Atmospheric Turbidity Across the Los Angeles Basin

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ABSTRACT

Atmospheric turbidity (aerosol optical thickness) was measured with sunphotometers across the Los Angeles Basin. Automobiles were used for east-west traverses of the metropolitan area (a distance of ~100 km) on two days with distinctly different meteorological conditions: a hazy, relatively humid day and a warmer, dryer, less hazy day with easterly Santa Ana wind flow. Additionally, incident global UV and total solar irradiance were measured at six sites (five urban and one rural) and nephelometer measurements of aerosol concentrations were made at two locations.

On the hazy day turbidity was remarkably uniform across the Los Angeles Basin. In contrast, significant variation of turbidity from west to east occurred on the less polluted day. Solar radiation measurements also reflected the day-to-day and spatial turbidity differences. During the hazy day the urban sites received only 64–76% as much UV energy as did the rural mountain site. With easterly Santa Ana wind flow, San Bernardino received 17% more total solar energy than on the hazy day.

1. Introduction

The radiative characteristics of aerosols over urban areas are essential parameters in the study of the effects of atmospheric pollutants. This paper focuses on one aspect of that topic: the variation of aerosol optical thickness (atmospheric turbidity) across an urban area and consequent variations of incident solar radiation.

During the Los Angeles Reactive Pollution Project (LARPP) in the autumn of 1973 the authors set up six sites in the Los Angeles area to measure incident total and ultraviolet global solar irradiance (Peterson and Flowers, 1977). Measurements were taken at five urban locations: Los Angeles International Airport (LAX), downtown Los Angeles (DLA), El Monte (ELM), Upland (UPL) and San Bernardino (SBD), and at a nonurban location on Mt. Disappointment (MTD) at 1820 m elevation (see Fig. 1). Additional measurements of direct solar radiation, atmospheric turbidity and atmospheric aerosol concentrations were made frequently at El Monte and Mt. Disappointment. In addition to the primary LARPP measurements, the variation of atmospheric turbidity across the Los Angeles Basin was measured with sunphotometers. Automobiles were used to traverse the Basin on two days with distinctly different meteorological conditions. Analyses of the data from the mobile turbidity cross sections and from the fixed solar radiation sites on those two days will be presented herein.

2. Experimental design

Observers in two vehicles drove across the Basin on Interstate Highway 10 (see Fig. 1) stopping at frequent intervals to measure turbidity. Data were taken from Santa Monica in the west, through Los Angeles, to just east of San Bernardino, a distance of about 100 km. The vehicles usually traveled in opposite directions so that they were each at an end point of the track and both at El Monte at about the same times. Measurements were made on two days. On Friday 21 September 1973, a day with high aerosol levels, data were taken from about 1030 to 1315 PST, and essentially consisted of only one space cross section. On Wednesday 26 September 1973, a day with lower turbidity levels because of a Santa Ana meteorological situation, four cross sections were obtained from about 0730 to 1545 PST.

The sunphotometer is a light-weight, hand-held, portable instrument that allows one to compute aerosol optical thickness (B) from a measurement of the intensity of the direct solar beam (I) (Flowers

