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RELATIONSHIP BETWEEN VISIBILITY AND ATMOSPHERIC TURBIDITY AT RALEIGH, NORTH CAROLINA

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ABSTRACT

Six years of turbidity measurements and visibility observations from rural Raleigh, North Carolina, are analyzed to determine their interdependence. Exponential least squares regression equations were computed by month for all data and for three stratifications by relative humidity. Regression results showed a distinct seasonal dependence with the best results (i.e., greatest explained variance) in summer and poorest in winter. Stratification of the data by relative humidity improved the results for all months, with marked improvement in August and September. During summer the best results were obtained with lowest relative humidities. Under these conditions the analyses indicate that there is a significant dependence of visibility on atmospheric turbidity; the explained variance exceeded 66% during June through September.

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I. Introduction

The United States Environmental Protection Agency (EPA) has proposed regulations to prevent future, and remedy existing, impaired visibility in such federal lands as national parks and wilderness areas (Costle, 1980). Impairment of visibility can reduce an individual's aesthetic appreciation of the landscape. This aesthetic perception, however, also is related to the "blueness" or color of the sky, which depends on atmospheric turbidity (vertically integrated light extinction due to aerosols) rather than on horizontal visibility. Thus, proposed regulations center on visibility whereas turbidity is more directly useful for certain atmospheric optical problems, including sky color and radiative energy budget computations. The purpose of this paper is to investigate the dependency of visibility on atmospheric turbidity.

Few researchers have studied how and under what circumstances visibility may be linked to turbidity. Although one is a horizontal and the other a vertical measurement, Hanel and Bullrich (1976) showed that the very large majority of aerosols in a vertical atmospheric column frequently are located within a few kilometers of the ground. Thus, when vertical mixing occurs through the atmospheric boundary layer there is a physical basis for expecting a visibility-turbidity link. Husar and Patterson (1980) used the inverse of visibility to research temporal and spatial aerosol variations over the eastern U.S. Others have studied the dependence of visibility on various measures of pollutants near ground level (e.g., Cass, 1979; Trijonis, 1979; Horvath and Noll, 1969; Patterson and Gillette, 1977) and the topic has been reviewed by Charlson et al. (1978). Some researchers (Griggs, 1972; McCormick and Baulch, 1962) explored the variation of turbidity with vertically integrated mass loading. Elterman (1970) computed the theoretical dependence of visibility on vertical aerosol attenuation. Hulstrom (1977) conducted one of the few experiments to collect simultaneous visibility and turbidity data. He found a fairly good correlation between parameters throughout a year at a rural North Dakota site where the average visibility exceeded 30 miles. However, in a paper precursory to this one, Peterson et al. (1980) showed a negative within-day correlation because turbidity slightly increased from sunrise to about 1300 while relative humidity decreased. They did find a more positive day-to-day dependence, especially for lower humidities.

Aerosol size is a strong function of relative humidity, especially for values greater than about 40% (Hanel, 1971). Moreover, empirical studies linking visibility and ground level pollutants also have showed a dependence of the link on relative humidity (Cass, 1979; Trijonis and Yuan, 1978). Consequently, relative humidity ought to have an important role in visibility-turbidity links.

Beginning in 1969, an extensive set of turbidity measurements and coincident meteorological information consisting of more than 8,000 individual observations was obtained at a non-urban site near Raleigh, N.C. (Peterson et al., 1980). These high quality measurements formed the basis for instrument calibrations for the EPA-sponsored U.S. turbidity network (Flowers et al., 1969). The analysis of this unique data set provided an opportunity to study the relation between atmospheric turbidity and visibility and its dependence on relative humidity in the southeastern U.S. Portions of the same data set were used recently by Griffing (1980) to investigate relations between visibility and turbidity on nephelometer scattering coefficient.

II. Data

In an earlier report (Peterson et al., 1981) we described in some detail the turbidity measurements at Raleigh, N.C. The turbidity (B) is obtained indirectly from a measurement of the intensity of the direct solar beam (I_λ) at wavelength λ (here 500 nm). Turbidity is customarily computed on the base 10 from

$$I_\lambda = I_{o\lambda}\, S\, 10^{-(\tau_{r\lambda} + \tau_{z\lambda} + B)m}, \qquad (1)$$

where $I_{o\lambda}$ is the solar intensity at the top of the earth's atmosphere, S is a correction factor for earth-sun distance, $\tau_{r\lambda}$ is the Rayleigh scattering coefficient for air molecules, $\tau_{z\lambda}$ is the ozone absorption coefficient, and m is the optical air mass. At sea level the 500 nm Rayleigh and ozone coefficients are 0.063 and 0.005, respectively. When converted to the natural base by multiplying by 2.3 the turbidity is termed the aerosol optical thickness.

