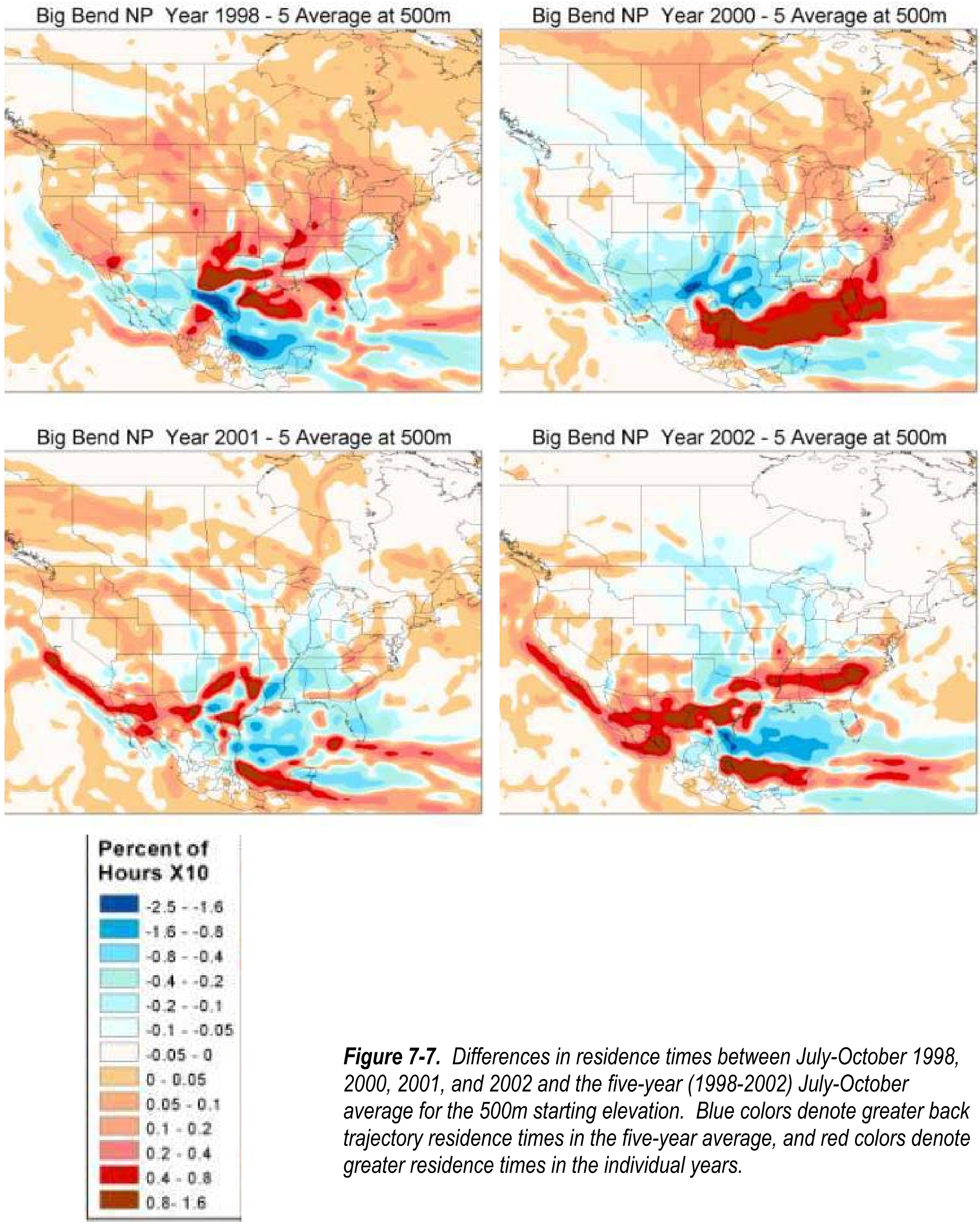

Figure 7-7. *Differences in residence times between July-October 1998, 2000, 2001, and 2002 and the five-year (1998-2002) July-October average for the 500m starting elevation. Blue colors denote greater back trajectory residence times in the five-year average, and red colors denote greater residence times in the individual years.*

From this analysis, we conclude that there were variations in year-to-year July-October transport frequency over the five-year period. In 1999, the year of the BRAVO Study, there was less than usual frequency of flow from the eastern U.S. and central Mexico. Flow toward Big Bend along the Texas/Mexico border area and across far northeastern Mexico was more frequent than on average. Flow from eastern Texas was less frequent in 1999 for the 10-meter back trajectories, but more frequent than average for 1,500 meters start heights. All years showed areas of notable departures from the five-year mean. Overall, the July-October 1999 BRAVO study period appears to be within the typical variation in transport frequencies (i.e., it is not atypical).