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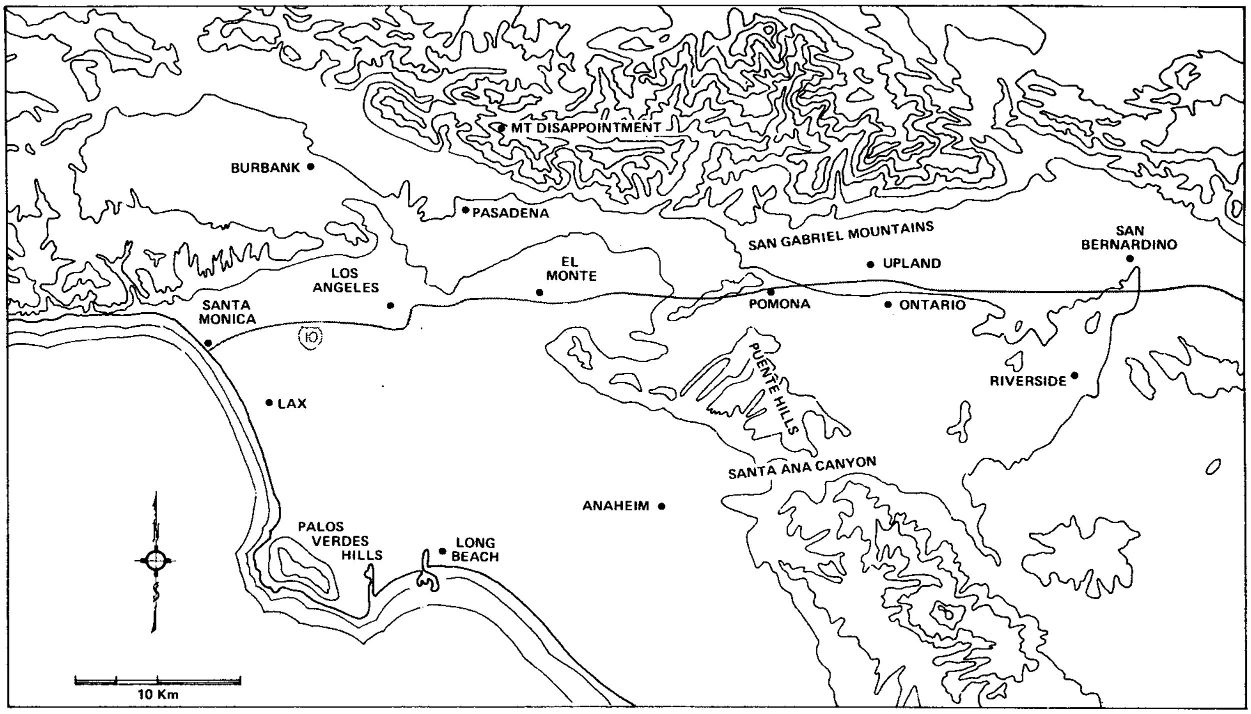

Fig. 1. Map of the Los Angeles Basin showing Interstate Highway 10, cities and topography. Terrain height is indicated by contours at 150 m, 300 m and at successive intervals of 300 m.

et al., 1969), using the relation

$$I/I_0=10^{-(R+Z+B)m}. \qquad (1)$$

In Eq. (1), I_0 is the spectral intensity at the top of the atmosphere, R the coefficient for Rayleigh (molecular) scattering, Z the coefficient for ozone absorption and m the optical air mass. Turbidity values are customarily presented on a decadic (base 10) scale. Climatological values were used for R and Z in the solution of (1). Although B is representative of the total atmosphere, a large fraction of the optical thickness is usually contributed by the lowest kilometer of the atmosphere (Hanel and Bullrich, 1976). Measurements were made at two wavelengths (0.38 and 0.50 μm) so that the wavelength exponent α, which is related to the aerosol size distribution, could also be calculated. Following Angstrom's (1961) terminology, B can be expressed as a function of wavelength (λ) by

$$B=\log_{10}e\beta\lambda^{-\alpha}, \qquad (2)$$

where β is Angstrom's turbidity coefficient corresponding to 1 μm wavelength. For measurements at two wavelengths, the expression

$$B_1\lambda_1{}^{\alpha}=B_2\lambda_2{}^{\alpha} \qquad (3)$$

can be used to solve for α. Moreover, if the number of particles (N) per unit volume of air as a function of size (r) is represented by a "Junge" distribution of the form

$$dN/dr\propto r^{-\gamma}, \qquad (4)$$

where γ is a constant, α is related to the "slope" of the particle size distribution by $\alpha=\gamma-3$ (Bullrich, 1964).

At the fixed sites, incident global total solar irradiance was measured with Eppley[3] Precision Spectral Pyranometers and incident global ultraviolet (UV) solar irradiance with Eppley photocell radiometers. The UV instruments use a broadband filter giving full wavelength sensitivity from 0.295 to 0.385 μm and half-power wavelength sensitivity from 0.315 to 0.368 μm. Data from these continuously operating instruments were recorded on strip charts, digitized and averaged over 10 min intervals. On the two experimental dates the UV sensor at San Bernardino was inoperable and no data are available. All other sensors functioned properly. All instruments were operated side by side before and/or after the LARPP experiment to obtain relative intercalibrations. At the same times, absolute calibrations were obtained by comparison to working standard pyranometers whose calibrations were traceable to the International Pyrheliometric Scale. Near-surface atmospheric aerosol concentrations were measured with Meteorology Research, Inc., integrating nephelometers at Mt. Dis-

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[3] Mention of company or product names should not be considered as endorsement by the U. S. Department of Commerce.