Observations began at Raleigh, N.C., in July 1969 and have continued to the present. Here we analyze data from August 1969 through December 1975, when data were taken most extensively. During most of this period measurements were made at the EPA facility at Research Triangle Park, N.C., a non-urban location about 15 km northwest of Raleigh. Although measurements cannot be made when clouds obscure the sun, at least one turbidity observation was obtained on 59% of all days.

As part of each measurement the observer recorded local meteorological conditions. Visibility was obtained from National Weather Service (NWS) observations at nearby (5 km east) Raleigh-Durham (RDU) airport. Although the turbidity and visibility sites were not co-located, there were no significant pollution sources between them in the predominantly forested terrain.

Raleigh-Durham airport unfortunately has a poor selection of distant markers by which to estimate visibility (Trijonis, 1980; Trijonis and Yuan, 1978). From the ground, visibility is limited in several directions by trees at the airport's perimeter; however, a better selection of distant markers is available from the air traffic controller's tower. Consequently, during good visibility conditions the reported value often depended on whether the observer contacted tower personnel. In addition, local NWS rules for reporting visibility changed during our data period. The maximum reported value in the RDU observations was 15 miles through 1970, but only 12 miles for 1971 through June 1975. Thereafter, values up to 30 miles have been recorded. Until June 1975, conditions of good visibility were regularly reported as 7 or 12 miles (or 15 miles before 1971), and infrequently as 10 miles. Thus a report of 7 miles could actually mean 7 miles or something much greater. Because of this ambiguity the 7-miles cases were deleted for the regression analyses presented below. We also deleted the few cases where visibility was 1 mile or less, since the airport and turbidity sites probably had different visibilities at those times.

III. Method

The relationship between visibility (V) and turbidity was studied by computing least-square regression equations with visibility as the dependent variable. Linear, second degree, and exponential equations were obtained. The latter, of the form

$$V = aB'^{b}, \qquad (2)$$

where a and b are derived coefficients, is similar to Koschmieder's formula (Middleton, 1968) with B replaced by the atmospheric extinction coefficient along a horizontal path. For our regression computations B + 0.063 was used as the independent variable (B'), to include the effect of Rayleigh scattering (Flowers et al., 1969).

Since aerosol size strongly depends on relative humidity, we stratified the regressions according to four relative humidity classes: less than 50%, 50%-69%, 70% and above, and all values combined. Finally, we computed all regressions monthly, except we grouped December-January-February and November-March because of similar turbidity and visibility values within each group.

IV. Results

Atmospheric turbidity and visibility at Raleigh undergo a large annual cycle (see Fig. 1 of Peterson et al., 1980). Turbidity is small with little day-to-day variation during winter. In contrast, quite large values occur during summer with large day-to-day changes. The annual minimum is near January 1 and the maximum about August 1.

Figures 1 to 4 show joint distributions of the number of occurrences of visibility and turbidity; the latter is summarized in intervals of 0.05 units. The solid curved lines are the derived least squares best fit exponential equations. As noted above, the 7-mile visibility occurrences were deleted for these and all subsequent regressions. They are included in the figures only for completeness. One figure is presented for each season. The annual variability of turbidity again is evident. During winter, the great majority of values were less than 0.1 whereas summer turbidities occurred over a wide range. April and

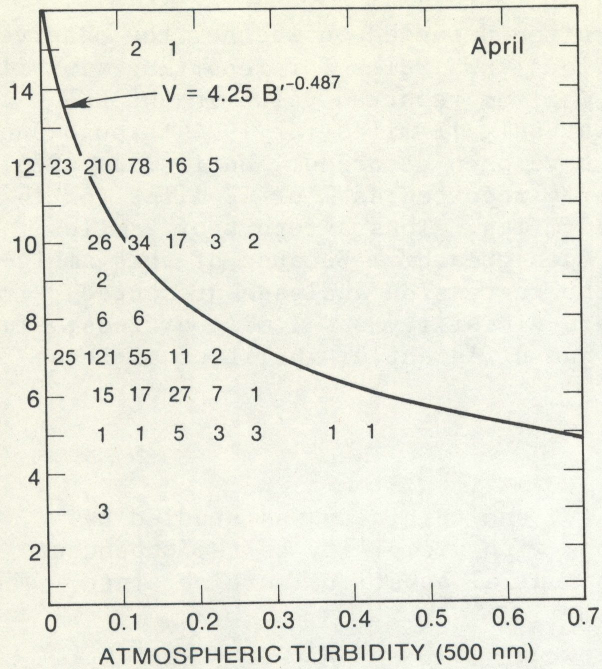

Figure 1. Joint distribution of the number of occurrences of visibility and turbidity at Raleigh, NC, during April. The solid line and associated equation is the derived least squares exponential best fit to the data.