7.3 Aerosol and Light Extinction

The inter- and intra-annual variation of particulate matter component concentrations and of measured and estimated light extinction were analyzed to understand how conditions during the BRAVO Study compared to those during the rest of the year and during other years.

As an overview, Figure 7-8 displays the variation of estimated total light extinction and its components during each of the five years 1998 to 2002. Note that the particulate components that contribute to Big Bend haze exhibit large interannual variations in their contributions to extinction and in the timing of episodes compared to the five-year average shown in Figure 7-9. For example, the multi-year averaged carbonaceous/sulfate/coarse particulate haze in spring shows a broad peak in Figure 7-9 that is, in fact, a composite of different patterns, some with narrow peaks (e.g., 1998, a year of unusually heavy smoke impacts), others with broader periods with some combination of elevated carbonaceous or sulfate or coarse particulate.

Looking at the July through October period, we see much larger episodicity and peaks of greater estimated light extinction in 1998 than in 1999 and the other years. From year to year, the average estimated light extinction due to sulfates in the July through October period does not bear a consistent relationship to the average sulfate extinction during the rest of the year.

To provide a more quantitative insight into the representativeness of the aerosol and haze during the BRAVO Study, the conditions at the K-Bar ranch site during the BRAVO Study period July through October 1999) were compared with conditions during three other periods: (1) the rest of 1999; (2) the July through October periods in 1995 through 1998, the four years preceding the BRAVO study; and (3) all of the five-year period of 1995 through 1999 (which includes the BRAVO study period). Average conditions, standard deviations, and frequency distributions of several variables during the BRAVO Study period were compared with corresponding values during each of the other three periods.

