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ON THE POTENTIAL OF REGIONAL-SCALE EMISSIONS ZONING AS AN AIR QUALITY MANAGEMENT TOOL FOR THE GRAND CANYON

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Abstract—Air arriving at the Grand Canyon of the Colorado River during 1988–1989 is attributed to one of four geographic quadrants—NE, SE, SW, NW—on the basis of routinely calculated back-trajectories. Most of the haze observed at the Canyon is attributed to the SW quadrant, which contains the populous and industrialized areas of southern California. Air from either northern quadrant tends to be significantly clearer than air from either southern quadrant. Clear northern air is most common during the winter, and is rarely observed during the summer tourist season, when steady flow from the southwest is the norm. Various possible interpretations of these empirical results are discussed, with varying implications for emissions management policy.

Key word index: Clean air corridor, extinction, Grand Canyon, haze, methylchloroform, sulfur, trajectory, transmissometer, visibility, zoning.

INTRODUCTION

The Grand Canyon of the Colorado River (Fig. 1) is an immense, steep-walled gully a mile (1.6 km) deep. Carved into rock layers exhibiting a remarkable palette of colors and situated in a region of excellent atmospheric visibility, it is widely regarded as one of the most spectacular natural sights on earth. Over 3 million people visit the rim each year, making Grand Canyon the most popular National Park in the western United States of America. Parts of the region surrounding the Canyon are experiencing population growth and development, and views of the Canyon during much of the summer are noticeably degraded by regional haze. Existing development is still somewhat limited geographically, and emissions zoning has come under consideration as a strategy for stabilizing certain aspects of the status quo.

The U.S. Clean Air Act includes provisions for the protection of visibility in Grand Canyon and other National Parks. Amendments to the Act in 1990 (42 USC 7491, §169B) specifically contemplate "the establishment of clean air corridors, in which additional restrictions on increases in emissions may be appropriate to protect visibility" in Grand Canyon National Park. Although the rationale for such zoning is not laid out in the Act, it presumably rests on the propositions that (1) identifiable geographic sectors of low emissions density are the main suppliers of the clearest air to the Canyon, and that (2) significant new emissions in these sectors could degrade the best visibilities currently observed at the Canyon. Neither of these propositions has yet received extensive scientific scrutiny.

The concept of a clean corridor was introduced by Pitchford *et al.* (1981), who related 1978–1979 visibilities at the Grand Canyon to airmass back-trajectories calculated from routine upper-air data by a standard program. Pitchford *et al.* found that 6 of the 10 clearest days, and none of the 10 haziest days, were associated with estimated trajectories from the north and northwest over largely unpopulated areas. The empirical association of air quality with air trajectories has since received a good deal of attention, but most subsequent work has focused on chemical species rather than visibility, and on worst-case rather than best-case conditions.

The present note revisits the relationship of Grand Canyon visibility to airmass history in the spirit of Pitchford *et al.*, utilizing the improved optical and air quality data now available. Relying on the same trajectory algorithm used by Pitchford *et al.*, and just 2 yr of data, it represents only an initial, exploratory, effort. The objective is to frame and illuminate, without necessarily resolving, some of the scientific issues raised by geographically targeted emissions limits.

DATABASE

The analyses presented here utilize ambient data collected at the Grand Canyon during 1988–1989 by the National Park Service (ARS, 1991b) and the multi-institution SCENES program (Mueller *et al.*, 1986). The NPS measurements began in mid-1987 and continue today, while the

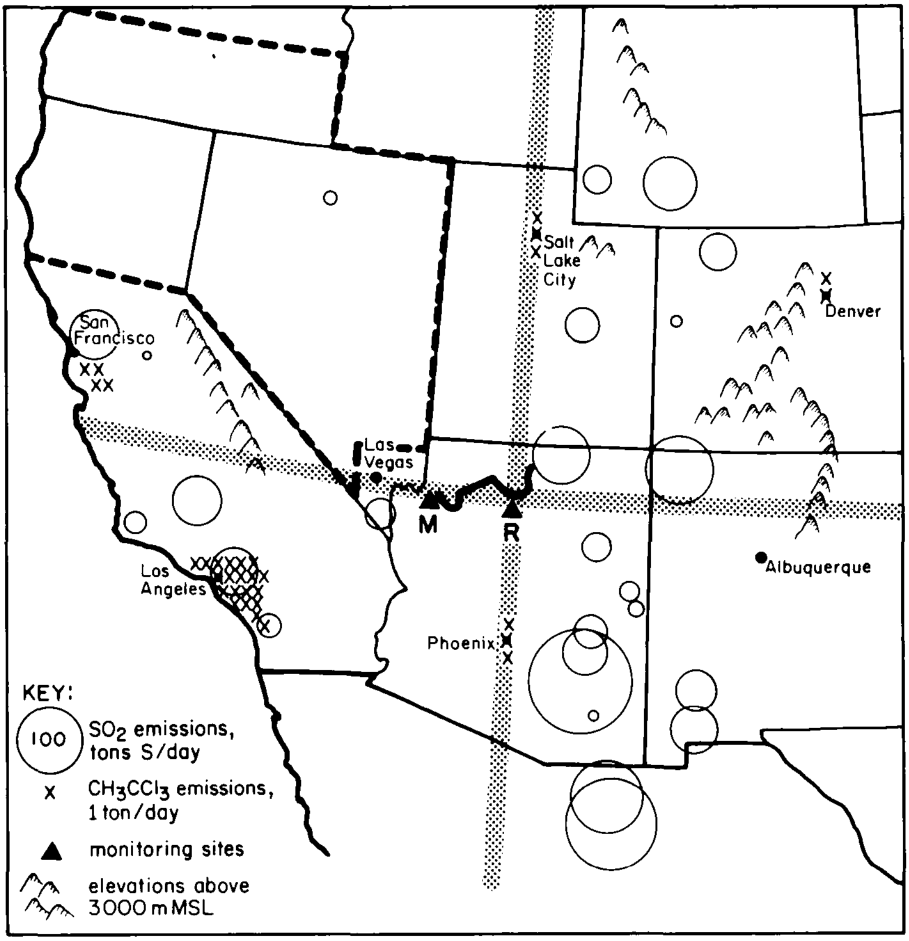

Fig. 1. The Grand Canyon (bold curve) and surroundings. Solid triangles labeled M and R denote monitoring locations at the mouth (Meadview) and rim (Hopi, Grandview, and Moran Points) of the Canyon. Shaded bars indicate quadrants defined by the rim monitoring location. Circle areas are proportional to estimated 1987 SO_2 emissions (adapted from Latimer, 1991). Each × represents 1 ton d^{-1} of estimated 1987 methylchloroform emissions (Sheiman et al., 1990). Average population density within dashed boundary to the northwest of Grand Canyon is less than 1/50 acres ($5/km^2$) (Census, 1991).