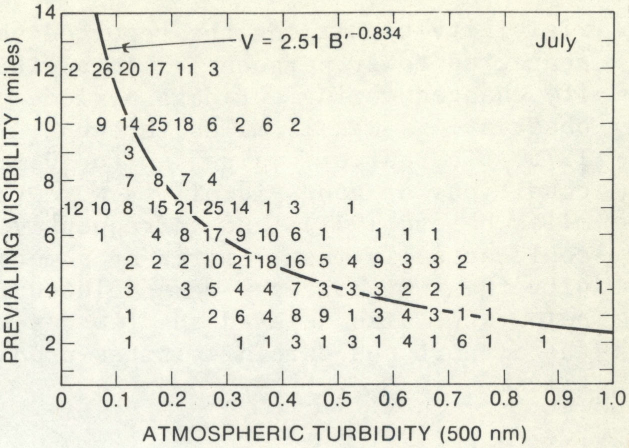

Figure 2. As in Fig. 1, except for July.

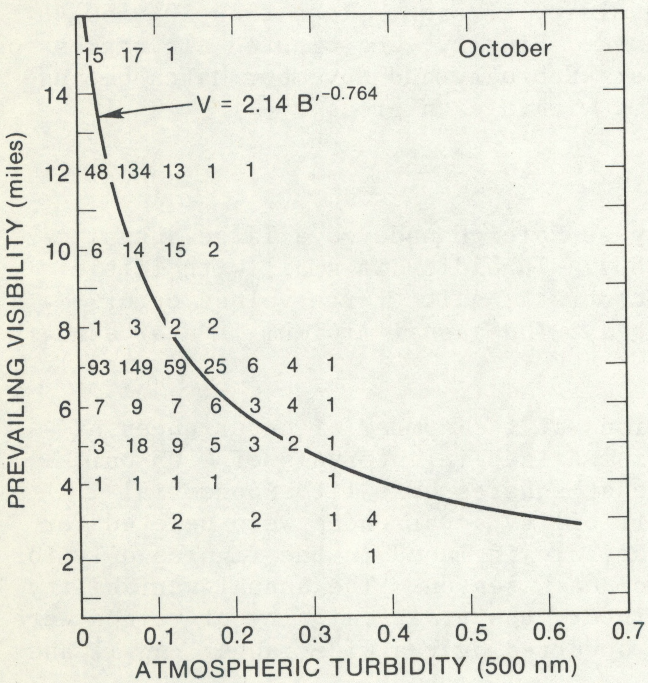

Figure 3. As in Fig. 1, except for October.

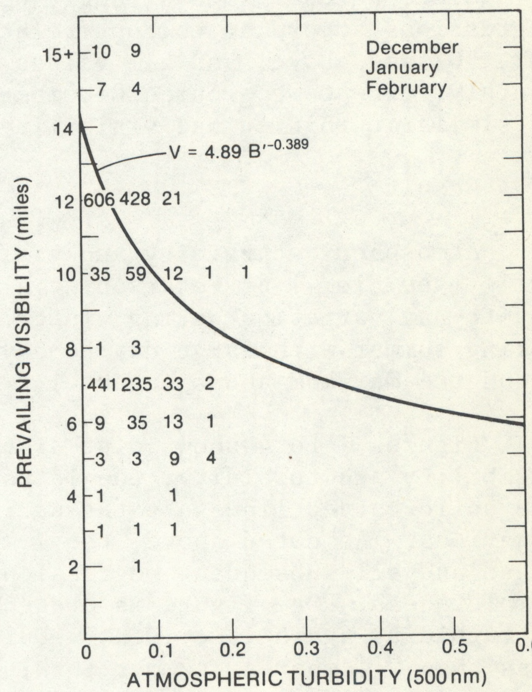

Figure 4. As in Fig. 1, except for December, January, and February combined.