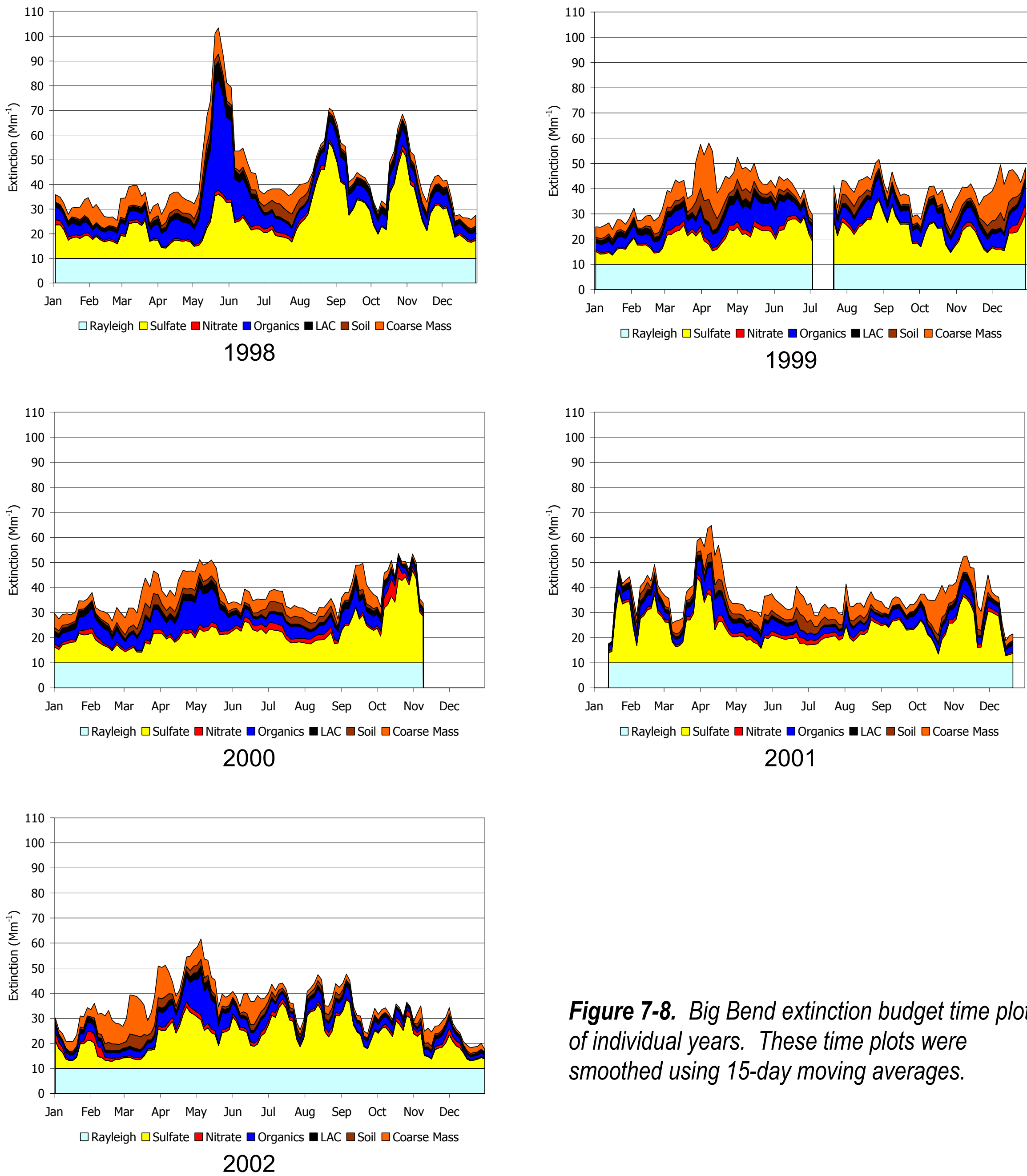

Figure 7-8. *Big Bend extinction budget time plots of individual years. These time plots were smoothed using 15-day moving averages.*

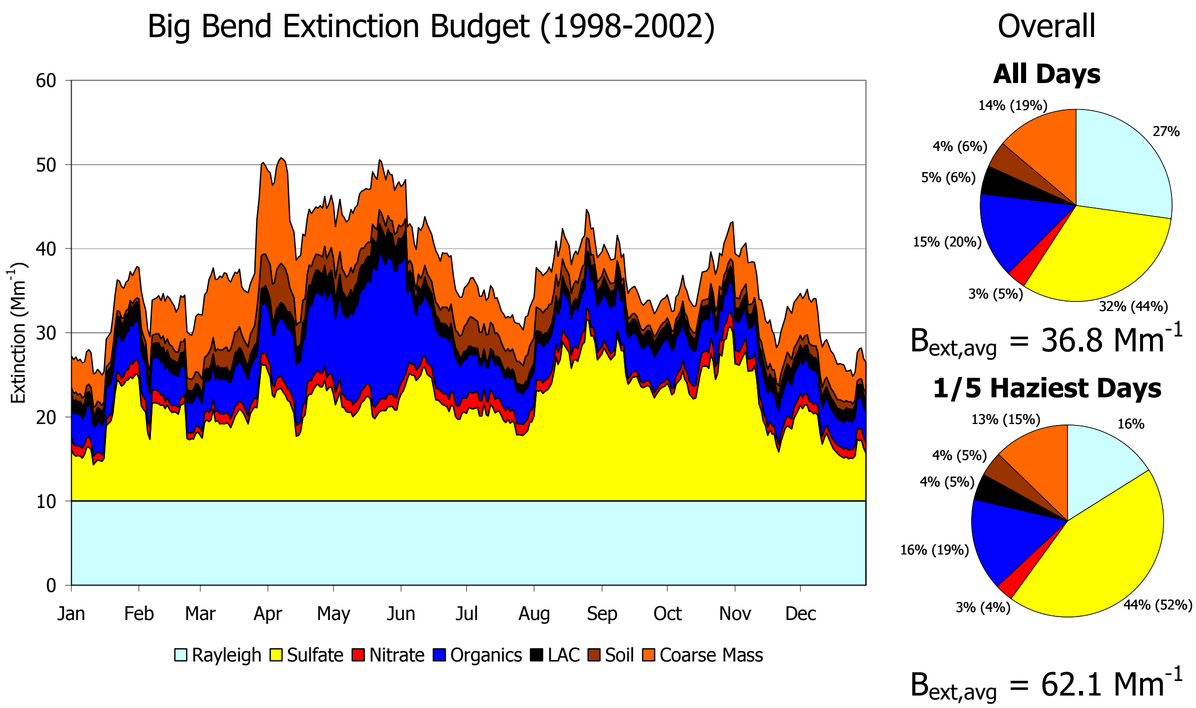

Figure 7-9. *Big Bend National Park five-year composite contributions to haze by components. The time plot was smoothed using a 15-day moving average. The pie graphs show the average percent contributions to light extinction for all days (top) and the annual haziest 1/5 of the days bottom. Percent contributions to particulate haze (the non-Rayleigh light extinction) are shown in parentheses.*

IMPROVE 24-hr particulate matter component measurements made twice weekly (every Wednesday and Saturday) were used as the basis for the evaluation, except that during the BRAVO period samples were taken daily. The BRAVO period sampling and analysis followed the same protocol as the regular IMPROVE measurements, except that the start and ending times of the sampling were at 0800 local time instead of the usual midnight of the IMPROVE protocol. However, the 5-year 1995 through 1999 data set used only the measurements made according to the regular Wednesday-Saturday IMPROVE schedule, even during the BRAVO Study period. The maximum potential numbers of samples for analysis were BRAVO period = 123, Rest of 1999 = 69, July through October 1995-1998 = 139; and 1995-1999 = 520. Sampling and analysis losses meant that actual numbers were lower than these, especially for analyses involving variables that were composites of simultaneous measurements of multiple components.

