NOTES

Reexamination of Turbidity Measurements Near Page, Arizona, and Navajo Generating Station

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Turbidity (McCormick and Baulch, 1962) is a measure of the attenuation of sunlight by aerosol in a vertical column of atmosphere. Turbidity is usually measured at 380 and 500 nm and is represented by B_λ, the attenuation of sunlight at some wavelength per unit air mass [see Malm *et al.* (1977) for a more complete discussion of turbidity theory]. Measurements made near Lake Powell from February 1973 to April 1974 were anomalous (Malm *et al.*, 1977), i.e., the turbidity coefficient was larger at 500 nm than at 380 nm. Turbidity coefficients over a longer time interval (three years) are presented in Fig. 1, a histogram comparing monthly means of B_{380} and B_{500}. The measurements include those presented in Malm *et al.* (1977), as well as those from summer 1974 to spring 1976. Table 1 is a seasonal tabulation of maxima, minima, arithmetic means and half 90% confidence intervals for B_{380} and B_{500}.

The measurements were made using an Eppley Sunphotometer, No. 4645, that was recalibrated by EPA at Research Triangle Park on 11 January 1973 and in December 1974. The calibration changed by less than 1.2% for both 500 and 380 nm. In addition, since a small but broad-band "red" leak in the 380 nm filter could account for the anomalous behavior, filter transmission characteristics were checked by the Eppley Laboratories during July 1978.

The 380 nm has a peak transmission of ~0.18 at 385 nm with a full-width-at-half-maximum (fwhm) of ~10 nm. The filter has a small red leak peaked at about 750 nm. Its peak transmission is $\sim 2\times 10^{-4}$, while the fwhm is about 75 nm. Within spectrometer sensitivity the filter shows zero transmission between 405 and 670 nm as well as between 840 and 1000 nm. The slight red light leak corresponds, in clean atmospheres, to a 10–15% positive error in the sunphotometer reading as well as a reduced calibration value. A shift in the calibration value and sunphotometer reading by the same multiplicative factor would not yield a change in calculated turbidity. Depending on the comparative quality of the radiation used for calibration and that coming from the sun after passing through the atmosphere, error in the calibration value and sunphotometer reading would not necessarily be the same. However, the turbidity coefficient at 380 nm

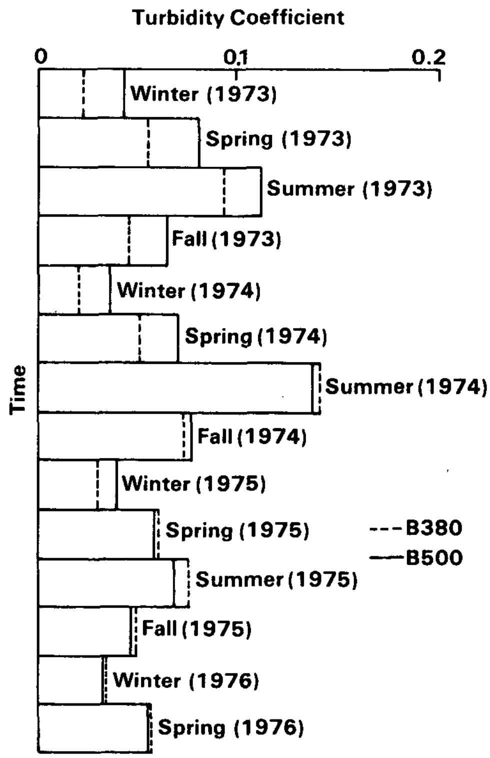

FIG. 1. Seasonal mean turbidity coefficients at 380 and 500 nm measured at Vermillion Court, Page, Arizona.

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TABLE 1. Turbidity coefficients B_{380} and B_{500}.

Year	Season	Maxi-mum	Mini-mum	Arith-metic mean	Half 90% confidence interval
		B_{380}			
1973	All	0.220	0.001	0.062	0.005
	Winter	0.038	0.012	0.022	0.004
	Spring	0.158	0.013	0.055	0.005
	Summer	0.220	0.005	0.094	0.010
	Fall	0.118	0.001	0.046	0.006
1974	All	0.248	0.004	0.086	0.009
	Winter	0.079	0.004	0.021	0.005
	Spring	0.109	0.018	0.051	0.011
	Summer	0.248	0.021	0.143	0.014
	Fall	0.123	0.026	0.074	0.007
1975	All	0.182	0.002	0.063	0.005
	Winter	0.037	0.022	0.031	0.004
	Spring	0.089	0.026	0.062	0.006
	Summer	0.182	0.033	0.077	0.008
	Fall	0.121	0.002	0.051	0.007
1976	All	0.064	0.019	0.040	0.004
	Winter	0.061	0.019	0.035	0.004
	Spring	0.064	0.054	0.058	0.003
		B_{500}			
1973	All	0.221	0.019	0.084	0.004
	Winter	0.061	0.026	0.043	0.005
	Spring	0.205	0.036	0.082	0.005
	Summer	0.220	0.041	0.114	0.008
	Fall	0.128	0.019	0.065	0.006
1974	All	0.335	0.017	0.092	0.008
	Winter	0.089	0.017	0.037	0.004
	Spring	0.136	0.038	0.072	0.001
	Summer	0.335	0.049	0.139	0.011
	Fall	0.124	0.035	0.078	0.006
1975	All	0.130	0.025	0.059	0.003
	Winter	0.052	0.029	0.040	0.007
	Spring	0.085	0.027	0.060	0.001
	Summer	0.130	0.035	0.070	0.005
	Fall	0.092	0.025	0.048	0.005
1976	All	0.068	0.020	0.038	0.004
	Winter	0.068	0.020	0.034	0.004
	Spring	0.067	0.047	0.058	0.005