October show transitions between these regimes. Several characteristics of the RDU visibility observations also can be seen in Figs. 1 to 4. First, there were few reports greater than 15 miles. Second, visibilities of 8, 9, 11, 13, and 14 miles were seldom reported and values of 10 miles had relatively few occurrences. Third, the distribution of turbidity for 7-mile visibilities was unusual with too many very low turbidities. As mentioned above, this occurred because local NWS rules allowed a report of 7 miles when the visibility was actually considerably better. Last, there was a pronounced seasonal variation. Although visibility less than 7 miles occurred infrequently with winter turbidity measurements, it occurred nearly half the time in July.

In Table 1 we present monthly summaries of the derived exponential regression equations (equation 2) of visibility as a function of turbidity for four relative humidity classes. Results from the linear and second degree equations are not presented; in the large majority of cases the explained variance from these equations was similar to, but somewhat less than, that of the exponential form. The exponential equation is also a more satisfactory mathematical form in that (with a negative exponent) visibility must approach very large and small values as turbidity becomes very small and large, respectively, in agreement with natural occurrences.

The regression results for all relative humidities are given in the first line of each monthly summary of Table 1. The variance explained ranges from a high of 62% in June to a low of 12% in September and the combined three winter months. Although the best results tend to occur during late spring and summer, explained variances for August and September are quite poor. When the data for these months are stratified by relative humidity, however, there is marked improvement in the results. Moreover, the best results tend to occur with the smallest (nearest -1) exponential coefficients (b of Table 1), supporting the Koschmeider form (equation 2) as a valid way to express the visibility-turbidity dependence.

During the summer half-year the variance of visibility explained by the exponential function of turbidity exceeds 50% for most of the relative humidity subclasses. The importance of relative humidity is further elucidated in Figs. 5 to 9, which give the joint distribution of visibility-turbidity measurements for May-September for each relative humidity class. The best summer relations occur with lowest relative humidity. In August and September the exponential fit is quite good for low humidities (although the number of observations is small) but rather poor for the highest humidities. As seen in the right hand panel of Fig. 8 (August), this latter feature occurs because of a scattered joint distribution when visibilities are less than 7 miles. At this time of year nocturnal inversions occur frequently at Raleigh with morning surface temperatures near saturation and reduced visibility. However, relative humidity may be much lower aloft. Thus, because of the strong dependence of aerosol size on relative humidity, surface visibility may be poorly correlated with the turbidity. Low summer relative humidities typically occur from mid-day through afternoon, the time of greatest wind speeds and vertical mixing. Consequently, surface observations of visibility are representative of a thicker atmospheric layer with better correlations to turbidity.

Table 1. Results of least-squares exponential regressions of visibility as a function of turbidity for four relative humidity classes.

Month	Relative Humidity (%)	Explained Variance	Coefficients a	b	Number of Observations
APRIL	ALL	0.213	4.25	-0.487	516
	<50	0.286	3.90	-0.556	357
	50-69	0.201	4.10	-0.451	79
	>69	0.540	2.88	-0.623	48
MAY	ALL	0.457	2.00	-0.906	353
	<50	0.578	2.09	-0.975	122
	50-69	0.528	2.16	-0.866	133
	>69	0.383	1.78	-0.796	90
JUNE	ALL	0.622	2.15	-0.877	539
	<50	0.773	2.31	-0.897	140
	50-69	0.559	2.61	-0.753	204
	>69	0.544	1.90	-0.852	172
JULY	ALL	0.589	2.51	-0.834	455
	<50	0.664	2.52	-0.913	99
	50-69	0.635	2.74	-0.807	202
	>69	0.579	1.92	-0.915	138
AUGUST	ALL	0.292	3.10	-0.597	303
	<50	0.777	2.71	-0.934	34
	50-69	0.321	3.49	-0.564	162
	>69	0.222	2.72	-0.502	102
SEPTEMBER	ALL	0.119	3.64	-0.415	212
	<50	0.717	3.78	-0.548	16
	50-69	0.600	3.85	-0.566	96
	>69	0.009	4.06	-0.140	100
OCTOBER	ALL	0.371	2.14	-0.764	368
	<50	0.446	4.78	-0.454	179
	50-69	0.707	2.42	-0.744	80
	>69	0.447	1.44	-0.784	109
NOVEMBER MARCH	ALL	0.261	2.71	-0.670	910
	<50	0.158	6.43	-0.284	555
	50-69	0.293	3.47	-0.553	191
	>69	0.447	0.62	-1.293	162
DECEMBER JANUARY FEBRUARY	ALL	0.122	4.89	-0.389	1280
	<50	0.025	9.17	-0.121	766
	50-69	0.130	5.57	-0.333	286
	>69	0.413	1.32	-0.907	223