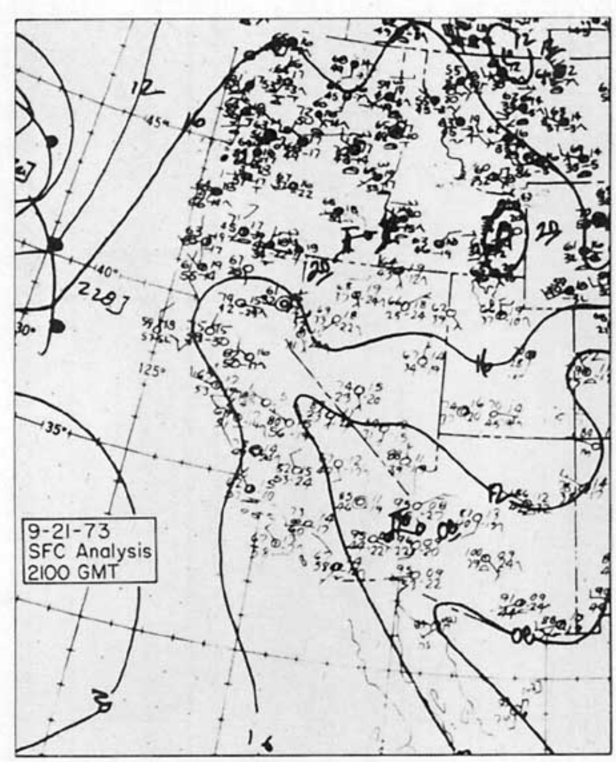

FIG. 2. National Weather Service surface analysis for 1300 PST 21 September 1973.

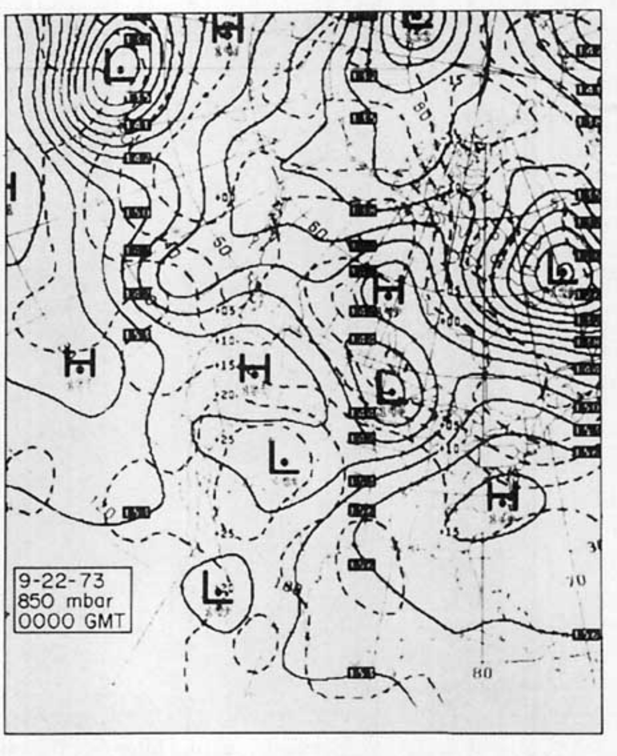

FIG. 3. National Weather Service 850 mb height and temperature analysis for 1600 PST 21 September 1973.

appointment, operated by the authors, and at El Monte, operated by the California Air Resources Board.

3. Prevailing meteorological conditions

The meteorological regime on 21 September was similar to that which commonly occurs over southern California during late summer and early autumn and leads to quite hazy conditions. The surface and 850 mb weather maps are shown in Figs. 2 and 3. Temperature and dew point soundings taken by the Environmental Meteorological Support Unit at El Monte Airport are shown in Fig. 4. Typical features include a subsidence inversion aloft, relatively high humidity near the surface, and a weak surface pressure gradient over Southern California. During early morning hours surface winds were light, but by noon a sea breeze was well established and surface winds were generally west to southwest at about 10 kt throughout the area. The visibility at El Monte did not exceed 5 km until after 1600 with restrictions due to haze and smoke. At noon, visibility at Ontario was only 1.5 km because of haze and smoke; by late afternoon it increased to 8 km.