(B_{380}) could be in error by as much as 40% and still be statistically lower (assuming a 90% confidence interval) than B_{500} (see Table 1).

Monthly geometric means of B_{380} and B_{500} gathered between February 1973 and May 1976 were plotted as a logarithmic probability plot presented in Malm *et al.* (1977). As the turbidity coefficient increases, the ratio of B_{500}/B_{380} changes from >1.0 to <1.0. The average maximum monthly ratio of 1.9 occurred in the winter of 1973, while minimum ratio of 0.9 was in the summer of 1975. As tropospheric aerosol concentrations increased, the number ratio of small to large particles increased. An increase in the number ratio of small to large particles will cause B_{500}/B_{380} to decrease (Malm *et al.*, 1977). Similar data are reported by Porch *et al.* (1971) and by the Environmental Data Service (1974, 1975, 1976, 1977). Ratios of 2.17 have been recorded at Kitt Peak, Arizona, and Cerro Tololo, Chile. Kitt Peak recorded an average ratio of 1.1 for 24 nights of observation.

Fig. 1 shows that the yearly averages of B_{500} and B_{380} increase from 1973–1974 and then decrease from 1974–1976. This temporal change is predominant during summer months while winter months show little change in B_{500} and a slow increase of B_{380}. Temporal changes correlate well with the population changes of Page, Arizona (Walther *et al.*, 1978). The population of Page reached a maximum in 1974 (the peak of construction activity at nearby Navajo Generating Station) and then decreased from 1974–1976. Atmospheric aerosol scattering coefficients, aerosol mass, lead, hydrocarbon and aerosol number concentrations show the same temporal trend (Walter *et al.*, 1978). All these parameters were highest in 1974 with subsequent decreases thereafter.

The change in B_{500}/B_{380} may be more significant. During the summer of 1974 the average B_{500} was smaller than B_{380} for the first time since the initiation of turbidity measurements. After winter 1975, average B_{500} coefficients were always smaller than B_{380}. Before summer 1974 average B_{380} coefficients never exceeded B_{500}. In our previous paper (Malm *et al.*, 1977) we examined three mechanisms which might contribute to $B_{500}/B_{380}>1$: 1) aerosol size distributions, 2) atmospheric water vapor concentration and 3) ozone concentration. Variations in ozone concentration were ruled out as explaining $B_{380}<B_{500}$. While increased water vapor content may cause a slight increase in B_{500}/B_{380}, it alone would not be sufficient to cause the high B_{500}/B_{380} ratios. Aerosol size distributions measured in the mixing layer in the vicinity of Lake Powell followed the power law proposed by Junge (1963). Calculations showed that the measured aerosol size distribution within the mixing layer should yield $B_{500}\approx B_{380}$. This implies that a monodisperse aerosol located above the mixing layer could be partially responsible for the anomalous turbidity coefficients.

During the winter months, when contributions to the total aerosol from local ground level sources were lowest, Fig. 1 shows B_{380} monotonically increasing from 1973–1976. This would seem to imply that the size distribution of "background" aerosol was changing. Increasing B_{380} without changing B_{500} would require an increase in concentration of particles $\lesssim 0.3$ μm diameter.

Unit One of the Navajo Generating Station started operation in January 1974, while Units Two and Three started in December 1974 and December 1975. Each 750 MW unit is equipped with hotside electrostatic precipitators with a design efficiency of 99.5%. These precipitators, while efficient in collecting particles $\gtrsim 1.0$ μm allow most particles <0.2 μm to escape into the atmosphere. The first observation of a monthly average of $B_{380}>B_{500}$ occurred after the startup of Unit One. After Unit Two came on line monthly averages of B_{380} always exceeded B_{500}.

In conclusion, there appears to be a trend of decreasing B_{500}/B_{380}, regardless of absolute instrument calibration. However, the instrument used to make the turbidity measurements was periodically checked for changes in calibration as well as for possible filter light "leaks." Therefore, it is suggested that the Navajo Generating Station has changed the background aerosol size distribution sufficiently to cause B_{380} to increase to levels comparable to other less pristine areas in the United States.

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