SCENES measurement program extended from mid-1984 through to the end of September 1989.

All but one of the variables were measured at or between overlooks along a 20 km stretch of the Canyon's south rim. Such separation between measurements is of little significance at the transport scales under consideration, and these overlooks will be referred to collectively as the south rim monitoring site (labeled *R* in Fig. 1). The remaining variable, methylchloroform, was measured at Meadview, overlooking the lower Colorado River about 180 km west of the south rim measurements. Meadview (labelled *M* in Fig. 1) is about 20 km downstream from the Canyon's mouth.

Visibility is governed largely by the extinction coefficient (NRC, 1993). The National Park Service (NPS) monitors total light extinction on the Canyon's south rim with a transmissometer spanning a major side canyon between Grandview and Moran Points. The optical path is 5.8 km long and nearly horizontal, at the local rim elevation of 2200 m (msl). The measurements are hourly, and are accompanied by hourly measurements of temperature and humidity at Grandview Point. Figure 2 shows the diurnal cycles of median extinction and relative humidity.

The extinction data are screened by NPS for potential meteorological interferences, such as clouds in the beam path. All extinction observations flagged as meteorologically suspect by the NPS are censored here. Since an extinction coefficient above 300 Mm^{-1} or a relative humidity above 90% is itself considered sufficient grounds for suspicion of the extinction measurement, this selection process introduces certain sampling biases. Over the 2 yr considered in this note, censored data represent 14% of the otherwise valid extinction observations. Data for variables other than extinction are presented in toto, without censorship.

Most studies of haze transport since Pitchford et al. (1981) have focused on fine-particle sulfur rather than extinction (Ashbaugh et al., 1984, 1985; Bresch et al., 1987; Iyer et al., 1987; Malm et al., 1990; Henry et al., 1991). SCENES monitored particle characteristics on the Canyon's south rim at Hopi Point. Sampling schedules varied during the program; from June 1988 through September 1989, daily fine-particle samples were collected on Teflon filters from 1100 to 1900 local standard time (LST). Every third sample was analysed for sulfur and other chemical species by X-ray fluorescence.

Previous work has identified methylchloroform (CH_3CCl_3, 1-1-1-trichloroethane) as a regional tracer for air from the Los Angeles basin (Miller et al., 1990; White et al., 1990; Fig. 1). This chemical tracer thus provides an independent test of transport classifications based on back-trajectories. Methylchloroform concentrations were not measured on

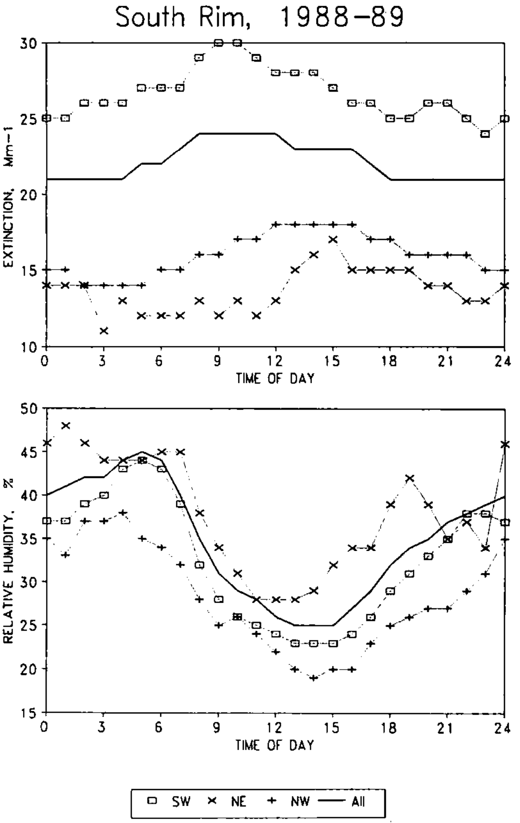

Fig. 2. Diurnal cycles of median extinction and relative humidity at Grandview Point (site R in Fig. 1). Solid curves show hourly medians for all days; dotted curves show hourly medians for days on which trajectories arriving at 1100 and 1700 LST both spent the entire previous 48 h in the indicated quadrants.

the Canyon's rim, but were monitored hourly by electron-capture gas chromatography near the Canyon's mouth, at the Meadview SCENES observatory.

In the analyses that follow, each day's hourly data for extinction, methylchloroform, temperature, and humidity are reduced to representative midday values. For compatibility with the filter data, and with the resolution of the trajectory calculations, the values presented are the 8-h averages over the period 1100–1900 LST. A minimum of six valid hourly observations are demanded for a valid 8-h average.

Back-trajectories of air arriving at the Canyon's south rim and mouth during 1988–1989 have been estimated with the NOAA Atmospheric Transport and Dispersion (ATAD) program (Heffter, 1980). This program runs on routine upper-air data from National Weather Service radiosondes, deriving centerline trajectories from mean mixed-layer winds. Calculations have been carried out for daily arrival times of 1100 and 1700 LST (1800 and 0000 GMT) at each site, with coordinates recorded every 3 h upwind. Hopi Point was chosen as the terminus for the south rim trajectories.

CLASSIFICATION OF BACK-TRAJECTORIES

Many of the issues raised by emissions zoning can be illuminated at even the coarsest spatial resolutions. Working at a low resolution allows our analysis to focus on concepts relevant to policy, rather than on technical concerns such as the uncertainties in trajectory estimates. Low resolution also places minimal statistical demands on the available data, as many observations fall within each large grid cell. Accordingly, we shall distinguish just four source regions for Grand Canyon air.

Back-trajectories will be categorized in terms of their sojourns in quadrants defined by the latitude and longitude of the ambient measurements. These quadrants, shown for the south rim in Fig. 1, have distinct emissions characteristics.