Similar representativeness analyses were not possible with the measurements of light extinction and scattering by transmissometer and integrating nephelometer at Big Bend. Although a transmissometer operated at Big Bend National Park during the entire five-year period of this comparison, the National Park Service has concluded that its measurements are not representative at all times of the year, has removed this transmissometer's data from the online IMPROVE data base, and has posted a warning concerning the use of transmissometer data in which the Big Bend measurements were used to make its point (Molenar, 2002). As for the integrating nephelometer, it was not installed until 1998, and thus measurements were not available for the full five-year period of this evaluation.

Figure 7-10 shows the average PM-10 concentrations and their compositions during the BRAVO Study period and the three comparison periods. For purposes of this analysis, the usual IMPROVE conventions were followed: i.e., sulfates were assumed to be in the form of ammonium sulfate and nitrates in the form of ammonium nitrate, and a factor of 1.4 was used to convert the mass concentration of measured organic carbon (OC) to that of organic carbonaceous compounds (OCM). As has been pointed out earlier in this report, the nitrate during the BRAVO study was predominantly sodium nitrate. But, since the form of the nitrate during the rest of the year is unknown, the form of ammonium nitrate was assumed for all of the five years. Since nitrate is not a major contributor to light extinction, the results of this representativeness analysis will not be altered greatly if the nitrate at Big Bend is actually sodium nitrate during part of the year or even all of the year.

In Figure 7-10, the bars on the left half indicate mean concentrations and the bars on the right half indicate the standard deviations of the concentrations, which provide a measure of the variability around the mean concentration of each component. Note that, as a rough rule of thumb, the standard deviations are about the same as the corresponding averages.

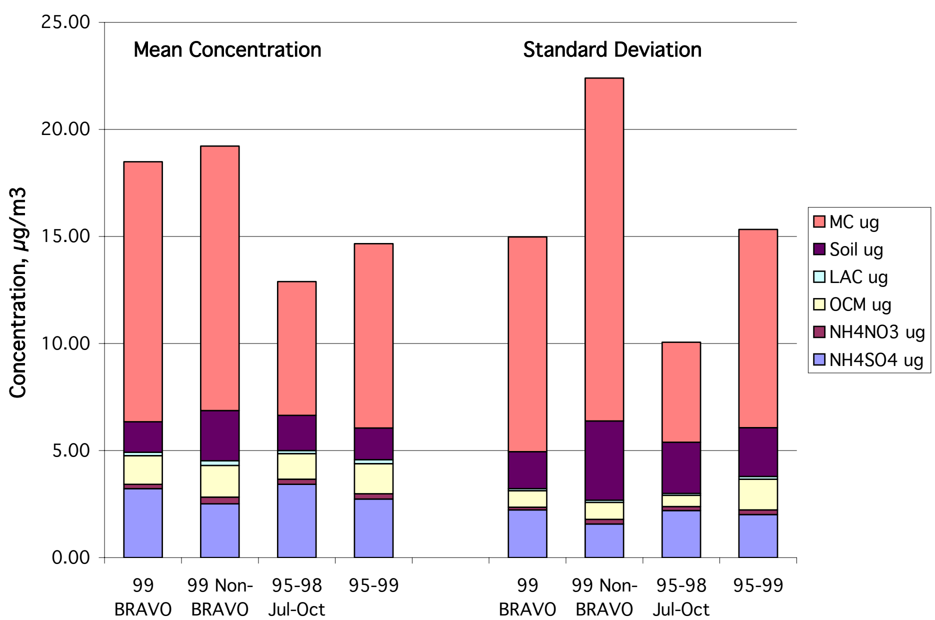

Figure 7-10. *Means and standard deviations of concentrations of components of PM_{10} at Big Bend National Park during four different averaging periods.*

Coarse matter (MC) generally dominated the average mass concentration and its variation. The BRAVO period appears to have been about twice as dusty as the average of the corresponding months in the previous four years, but the rest of 1999 appears to have been about as dusty (and the MC nearly twice as variable) as the BRAVO period.

Looking at the fine ($PM_{2.5}$) portion underneath the MC, there is not very much difference in the averages of the totals of the fine components between the four periods, with all lying between 6 and 7 μg/m^3. The standard deviations show somewhat greater variability, with the biggest variation in the non-BRAVO period of 1999, during which the variation in fine soil dominated (in tandem with the large standard deviation in CM during this same period. The smaller fine soil contribution and variation during the BRAVO Study period than during the rest of the year suggests less windy conditions or greater precipitation during the BRAVO period.