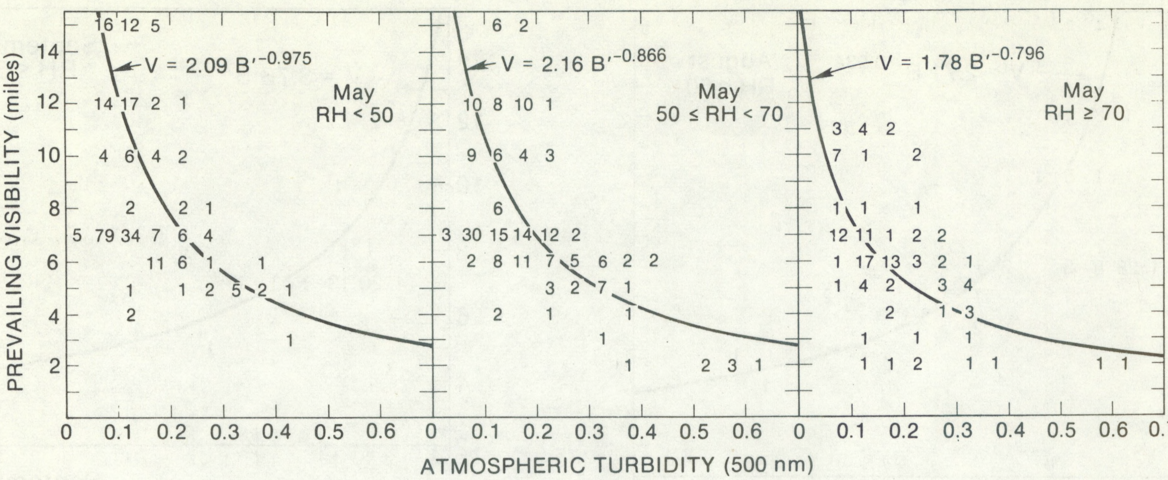

Figure 5. Joint distribution of the number of occurrences of visibility and turbidity at Raleigh, NC, during May, with the data stratified for three relative humidity intervals. The solid lines and associated equations are the derived least squares exponential best fits to the data.

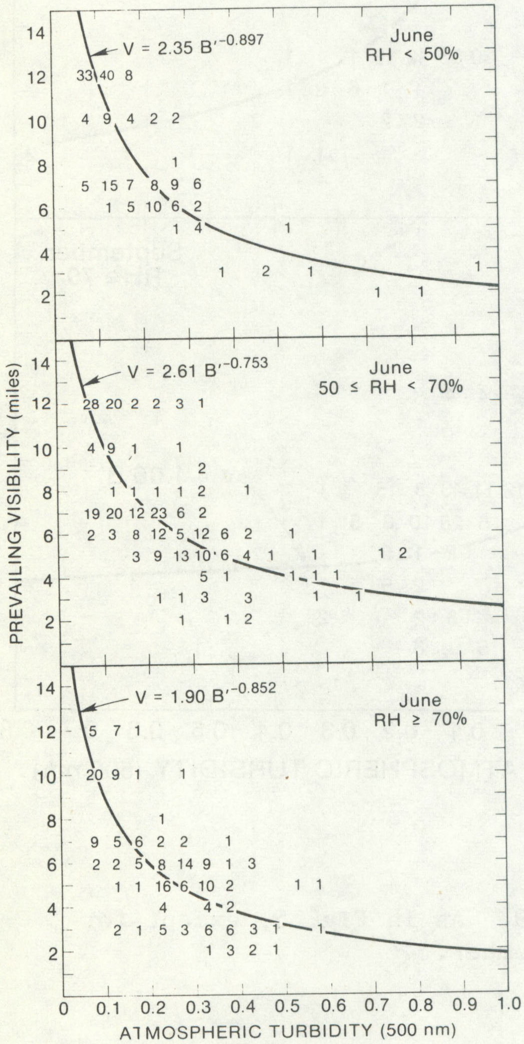

Figure 6. As in Fig. 5, except for June.