- The southwest includes southern California, with more than 18 million inhabitants (Census, 1991), a wide range of light and heavy industry, and the most severe photochemical smog in the U.S.A. Already densely populated, this sector continues to develop: metropolitan Los Angeles alone grew by 3.0 million between 1980 and 1990. Additional emissions come from the rapidly industrializing Mexican side of the border.
- Broad areas of the northwest are thinly settled and relatively undeveloped, and discussions of "clean air corridors" often focus on this approach to the Grand Canyon. As an example, only 2.3 million people live in the corridor comprising all of Nevada north of Las Vegas, the northern third of California, and the southern half of Oregon (dashed outline in Fig. 1), for an average population density of less than 1/50 acres (5/km^2) (Census, 1991). The SO_2 emissions density of this corridor is also very low.
- The northeast contains extensive coal deposits, which fuel several major electricity generating stations. The actual and potential visibility impacts of SO_2 emissions from these plants have generated continuing controversy (Jepperson *et al.*, 1981; NRC, 1990).
- The southeast includes several large copper smelters in southeast Arizona and northern Mexico. These installations remain significant SO_2 sources even with recently installed emissions controls (Sisler and Malm, 1990).

Observations will be categorized in terms of the back-trajectories of the sampled air. Two trajectories (arriving at 1100 and 1700 LST) were calculated for each daytime observation (averaged over 1100–1900 LST) at each measurement site. An observation is assigned to a particular quadrant if both estimated back-trajectories spent the entire final 48 h within that quadrant. Table 1 summarizes the distribution of classified 1988–1989 observing periods according to this scheme.

Table 1 shows that the back-calculation of both daytime trajectories to at least 48 h upwind was successful on about 70% of all days. Calculations for the remaining days were terminated early due to missing upper air data and limitations of the algorithm. About 40% of the successfully calculated trajectory pairs met the criterion that both trajectories spent the final 48 h within a single quadrant. Observing periods were classifiable most often in the 2nd quarter (50%) and least often in the 4th quarter (33%). As the shaded bands in Fig. 1 are intended to suggest, observations affected by emissions from Salt Lake City, Phoenix, and other sources on quadrant boundaries are *a priori* less than others to be classifiable.

The overall classification rates in Table 1 are much lower than those achievable with cluster analysis techniques, which can yield exhaustive taxonomic systems that categorize all or nearly all trajectories (Dorling *et al.*, 1992; Iyer *et al.*, 1992). However, the empirical categories produced by cluster analysis are not necessarily relevant to the issues raised by zoning. The present study focuses on just those observing periods in which air arrived wholly through pre-specified geographic sectors, because such pure representatives of the geographic sectors provide the most direct insights into the potential effects of geographically targeted emissions limits. The fact that our classification system accepts only a minority of all observing periods is a reflection of our objectives, not a shortcoming of the scheme.

Table 1. Distribution of 1988–1989 observing periods on the southern rim of Grand Canyon. Entries give the number of 1988–1989 days (total 731) in which trajectories arriving at 1100 and 1700 LST spent the entire previous 48 h in a single quadrant (classified), in more than one quadrant (mixed), or were not successfully calculated (NA)

	Classified					
	SW	SE	NE	NW	Mixed	NA
Quarter						
1	18	1	11	15	81	55
2	51	1	1	11	63	55
3	43	5	0	1	76	59
4	20	2	11	12	91	48
Annual	132	9	23	39	311	217

Figures 3 and 4 show 1988–1989 methylchloroform and fine-particle sulfur observations classified as described above. Unclassifiable observations are not plotted. The sulfur series begins in May 1988, when the filter sampling period went from 0000–2400 LST to 1100–1900 LST, and both series end in September 1989 with the completion of the SCENES measurement program.

Methylchloroform was monitored at Meadview, at the western mouth of the Canyon, and the classification in Fig. 3 refers to quadrants centered on that site rather than the rim-centered quadrants shown in Fig. 1. The shaded band in Fig. 3 indicates typical background concentrations in the Northern Hemisphere. It is based on observations by Khalil and Rasmussen (1989) at remote sites, and rises slightly with time due to continuing emissions.

Sulfur was monitored at Hopi Point, on the south rim of the Canyon, and the classification in Fig. 4 refers to the quadrants shown in Fig. 1. The shaded band in Fig. 4 shows the 25th–75th percentile range of fine-particle sulfur at Hopi Point. It is calculated from all 1984–1989 daytime and 24-h data taken within 2 weeks of the indicated month and day, and thus repeats with an annual cycle. Sulfur data are relatively sparse, because filter samples were chemically ana-

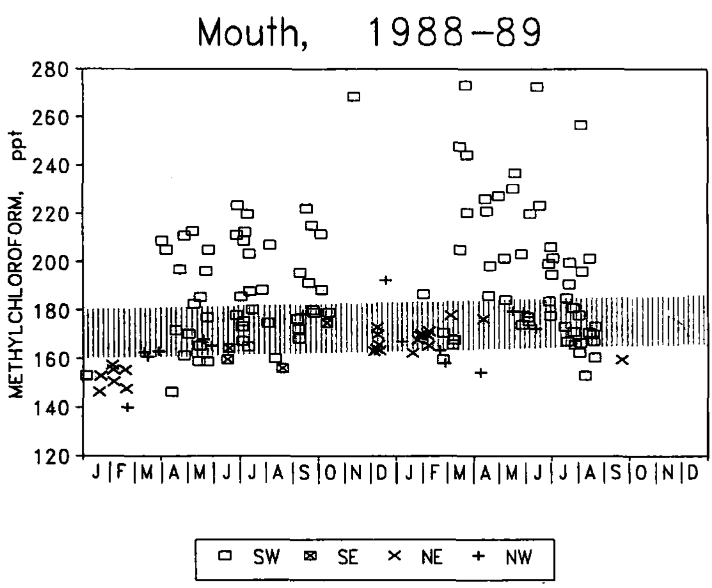

Fig. 3. Daytime methylchloroform (CH_3CCl_3) concentration at Meadview (site M in Fig. 1) as a function of airmass history. Symbols show 8-h averages (1100–1900 LST) for days on which trajectories arriving at 1100 and 1700 LST both spent the entire previous 48 h in the indicated quadrants. Shaded band shows range of typical background concentrations in the Northern Hemisphere (Khalil and Rasmussen, 1989).