The other main component of $PM_{2.5}$, organic carbonaceous matter (OCM), had about the same average concentration (between 1.3 and 1.5 μg/m^3) during all four of the averaging periods. Peculiarly, it showed a greater standard deviation during the 1995-1999 averaging period than during the shorter subset periods, which must mean that there was large variation during the non-BRAVO months in 1995-1998. The large organics spike in May-June 1998, shown in Figure 7-8, is a likely candidate.

The estimated light extinction associated with this particulate matter (i.e., not including scattering by gases) is shown in the same format in Figure 7-11. This light extinction (sometimes called "chemical light extinction" because it is calculated from chemical component concentrations), was calculated using the IMPROVE formula for estimating light extinction from particulate matter component concentrations, which was presented in Section 7.4 (but without Rayleigh scattering), using the same chemical composition assumptions that were used for Figure 7-10. The growth of particles with humidity was determined by calculating the humidity growth factor *f*(RH) hourly and then using a 24-hr average with the measured sulfate and nitrate concentrations.

Although the mean concentrations of PM_{10} shown in Figure 7-10 varied quite a bit over the four averaging periods, the mean light extinctions associated with the particulate matter during those periods were quite similar and ranged from 27.4 to 29.7 Mm^{-1}, a difference of less than 10%. The average composition that led to each of these values is quite different for each period, however, and the standard deviations are also different. Specifically, sulfates played a larger role during the BRAVO period in 1999 (and during the BRAVO months in 1995-1998) than during the other months of the same year, while the role of organics appears to be smaller. Coarse matter during the BRAVO period was a bigger contributor than during the same months in other years, but 1999 seems to have been a dustier year all around. Interestingly, except for the coarse matter contribution, the apportionment of light extinction to particulate species during the BRAVO Study is almost identical to the 5-year average from 1995 to 1999 (but the standard deviations over the 5-year period were greater than those during BRAVO for all non-soil components).

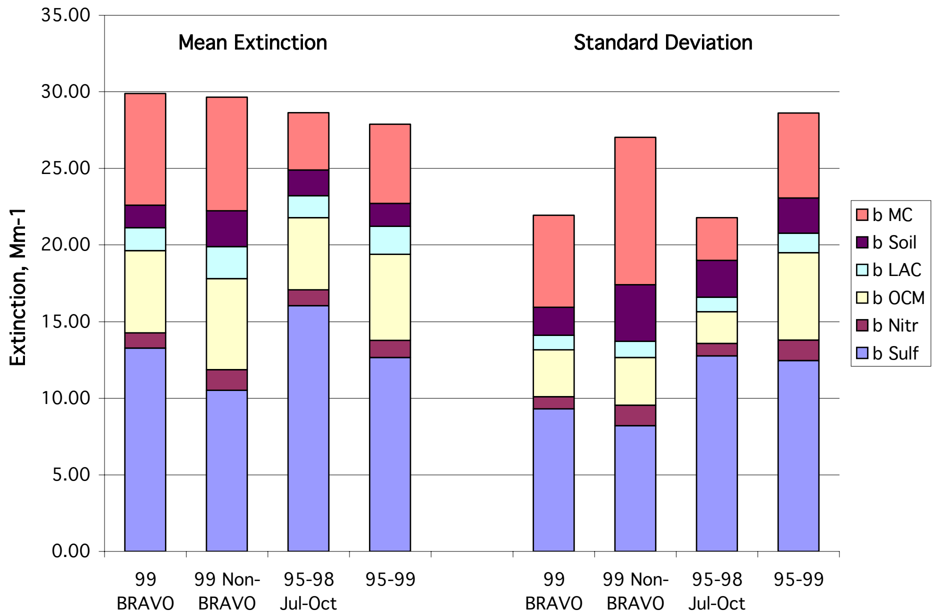

Figure 7-11. *Means and standard deviations of particle-caused light extinction estimated from concentrations of components of PM_{10} at Big Bend National Park during four different averaging periods. The notation b Xyz denotes the estimated extinction attributed to particulate matter component Xyz.*

Further insight is provided by looking at the relative contributions to average particle extinction by the various components, as displayed in the pie charts in Figure 7-12. The 1999 BRAVO Study period had relatively less extinction by sulfates and more by coarse particles than the average of the same July-October periods in the preceding four years. Organics, light absorbing carbon (LAC), and fine soil all played larger relative roles in extinction in the non-BRAVO months of 1999 than during the BRAVO Study. The BRAVO relative apportionment of extinction to sulfates was very similar to the 5-year average.