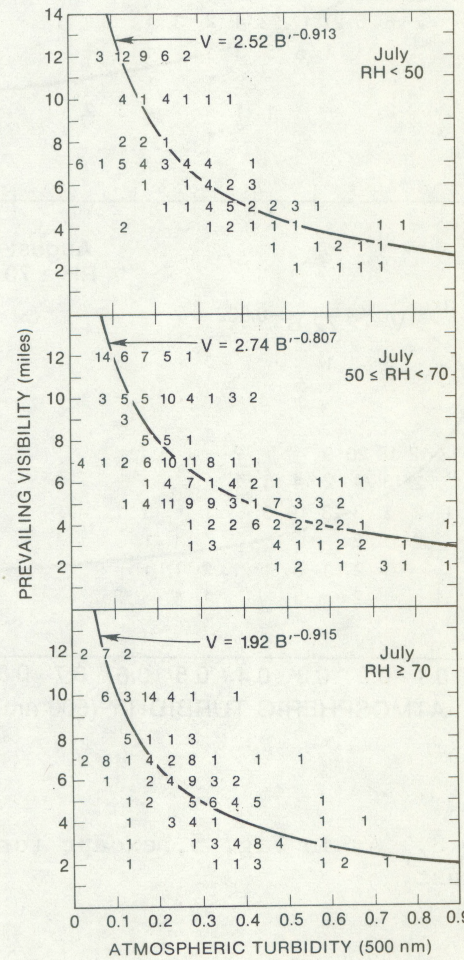

Figure 7. As in Fig. 5, except for July.

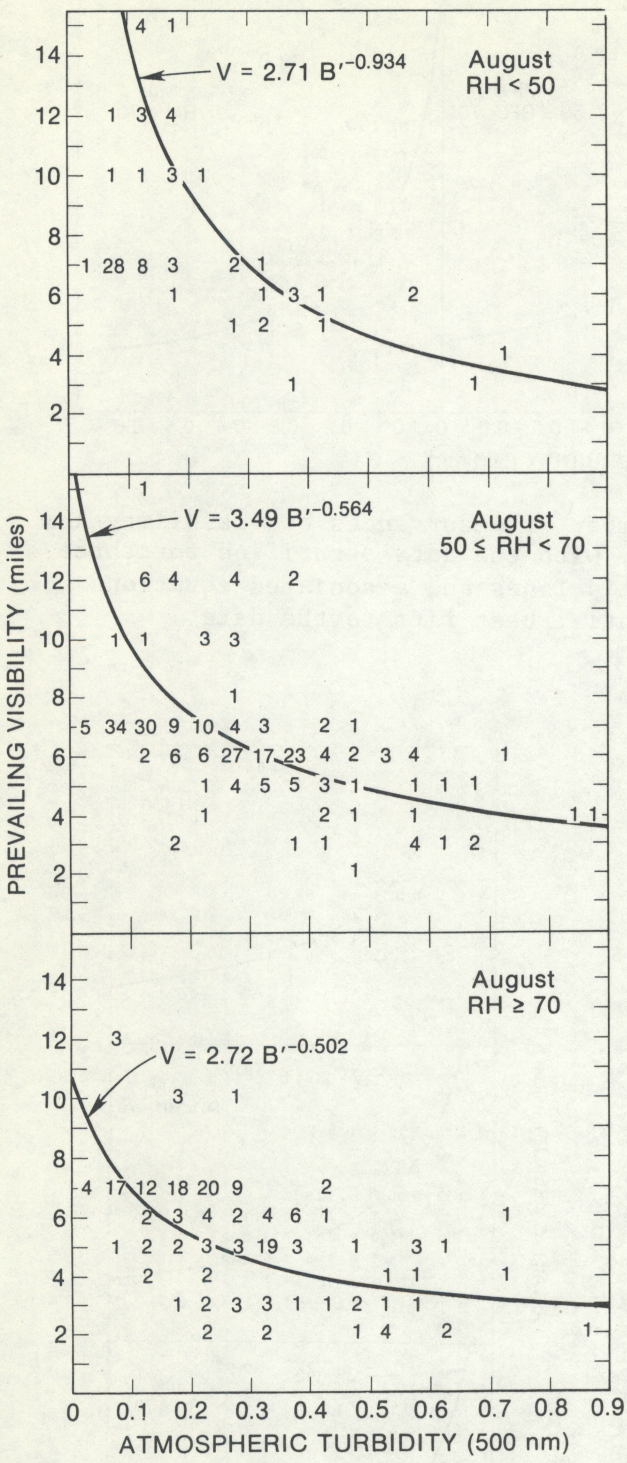

Figure 8. As in Fig. 5, except for August.