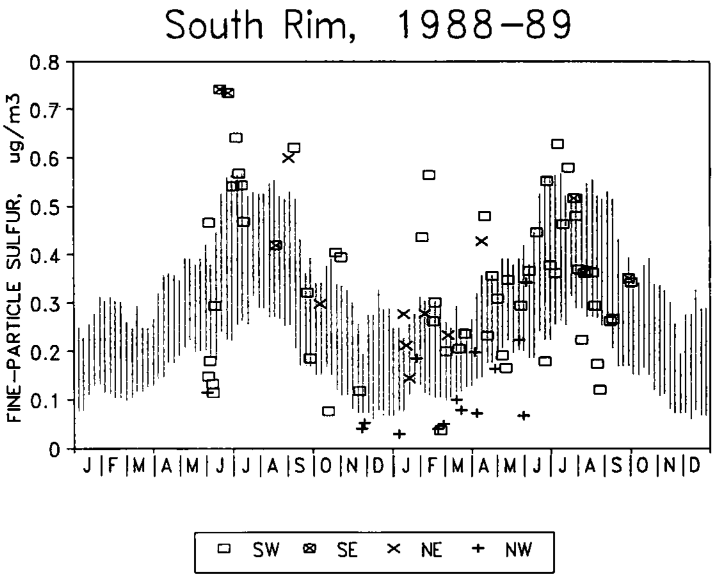

Fig. 4. Daytime fine-particle sulfur concentration at Hopi Point (site R in Fig. 1) as a function of airmass history. Symbols show 8-h averages (1100–1900 LST) for days on which the two trajectories arriving at 1100 and 1700 LST spent at least three-quarters of the previous 48 h in the indicated quadrants. Shaded band shows the 25th–75th percentile range for all 1984–1989 daytime and 24-h data taken within 2 weeks of the indicated month and day.

lysed only every third day. To conserve these data, the classification criterion is relaxed slightly in this one figure to require that arriving trajectories spend at least 36 (rather than all) of the final 48 h in the indicated quadrant.

Figures 3 and 4 lend credibility to our trajectory computations and classification scheme. Of the many classified methylchloroform observations exceeding the background range in Fig. 3, all but one are attributed to air from the SW. Regional emissions of methylchloroform have not been thoroughly inventoried, but known emissions (Sheiman *et al.*, 1990) are in fact concentrated in the SW quadrant (Fig. 1) and this distribution is consistent with results from a limited program of exploratory ambient measurements (Rogers *et al.*, 1989). Conversely, of the 15 sulfur observations attributed to the NW in Fig. 4, 11 are below seasonal norms and none are above, which is consistent with that quadrant's relative lack of SO_2 sources (Fig. 1). The distribution of concentrations in the eight observations attributed to the NE is quite different, although these are similarly concentrated in the winter months: three of the NE observations are above seasonal norms, and none are below.

ASSOCIATION OF VISIBILITY WITH BACK-TRAJECTORIES

The target of the Clean Air Act's zoning provisions is haze, rather than sulfur or other chemical species. Figure 5 shows 1988–1989 observations of total extinction on the Canyon's south rim, classified by airmass history as described in the preceding section. The symbols show 1100–1900 LST averages from the transmissometer spanning Grandview and Moran Points, for days when arriving air had spent the entire final 48 h within one of the quadrants shown in Fig. 1. The shaded band shows the 25th–75th percentile range of 1100–1900 LST averages, calculated from all September 1987–August 1992 data taken within 2 weeks of the indicated month and day.

Figure 5 clearly shows that visibility on the Canyon rim is associated with the direction of the large scale airflow. Hazy air tends to come from the SW and SE, and clear air tends to come from the NW and NE. This association is what generates interest in emissions zoning as a visibility management tool. The association is an empirical one, whose causal mechanisms remain to be elucidated.

The superior clarity of air from NW and NE is not, as might be supposed, some simple effect of ambient relative humidity. Figure 6 shows that most unseasonably humid observations were in air from the SW and SE, and scattering by condensed atmospheric water must have inflated the extinction measured in these observations. However, southerly winds tended to bring haze even during periods of consistently low humidity, such as the 2nd quarter of 1989.

The association of visibility with airmass history is expressed as sensible differences between individual days, not just statistical differences between annual averages. During the above-noted 2nd quarter of 1989, for example, when airmasses arrived from both the NW and SW, the median non-Rayleigh extinction in

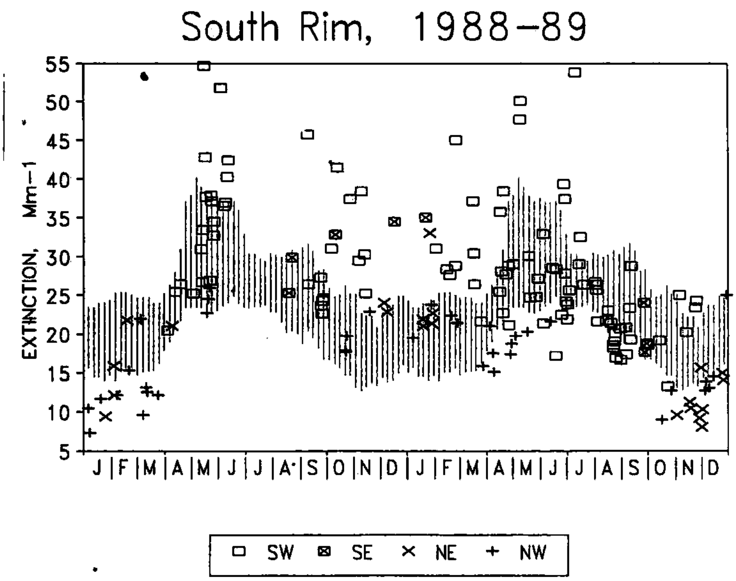

Fig. 5. Daytime extinction between Grandview and Moran Points (site R in Fig. 1) as a function of airmass history. Rayleigh background is about 10 Mm^{-1}. Symbols show 8-h averages (1100–1900 LST) for days on which trajectories arriving at 1100 and 1700 LST both spent the entire previous 48 h in the indicated quadrants. Shaded band shows the 25th–75th percentile range for all 1987–1992 data taken within 2 weeks of the indicated month and day. The instrument was out of service from 16 June to 20 July, 1988.