The weather on 26 September was quite different from that on the 21st. The surface and 850 mb charts are presented in Figs. 5 and 6; temperature and dew point soundings from El Monte can be seen in Fig. 7. High pressure over the Pacific Northwest caused easterly wind flow over Southern California. These Santa Ana winds brought warmer and dryer air over the Basin. With the absence of the temperature inversion aloft, pollutants were more readily dispersed and visibilities significantly improved. Early afternoon visibilities at Ontario were 88 km. The Santa Ana was not strong enough, however, to completely overcome the sea breeze over the western part of the Basin where pollutants did accumulate and visibilities were reduced. At 1300 the visibilities at El Monte and LAX were 24 and 10 km, respectively.

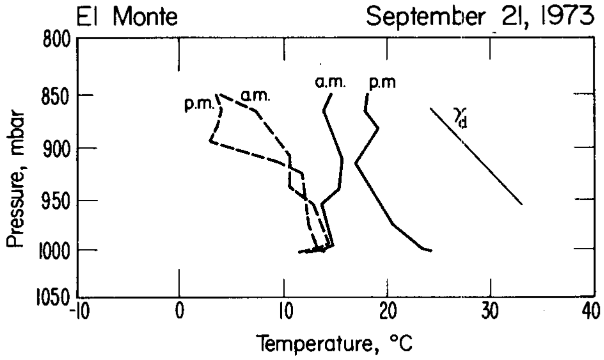

FIG. 4. Temperature (solid) and dew point (dashed) (°C) as a function of pressure (mb) at El Monte, Calif., 21 September 1973. Balloon release was at 0535 PST for the morning sounding and at 1244 PST for the afternoon sounding.

4. Results

a. Atmospheric turbidity

The turbidity measurements for 21 and 26 September are presented in Figs. 8 and 9, respectively. The decadic turbidity coefficient (B) at 0.50 μm wavelength is the upper number; its decimal point indicates the space-time location of the observation. The lower entry in parentheses is the corresponding wavelength exponent α. Large (small) α values indicate relatively more small (large) particles.

The outstanding feature of the data from the 21st is the uniformity of both B and α across the basin. From the Pacific Coast to Upland, the turbidity coefficients varied by only 0.05 after 1200 PST. Thus, in spite of the very high turbidities over this extensive metropolitan area, the measurements indicate that the atmospheric aerosols were spatially homogeneous at this time. A turbidity of 0.37, for example, corresponds to an atmospheric direct beam transmission at 0.50 μm wavelength due to aerosols of only 0.43. The measurement (0.77; 0.1) near San Bernardino departs from the other observations but can be tentatively explained. That measurement was taken at the intersection of I-10 and Riverside Avenue at 1149 PST, some 12 km to the east-southeast of an industrial complex and steel plant near Fontana. Analysis of wind measurements at Riverside and Ontario airports and at Norton Air Force Base (5 km east of SBD) showed the surface winds to be generally from the west to northwest at about 5–10 kt from 1000 to 1200 PST. Thus, the high turbidity, with relatively high numbers of large particles (small α), could have resulted from industrial emissions of particles upwind of the measurement site.

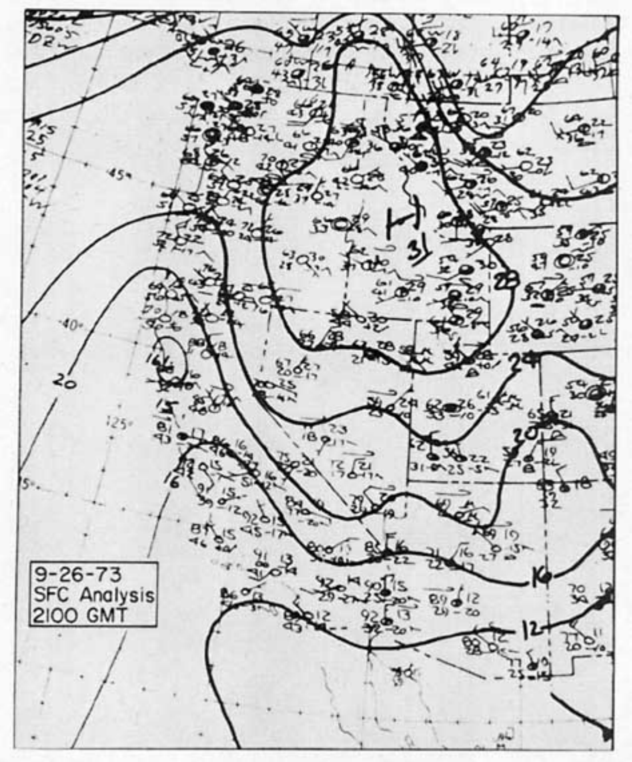

Fig. 5. National Weather Service surface analysis for 1300 PST 26 September 1973.