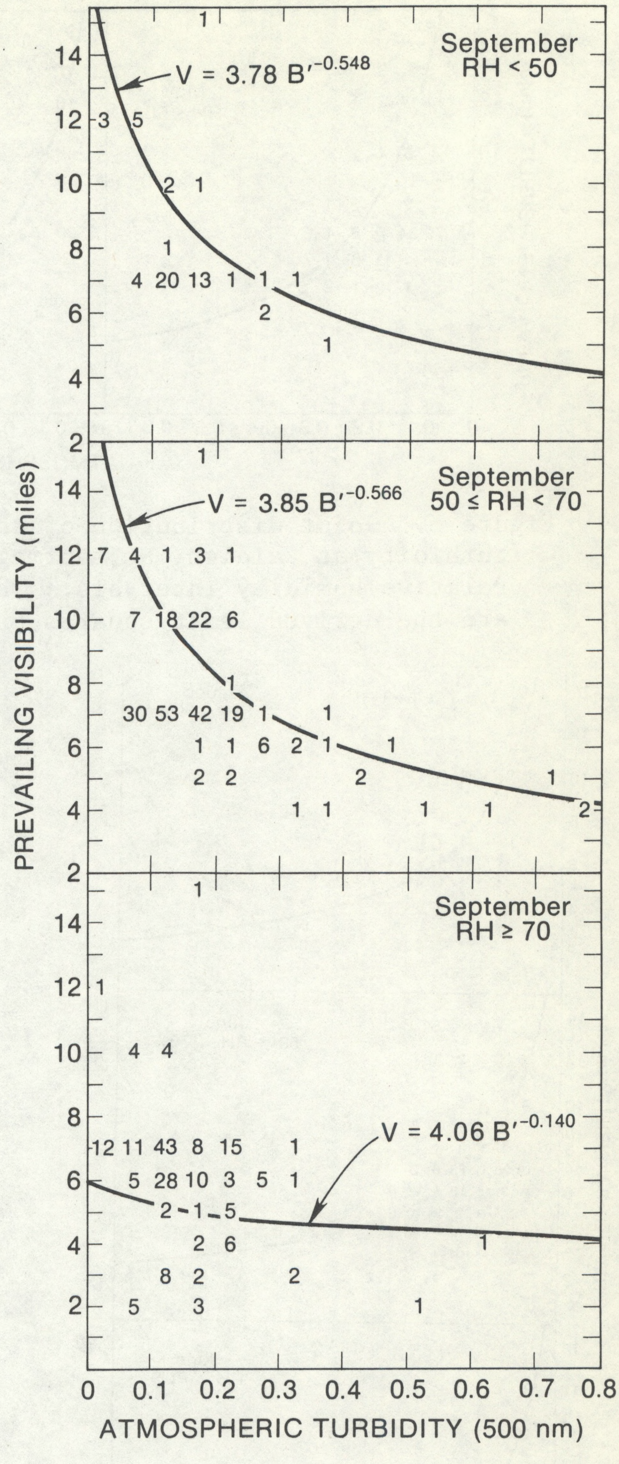

Figure 9. As in Fig. 5, except for September.

Comparison of the regression curves for the three humidity subclasses in each of Figs. 5 to 9 shows that the curves tend to shift to the lower left as relative humidity increases. That is, as humidity increases a given turbidity corresponds to lower visibilities; this result is expected since the surface observations of visibility respond more directly to the surface measurement of relative humidity. Correspondingly, for a given visibility, turbidity decreases as relative humidity increases. A similar relative humidity effect on visibility-pollutant relations has been reported by Griggs (1972) and Trijonis and Yuan (1978).

From November through April, the best visibility-turbidity relations are found with the highest relative humidities, the reverse of the summer relations. This humidity dependence is especially evident for the December to February group (Fig. 10). Then, with low humidity, very few turbidities were greater than 0.1 and visibility was less than 7 miles for only 14 occurrences (out of 766). Visibility of 12 miles was reported on 705 occasions. With such a great clustering of the data, the regressions simply did not account for any appreciable amount of variance.