Another way to look at representativeness is to compare frequency distributions, especially via metrics such as the median and values of specific percentiles. Figure 7-13 presents side-by-side box plots for the distributions of the averages of the measured fine mass concentrations for the BRAVO Study period and the other three periods. (The gravimetrically-measured fine mass concentration used here differs slightly from the reconstructed fine mass that was represented by the sum of the bottom five segments in the bar graphs of Figure 7-10.) The yellow shaded box extends from the 25th to the 75th percentile and the line crossing it represents the median (the 50th percentile). The width of the notch at the median represents the 95% confidence interval around the median. (The practical importance of this is that if the median of one period falls within the notch of another period, then the first median is within the confidence interval of the second and thus is potentially comparable with the second.) The crossbars above and below each yellow shaded box indicate the 10th and 90th percentiles. Values below the 10th percentile and above the 90th percentile are plotted explicitly. In order to maintain usable plot scales, some outlier points lie off the top of the chart. Values of such outliers are given in the upper right corner.

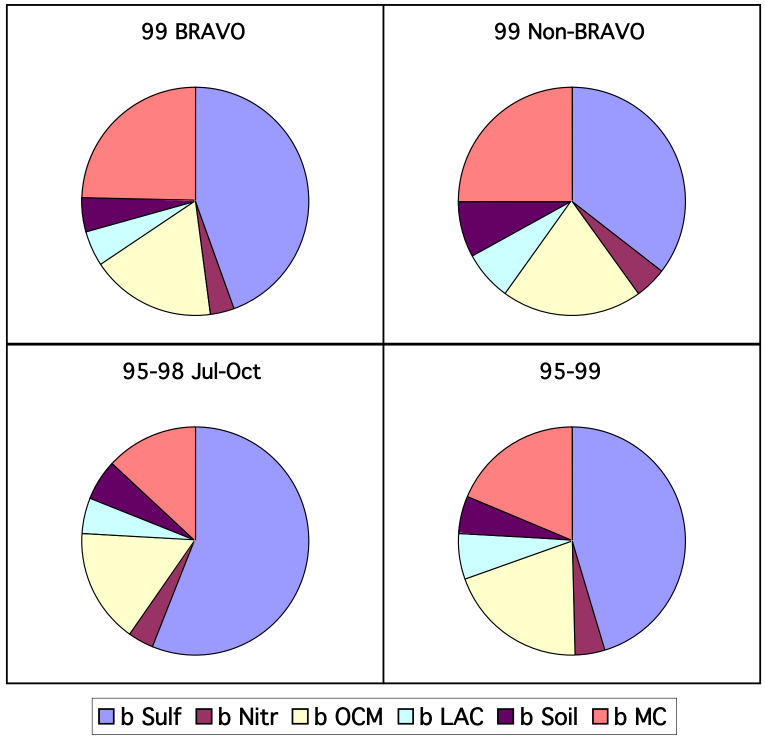

Figure 7-12. *Estimated relative contributions of various particulate matter components to particle-caused light extinction during four different averaging periods.*

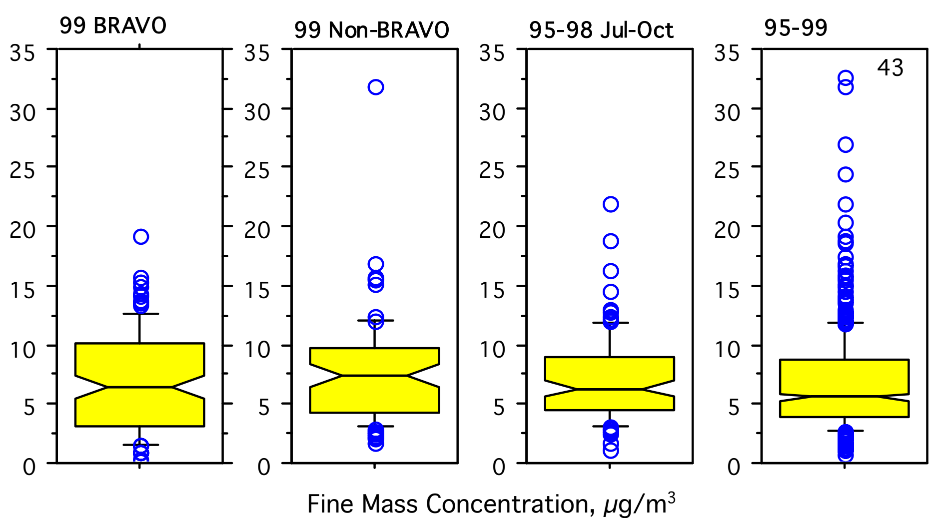

Figure 7-13. *Box plots of measured fine mass concentration frequency distributions during four different averaging periods.*

Figure 7-13 shows that the median fine mass concentration during the BRAVO study is close to and potentially comparable to that of the same months in 1995-1998, but differs significantly from that of the non-BRAVO months of 1999. The BRAVO period had lower 10th and 25th percentile concentrations than any of the other periods, and also had the lowest absolute concentration values. On the other hand, at the upper end, the BRAVO period 75th percentile concentration was similar to that of the non-BRAVO part of 1999 but both were greater than those of the July-October 1995-1998 and of 1995-1999. The 90th percentile concentrations were similar for all four periods. Thus, the BRAVO period had lower fine mass concentrations than the rest of 1999, but doesn't appear to differ greatly from the same periods in other years.