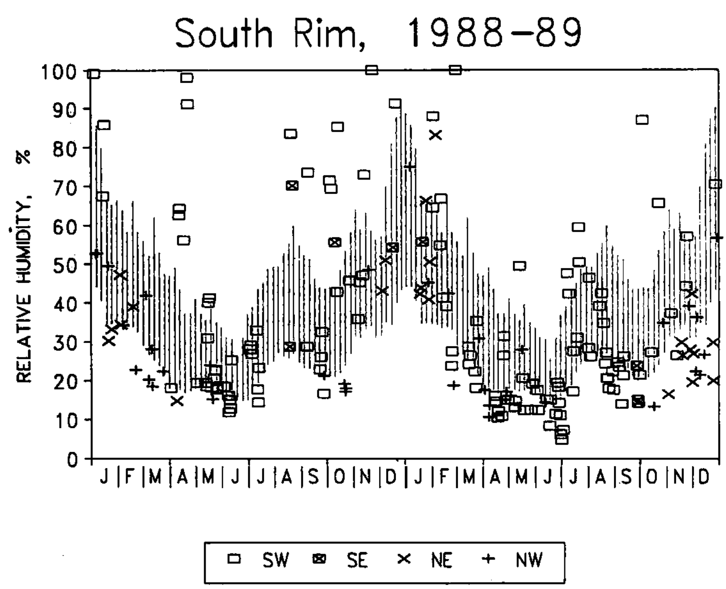

Fig. 6. Daytime relative humidity at Grandview Point (site R in Fig. 1) as a function of airmass history. Format is that of Fig. 5.

the southern air was about twice that in the northern air. As Figs 3 and 4 already suggested, different quadrants' emissions seem to arrive on different days.

Conclusions drawn from Fig. 5 must be tempered by the recognition that its compressed time axis tends to exaggerate the abruptness of changes in visibility. In actuality, the arrival today of "clean corridor" air from the NW typically brings little improvement over yesterday's visibility. This point is illustrated in Fig. 7, which plots extinction measured in air from the NW as a function of the extinction measured the day before. Observations in which air from the NW brought improved visibility lie to the right of the indicated 1–1 line, and the symbols indicate the trajectory class of the observation preceding the NW observation. When the visibility was initially (day $n-1$) average or better,

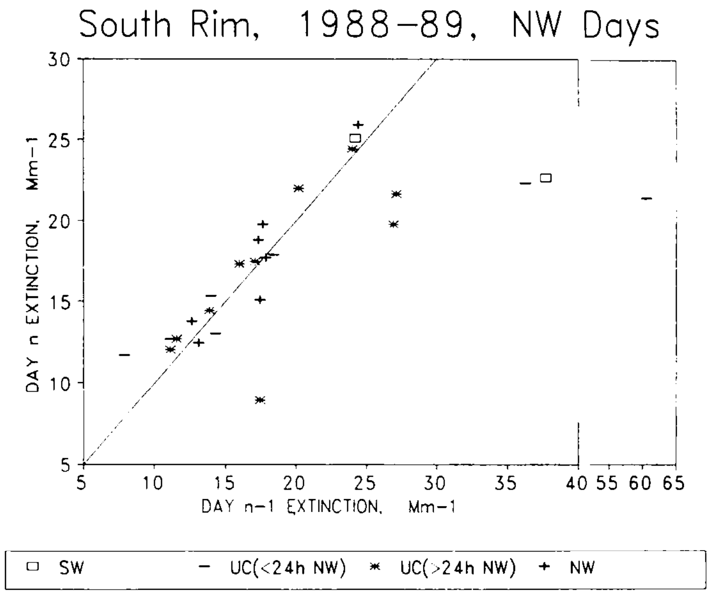

Fig. 7. Daytime extinction in air from the NW as a function of daytime extinction on the preceding day. Each data point represent 8-h averages (1100–1900 LST) for extinction between Grandview and Moran Points (site R in Fig. 1) on two successive days. For each point, the trajectories arriving on the second day (day *n*) spent the entire previous 48 h in the NW quadrant; plotting symbols indicate the histories of the trajectories arriving on the first day (day *n*-1). Unclassified (UC) first days are distinguished according to whether the arriving trajectories spent more or less than 24 of the previous 48 h in the NW quadrant. Note that the first-day scale has a discontinuity at 40 Mm^{-1} in order to accommodate one observation.

the arrival (day *n*) of NW air, whether as a continuation of northwesterly flow or a shift from other directions, brought no consistent improvement.

Most of the very lowest extinction coefficients during 1988–1989 were observed in air from the NW and NE. Of the 25 observations at or below 15 Mm^{-1}, for example, 14 were from the NW and 10 were from the NE. Only 1 was from the SW or SE, suggesting that the survival of the best current visibilities may depend on the future evolution of emissions in only the northern quadrants. Under our interpretation of the 1990 Clean Air Act Amendments, this possibility is what motivates consideration of "clean air corridors".

The incidence of transport regimes limits the potential benefits of emissions zoning, as no regulatory strategy can change the frequency or timing of trajectories from given quadrants. Figure 5 shows the NW and NE to have been infrequent suppliers of clear air to the Grand Canyon during the summer tourist season, between early June and mid-September. Indeed, Table 1 shows just one 3rd quarter observation attributed to the NW or NE in 1988 and 1989 combined. This is consistent with the findings of Pitchford *et al.* (1981), all 6 of whose 1978–1979 clean corridor days occurred during the two months of October and November. (It should be noted that Pitchford *et al.* deleted all winter and early spring observations from their database, because of limitations in their visibility measurement.) Just as emissions from the southern quadrants apparently have little impact on the clearest days, increased emissions from the northern quadrants would apparently have little impact during the summer.

The good visibilities observed in air from the NE (Fig. 5) are of interest because SO_2 emissions in this quadrant are substantial (Fig. 1). Airmasses from the NE were confined largely to the 1st and 4th quarters during 1988–1989, but when they did arrive they brought extinction coefficients just as low as those from the NW. This pattern contrasts with that observed for sulfur: fine-particle sulfur concentrations (Fig. 4) attributed to the NE were, as expected from the distribution of emissions, significantly higher than those attributed to the NW. Extinction and sulfur were decoupled seasonally as well as spatially. The annual cycles in Figs 4 and 5 are out of phase, the 1984–1989 norm for sulfur peaking in the 3rd quarter and the 1987–1992 norm for extinction peaking in the 2nd quarter.

A particular source in the NE quadrant that has received intense scrutiny in recent years is a coal-fired power plant near the canyon entrance (Malm *et al.*, 1989; Richards *et al.*, 1991). One thesis at issue is that local flows occasionally carry emissions from this plant directly into the Canyon proper, below the level of the rim (ARS, 1991a). Figures 4 and 5 shed no light on this question, because the ATAD trajectories are derived from coarse upper-air data, and the sulfur and extinction data are from measurements up on the rim.

RELATIONSHIP TO RESIDENCE TIME ANALYSIS

Figure 5 displays only about 2 of every 5 observations actually recorded, those classified as exposed to emissions from a single quadrant. It is admittedly somewhat distasteful to "waste" 3 out of 5 observations, even if those shown are the most directly relevant to the potential effects of emissions zoning. Accordingly, several authors have developed analytical approaches that utilize all observations, including those exposed to emissions from more than one quadrant. This section will show the results of these alternative approaches, collectively referred to as residence time analyses, to be consistent with those derived from classifiable observations only.