V. Discussion

Several interesting points arise from our analyses of visibility vs. turbidity. First, there is a distinct seasonal dependence in the percent variance of visibility explained by the exponential function of turbidity with best results in summer and poorest in winter. The smaller winter correlations resulted partly from the lack of suitable distant markers visible to the observers at RDU, local NWS rules (effective during the period of this study) that allowed observers to report 7 miles when the visibility was actually much better, and the larger relative measurement errors associated with small turbidities. Because of these limitations we were unable to explore fully the visibility-turbidity relation for the winter season. In contrast, the summer data exhibited much higher turbidities and lower visibilities. With this broader range of measurements, underlying physical relations were more evident.

Second, by stratifying the visibility-turbidity data by relative humidity, the percent explained variance by the exponential regression was improved for every month but one in at least two humidity classes compared to that for all humidities combined. In August and September the percent explained variances for the driest humidity class were very markedly improved over those for all measurements.

Third, during summer the best regressions were obtained with lowest relative humidities. For this class more than 66% of the variance of visibility was explained during June through September. The very best result was nearly 78% for August. During summer relative humidity undergoes a pronounced diurnal cycle inversely proportional to the daily temperature cycle. Thus the turbidity measurements associated with lowest humidities tended to be those obtained during the afternoons when wind speeds and vertical atmospheric mixing are (on the average) at their maxima and the atmosphere is well mixed through the boundary layer. Therefore, the horizontal visibility observation is well related to the vertical turbidity measurement.

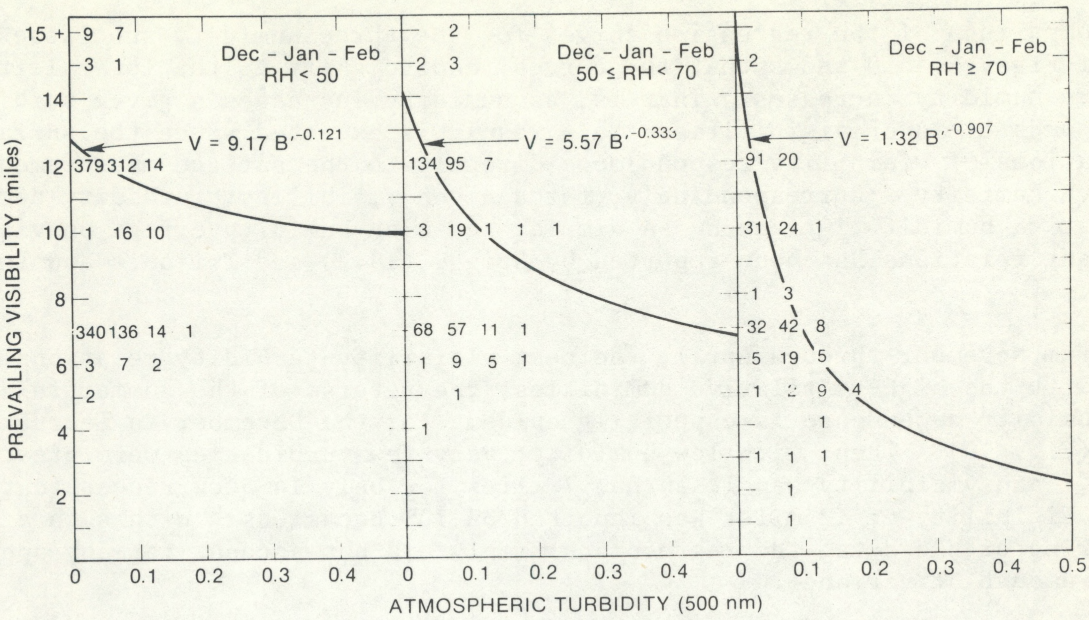

Figure 10. As in Fig. 5, except for December, January, and February combined.

Fourth, during winter the best regressions were obtained with highest relative humidities, opposite to the humidity dependence of summer. This contrast may have been caused by characteristics of our data set rather than a real physical effect. When winter humidities were high there were more occurrences of reduced visibility less than 7 miles along with slightly higher turbidity, conditions most optimum for developing visibility-turbidity relations with our available data. Although a good interdependence may exist for the low humidity, more transparent winter atmospheres, more sophisticated and accurate instruments would be necessary to collect the needed data.

In summary, the analyses of our data here indicate a significant dependence of visibility on atmospheric turbidity during summer, especially when relative humidity is low. Thus, at least for central North Carolina, spatial and temporal visibility variations can be transformed into turbidity variations with some confidence. Such transformations may be quite useful for investigations of the aesthetic blueness of the sky or radiative energy budgets, when visibility information is available but a measure of vertical aerosol extinction is needed.

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