The comparable analysis for coarse mass, in Figure 7-14, shows potential comparability of the medians for the BRAVO period and the non-BRAVO period of 1999, but both are substantially greater (by nearly a factor of two) than the value for the July-October months of 1995-1998 and also greater than the value for the 1995-1999 years. The same relative relationships hold for the 25th percentile values, but the 75th percentile coarse mass concentration during the BRAVO period was greater than that during all other periods by factor of 1.6 to 2.1, which indicates more high concentration values during BRAVO than during the other periods. Interestingly, though, the 90th percentile values for the BRAVO and the non-BRAVO period of 1999 were quite similar and were both much greater than the corresponding values for the other two periods. Even the values above the 90th percentile during the BRAVO Study extended up to twice the concentration of those during the July-October periods in four preceding years. Thus, as noted earlier in this discussion, all of 1999, and especially the BRAVO Study period, appeared to be a dustier than the previous years.

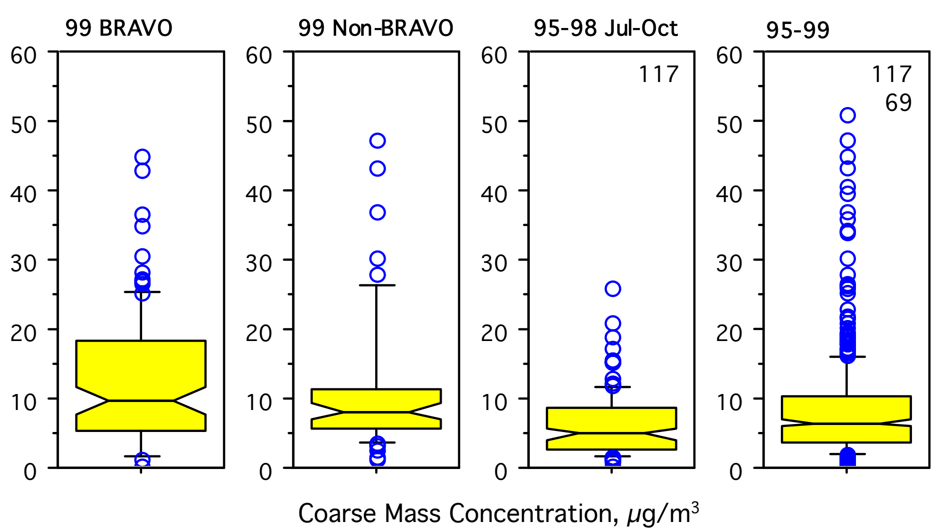

Figure 7-14. *Box plots of measured coarse mass concentration frequency distributions during four different averaging periods.*

Sulfates were a principal focus of the BRAVO Study. Box plots for sulfates, assumed to be in the form of ammonium sulfate, are shown in Figure 7-15. The differences between the BRAVO period and other periods are relatively small, with a noticeable difference between the higher sulfate concentrations at all percentile levels during the BRAVO months, whether in 1999 or in 1995-1998, and the lower concentrations the rest of the year. This is consistent with the setting of the BRAVO Study in the months of the year with historically higher sulfate concentrations at Big Bend. The BRAVO period sulfate median is less than the average median for July-October 1995-1998, though.

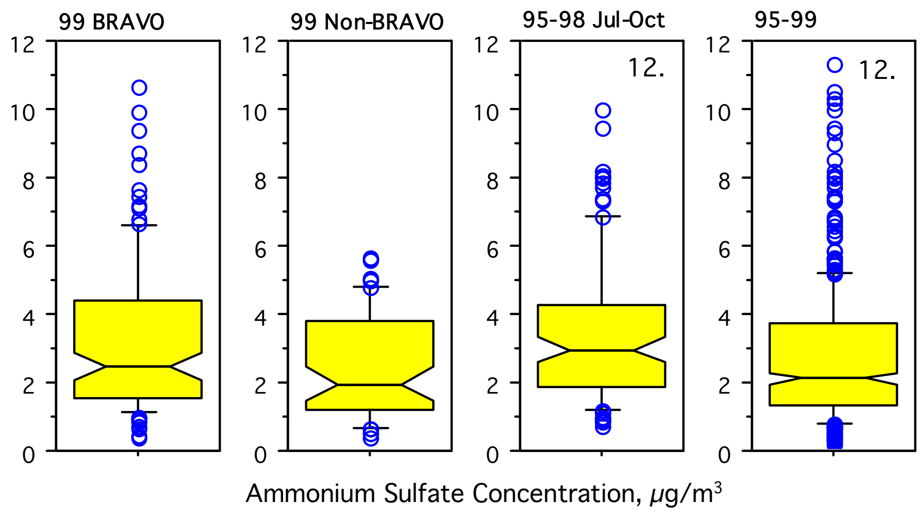

Figure 7-15. *Box plots of ammonium sulfate concentration frequency distributions during four different averaging periods.*