Residence time analyses examine the empirical association between observed air quality and the residence times of back-trajectories in the cells of a spatial grid. Several approaches are based on the following simple model of the relationship between air quality and trajectory history

$$b_k = \sum_q B_q \tau_{kq}. \qquad (1)$$

In the present context, b_k is the extinction (Mm^{-1}) observed on the Canyon rim during the 8-h averaging period k, and τ_{kq} is the average fractional sojourn in quadrant q (quadrant hours per 48 h) of the two 48-h back-trajectories arriving during period k. The parameter B_q is known as the *transfer coefficient* between quadrant q and the measurement site, and may be thought of as the characteristic extinction at the Canyon attributable to quadrant q.

The quadrant-specific extinctions B_q in equation (1) can be empirically estimated in a variety of ways. Regression of b on the τ_q is one option (Iyer *et al.*, 1987), and direct calculation of weighted means such as $m_q(b) = \sum_k \tau_{kq} b_k / \sum_k \tau_{kq}$ is another (Keeler and Samson, 1989). Either of these approaches can be motivated by considering the hypothetical situation in which all observations are classifiable, so that all τ_{kq} are either 0 or 1. In that case, the OLS regression coefficient B_q^{OLS} and the weighted average $m_q(b)$ would each yield the obvious index of quadrant-specific extinction, the ordinary mean over all observations attributed to quadrant q. Table 2 compares B_q^{OLS} and $m_q(b)$ with the means and medians of classified observations for the actual extinction and trajectory data.

Table 2 shows that transfer coefficients based on residence time analyses of all observations are nearly indistinguishable from simple averages of classifiable observations. These results support Fig. 5's message that hazy air tends to come from the SW and SE, and that air from the NE is at least as clear as air from the NW.

Residence time analyses can provide spatial resolution far exceeding that attainable through any classification of discrete observations. The usual product of residence time analysis is a grid or contour map on which areas strongly associated with observed air quality stand out as presumptive source locations. The tradeoff for this improved spatial resolution is sharply diminished temporal resolution: residence time analyses statistically aggregate large numbers of observations, typically spanning one or more years. Because annual cycles modulate many factors in addition to the prevailing wind direction, seasonality has the potential to produce spurious associations between air quality and trajectory history.

Temperature provides an obvious but instructive example of how seasonality can confound temporally aggregated analyses. The quadrant-weighted 1988–1989 temperatures on the south rim of Grand Canyon are as follows:

	SW	SE	NE	NW
$m_q(T)$, °C	17	15	7	11.

Applying the usual naive interpretation to these results would yield the conclusion that the SE and SW are thermal source areas. However, Fig. 8 shows that it

Table 2. Association of 1988–1989 daytime extinction with airmass history on the south rim of Grand Canyon

		Classified			
	All	SW	SE	NE	NW
Observations	100%	23%	2%	5%	9%
Median extinction (Mm^{-1})	23	27	28	16	18
Mean extinction (Mm^{-1})	24	29	27	17	17
Residence time	100%	41%	11%	18%	30%
Weighted mean extinction (Mm^{-1})		28	26	19	20
OLS regression coefficient (Mm^{-1})		29	27	17	19

Valid 8-h averages (1100–1900 LST) of extinction between Grandview and Moran Points were recorded on 593 (81%) of the 731 days in 1988–1989. Back-trajectories of the arriving air were successfully calculated for 427 (72%) of these 593 observations, a subset with the same median and mean extinction as all observations. The top three lines give the distribution (%) of observations for which arriving trajectories spent the entire previous 48 h in a single quadrant, and the median and mean extinction (Mm^{-1}) associated with these observations. The bottom three lines give the distribution (%) of trajectory residence times in individual quadrants, and the extinction (Mm^{-1}) associated with these quadrants by two different statistical measures.

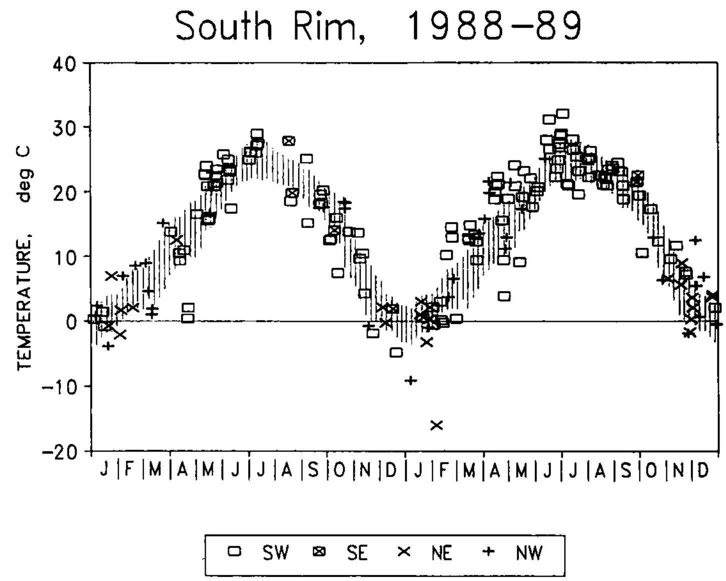

Fig. 8. Daytime temperature at Grandview Point (site R in Fig. 1) as a function of airmass history. Format is that of Fig. 5.

is more accurate to speak of summer as a thermal source period. Although southern latitudes are unquestionably warmer than northern latitudes on average (in the Northern Hemisphere), air arriving from the SW is often cooler than seasonal norms and air arriving from the NW is often warmer than seasonal norms. Figure 8 shows that most of the annual-average difference in quadrant-weighted temperature is due to the fact that air tends to arrive from the south in the summer and from the north in the winter.

Residence time analyses for the Grand Canyon region have often been reported in terms of probability rather than concentration or extinction (Ashbaugh *et al.*, 1985; Bresch *et al.*, 1987; Gebhart and Malm, 1991). The focus in these analyses is on the probability that a random air parcel carried from a given grid cell to the measurement site will arrive with air quality within a preselected range. This is the conditional probability that the air quality is within range $\mathscr{R}$ given that the air trajectory passes through grid cell q. It is estimated as the ratio $\sum_{j\in\mathscr{R}}\tau_{jq}/\sum_k \tau_{kq}$, where $\sum_k \tau_{kq}$ is the aggregate residence time in cell q of all trajectories and $\sum_{j\in\mathscr{R}}\tau_{jq}$ is the aggregate residence time in cell q of trajectories arriving with air quality in the range $\mathscr{R}$.

The air quality range of most interest for the present application is that defined by the lowest extinction coefficients. Selecting 15 $\mathrm{Mm^{-1}}$ as the upper bound of this range yields the following calculations for the probabilities of excellent visibility on the south rim of Grand Canyon in 1988–1989. The residence time distributions are expressed as percentages of the total, 40,992 h = (427 observations with valid extinction data and successfully calculated back-trajectories) × (2 back-trajectories per observation) × (48-h per back-trajectory).

	SW	SE	NE	NW
τ(all k)	41%	11%	18%	30%
$\tau(b_k \leqslant 15\ \mathrm{Mm^{-1}})$	2%	2%	8%	10%
$P(b_k \leqslant 15\ \mathrm{Mm^{-1}})$	0.05	0.16	0.42	0.32

These results support Fig. 5's attribution of the clearest observations disproportionately to the NW and, particularly, the NE.

The probability plots of Ashbaugh *et al.* (1985), Bresch *et al.* (1987), and Gebhart and Malm (1991) focussed on sulfur and other particle fractions rather than total extinction. For comparison with this earlier work, the probabilities of low fine-particle sulfur concentrations derived from the daytime 1988–1989 Canyon rim data are as follows

	SW	SE	NE	NW
$P(S_p \leqslant 0.2\ \mu\mathrm{g\ m^{-3}})$	0.19	0.08	0.13	0.51

These results support Fig. 4's identification of the NW as the only reliable supplier of sulfur-poor air.

DISCUSSION

For the policy analyst, the scientific questions raised by a clean corridor strategy are essentially two: would it be *sufficient*, and is it *necessary*? More precisely, would severe restrictions on emissions growth within a specified geographic corridor suffice to preserve excellent visibilities on certain days, in the face of future emissions growth outside the corridor? And would visibilities on these days in fact deteriorate if emissions within the corridor were instead allowed to increase? As indicated in the introduction, the exploratory analyses presented here cannot themselves resolve these questions.

None of our results conflict with the thesis that preservation of a low-emissions corridor would, by itself, suffice to preserve some days of excellent visibility at the Grand Canyon. For this reason they encourage further study of the corridor strategy. At the same time, the results do not address the question of how wide (or how long) a low-emissions corridor would have to be to transmit near-pristine air parcels intact, without significant contamination by adjacent higher-emissions sectors. Indeed, it is not clear that even a quadrant is sufficient in this regard. There were significant levels of non-Rayleigh extinction present in much of the relatively clear air attributed to the NW, after all, and the centerline trajectory analyses employed here cannot rule out "leakage" from the high-emissions SW as a possible contributor. To the degree that corridor air is contaminated by outside emissions, limits on growth within the corridor will of course not protect visibility against growth outside the corridor.

The sensitivity of visibility at the Grand Canyon to future emissions in the NW is difficult to assess from empirical analyses of current conditions. Most 1988–1989 observations of near-Rayleigh visibilities, those most sensitive to a given increment in particle concentrations, occurred in the 1st and 4th quarters. Gas-phase photochemistry slows at this time of year, in response to diminished ultra-violet fluxes, and this would tend to retard the conversion of gaseous precursors to secondary particles. At the same time, however, seasonal increases in the frequency of low clouds and fog might facilitate heterogeneous processes, promoting conversion. The net impact of SO_2 emissions on ambient sulfate concentrations can be studied empirically in the NE, where sources already exist. However, the equivalence of the emissions-ambient relationships typical of NW and NE flow remains to be established by detailed mechanistic analyses.

During much of the year air from the north, though clearer than air from the south, nevertheless brings extinction coefficients significantly above Rayleigh. The sensitivity of these observations to emissions depends largely on the origin of the existing aerosol. If a corridor's aerosol is predominantly from anthropic emissions within that corridor, then the associated extinction can reasonably be expected to increase roughly in proportion with those emissions. If the aerosol is instead predominantly from emissions adjacent to the corridor, background at the entrance to the corridor, or natural sources within the corridor, then it should increase or decrease less than proportionally with anthropic corridor emissions.

Our centerline trajectory analyses do not account for dispersion, and thus do not address the possibility that atmospheric dispersion is empirically associated with wind direction. More fundamentally they do not account for bulk vertical motion, and thus do not address an alternative explanation offered by Ostapuk and Fosdick (1982) for Pitchford et al.'s (1981) results. Ostapuk and Fosdick judged that at least four of Pitchford et al.'s six clean corridor trajectories were associated with intense subsidence, following vigorous cyclonic waves through the southwest U.S.A. They suggested that these trajectories brought air from the upper atmosphere rapidly to the surface, giving it little time to accumulate emissions in the boundary layer. In Ostapuk and Fosdick's interpretation it was favorable meteorology that brought clear air from the north, and would continue to bring relatively clear air even if emissions densities were to rise. A more extensive sample of isentropic (three-dimensional) back-trajectories, computed by Haagenson and Sperry (1989) for the North Atlantic, supports Ostapuk and Fosdick's association of subsidence with flow from the north.

The issues raised here are not intractable, but require for their resolution a more thorough examination of regional transport and dispersion, and more comprehensive data on atmospheric chemistry. Both these needs are being addressed in continuing work.

CONCLUSIONS

Some limited but fairly robust conclusions can be drawn directly from the empirical analyses presented here.

- Routinely calculated back-trajectories do carry information about airmass history. The terrain surrounding the Grand Canyon is complex, and the data available for the calculation are sparse, yet the estimated trajectories correlate—for whatever reasons—with observed visibility. Correlations with individual species are consistent with known source distributions: high methylchloroform concentrations are associated with the emissions-rich SW quadrant, and low particle sulfur concentrations are associated with the emissions-poor NW quadrant.
- Existing "clean corridors" for visibility can differ from those for sulfur and other individual aerosol fractions. As previous work has shown, the lowest fine-particle sulfur concentrations at Grand Canyon tend to arrive from the northwest. However, the best visibilities arrive from the entire northern half of the compass—their source region is better described as a "frontier" than a "corridor".
- The north seldom supplied clear air to the Grand Canyon during the summer tourist season. The southwest is a regular supplier of haze.