Another important constituent of the particulate matter, organics, did not show a strong variation between the four averaging period, so box plots for organics are not shown here. The medians for all but the non-BRAVO period of 1999 were within a 10% range, with that period showing a median that was higher than the BRAVO period by about 20%. All of the 25th percentile values were within 10% of the BRAVO period value. The 75th percentile non-BRAVO 1999 value was virtually identical to the value for the BRAVO period, but the values for the BRAVO months in 1995-1998 and for the years 1995-1999 were both lower. All this suggests that there is no strong seasonality in the organic matter concentrations but that 1999 in general appeared to have higher concentrations than previous years.

Finally, Figure 7-16 summarizes the implications of all of these component distributions on the distribution of the estimated particle extinction (the same variable whose means were displayed in Figure 7-11). No clear pattern emerges from Figure 7-16 concerning the extinction representativeness of the BRAVO Study period, as the 25th, 50th, and 75th percentile values do not behave consistently between the four study periods. The differences are not very large, though (except at the 75th percentile alone), which suggests that the BRAVO observations are not atypical.

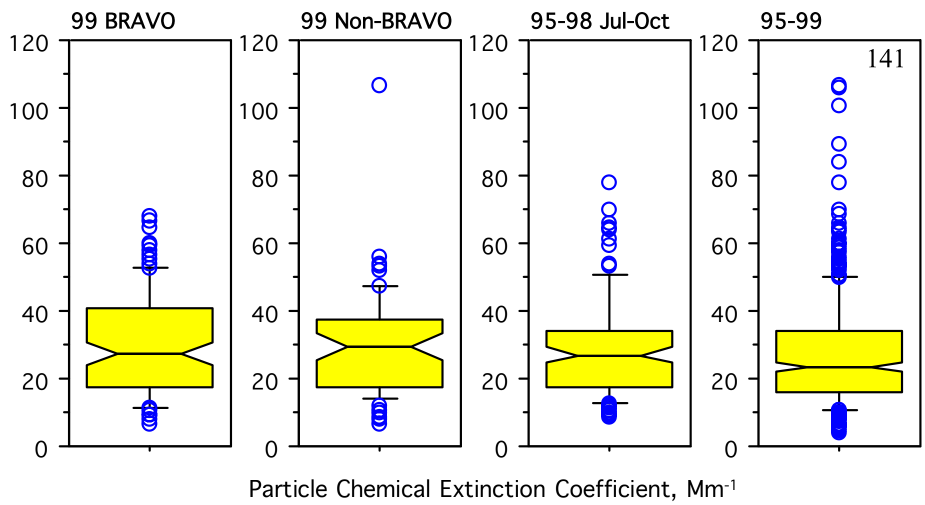

Figure 7-16. *Box plots of particle chemical extinction frequency distributions during four different averaging periods.*

Thus, to summarize, this evaluation of the components of the particulate matter and of the chemical extinction estimated from the component concentrations produces the following conclusions concerning the chemical composition and component concentrations of the BRAVO Study period particulate matter:

- The BRAVO PM differed from that during the rest of 1999, principally in that (1) the mean sulfate concentrations were higher and organics concentrations were lower, (2) the variability (standard deviation) of both coarse particle and fine soil concentrations was considerably smaller, although (3) the mean fine and coarse particle mass concentrations and chemical light extinction were relatively comparable.

- The BRAVO PM differed from the PM during the July-October months in the preceding four years, 1995-1998, principally in that (1) coarse matter and fine soil concentrations were substantially greater, (2) sulfate variability was considerably less, although (3) the ammonium sulfate concentrations and the distribution of chemical light extinction between the particulate components was relatively similar.

- The BRAVO PM composition (1) matched the 5-year average fine particle composition, concentrations, and relative contributions to light extinction quite well, although (2) the variability of the BRAVO fine data was smaller. Also, (3) BRAVO coarse concentrations and their variability substantially exceeded the 5-year average values.

7.4 Assessment of BRAVO Study Representativeness

The assessments of meteorology, transport climatology, and aerosol and light extinction in this chapter all arrive at the same conclusions:

1. Conditions during the BRAVO study period in 1999 differed in many respects from those in the July-October period in other years, but the differences generally appeared to be within the normal bounds of inter-annual variability.

2. The average conditions during the July-October 1999 BRAVO Study period cannot be considered to represent average conditions during the other months of 1999.