Note added in press: Since this paper was accepted for publication, minor changes have been made in the empirical formula used to account for transmissometer calibration drift due to lamp aging. Retrospective application of the new procedure to the 1988–1989 data yields no substantive change in any of the results reported here.

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REFERENCES

ARS (1991a) Technical Information Regarding Visibility Degradation Caused by the Navajo Generating Station (NGS) in the Grand Canyon and other National Parks and Wilderness Areas within 500 km of NGS. Submission to Air Docket LE-131, NGS Rulemaking, Air Resource Specialists, Fort Collins.

ARS (1991b) National Park Service Visibility Monitoring and Data Analysis Program: Summary of Revised Transmissometer-Based Visibility Data. Report ARS/Rev87-91.Rpt, Air Resource Specialists, Fort Collins.

Ashbaugh L. L., Myrup L. O. and Flocchini R. G. (1984) Surface layer transport of sulfate particles in the western United States by the large-scale wind field. *Mon. Weath. Rev.* **112**, 1067–1073.

Ashbaugh L. L., Malm W. C. and Sadeh W. Z. (1985) A residence time probability analysis of sulfur concentrations at Grand Canyon National Park. *Atmospheric Environment* **19**, 1263–1270.

Bresch J. F., Reiter E. R., Klitch M. A., Iyer H. K., Malm W. C. and Gebhart K. A. (1987) Origins of sulfur-laden air at national parks in the continental United States. In *APCA Transactions 10: Visibility Protection* (edited by Bhardwaja P. S.). Air Pollution Control Association, Pittsburgh.

Census (1991) Reported in *The World Almanac and Book of Facts 1992* (edited by Hoffman M. S.). World Almanac, New York.

Dorling S. R., Davies T. D. and Pierce C. E. (1992) Cluster analysis: a technique for estimating the synoptic meteorological controls on air and precipitation chemistry—method and applications. *Atmospheric Environment* **26A**, 2575–2581.

Gebhart K. A. and Malm W. C. (1991) Examination of source regions and transport pathways of organic and light absorbing carbon into remote areas of the United States. Paper 91-82.4, presented at Air & Waste Management Association Annual Meeting, Vancouver.

Haagenson P. L. and Sperry P. D. (1989) A relationship of isentropic back trajectories with observed wind direction and synoptic type in the North Atlantic. *J. appl. Met.* **28**, 25–42.

Heffter J. L. (1980) Air Resources Laboratories Atmospheric Transport and Dispersion Model (ARL-ATAD). Technical Memo ERL ARL-81, NOAA, Rockville.

Henry R. C., Wang Y.-J. and Gebhart K. A. (1991) The relationship between empirical orthogonal functions and sources of air pollution. *Atmospheric Environment* **25A**, 503–509.

Iyer H. K., Gui R., Gebhart K. A. and Brown E. (1992) Some approaches to cluster analysis of air mass trajectories to determine major aerosol transport pathways. *Atmospheric Environment* (in press).

Iyer H. K., Malm W. C. and Ahlbrandt R. A. (1987) A mass balance method for estimating the fractional contributions of pollutants from various sources to a receptor site. In *APCA Transactions 10: Visibility Protection* (edited by Bhardwaja P. S.). Air Pollution Control Association, Pittsburgh, PA.

Jepperson R., Hemel E. and Hauptman R. (1981) *The Kaiparowits Coal Project and the Environment.* Ann Arbor Science, Ann Arbor.

Keeler G. J. and Samson P. J. (1989) Spatial representativeness of trace element ratios. *Envir. Sci. Technol.* **23**, 1358–1364.

Khalil M. A. K. and Rasmussen R. A. (1989) The role of methylchloroform in the global chlorine budget. Paper 89-5.4, presented at Air & Waste Management Association Annual Meeting, Anaheim.

Latimer D. A. (1991) Grand Canyon haze: its magnitude, variability, composition, and sources. Technical background document for the Grand Canyon Visibility Transport Commission, San Francisco.

Malm W., Gebhart K., Latimer D., Cahill T., Pielke R., Stocker R. and Watson J. (1989) *National Park Service Report on the Winter Haze Intensive Tracer Experiment.* National Park Service, Fort Collins.

Malm W. C., Gebhart K. A. and Henry R. C. (1990) An investigation of the dominant source regions of fine sulfur in the western United States and their areas of influence. *Atmospheric Environment* **24A**, 3047–3060.

Miller D. F., Schorran D. E., Hoffer T. E., Rogers D. P., White W. H. and Macias E. S. (1990) An Analysis of regional haze using tracers of opportunity. *J. Air Waste Man. Ass.* **40**, 757–761.

Mueller P. K., Hansen D. A. and Watson J. G. Jr (1986) The Subregional Cooperative Electric Utility, Department of Defense, National Park Service, and EPA Study (SCENES) on Visibility: an Overview. Report EA-4664-SR, Electric Power Research Institute, Palo Alto.

NRC (National Research Council) (1990) *Haze in the Grand Canyon: an Evaluation of the Winter Haze Intensive Tracer Experiment.* National Academy Press, Washington.

NRC (National Research Council) (1993) *Protecting Visibility in National Parks and Wilderness Areas.* National Academy Press, Washington.

Ostapuk P. M. and Fosdick E. (1982) Regional analysis of factors affecting visual air quality (Discussion). *Atmospheric Environment* **16**, 2369–2372.

Pitchford A., Pitchford M., Malm W., Flocchini R., Cahill T. and Walther E. (1981) Regional analysis of factors affecting visual air quality. *Atmospheric Environment* **15**, 2043–2054.

Richards L. W., Blanchard C. L. and Blumenthal D. L. (1991) Navajo Generating Station Visibility Study. Final Report STI-90200-1124-FR, Sonoma Technology Inc., Santa Rosa.

Rogers D., Bastable H., Miller D., Schorran D., Hoffer T., Macias E. and White W. (1989) The Greater Los Angeles District Study. Desert Research Institute, Reno, NV.

Sheiman D. A., Doniger D. D. and Dator L. L. (1990) *A Who's Who of American Ozone Depleters.* Natural Resources Defense Council, New York.

Sisler J. F. and Malm W. C. (1990) *AWMA Transactions 17: Visibility and Fine Particles* (edited by Mathai C. V.). Air and Waste Management Association, Pittsburgh, PA.

White W. H., Macias E. S., Miller D. F., Schorran D. E., Hoffer T. E. and Rogers D. P. (1990) Regional transport of the urban workweek: methylchloroform cycles in the Nevada–Arizona desert. *Geophys. Res. Lett.* **17**, 1081–1084.