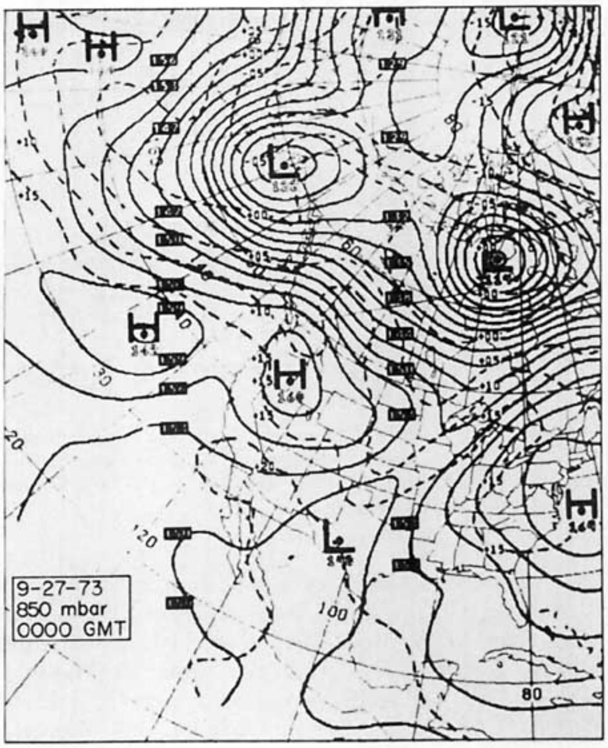

Fig. 6. National Weather Service 850 mb height and temperature analysis for 1600 PST 26 September 1973.

The turbidity coefficients from the 26th are everywhere less than those from the 21st. Cleanest air with smallest α values occurred in the east; highest turbidities occurred in the Los Angeles–El Monte area. The higher turbidities were also associated with larger

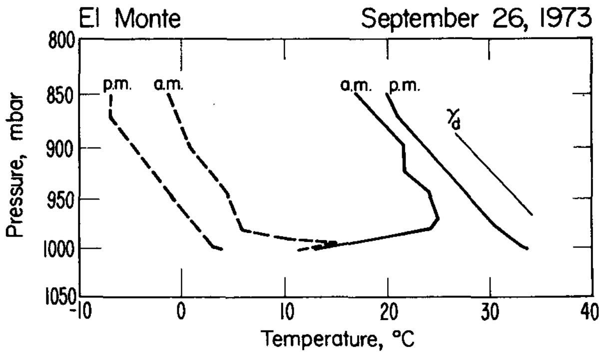

Fig. 7. Temperature (solid) and dew point (dashed) (°C) as a function of pressure (mb) at El Monte, Calif., 26 September 1973. Balloon release was at 0545 PST for the morning sounding and at 1235 PST for the afternoon sounding.

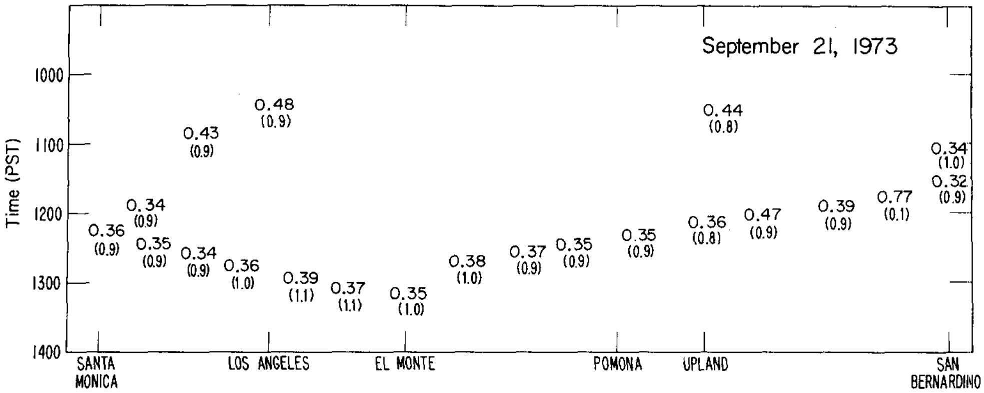

FIG. 8. Atmospheric turibidity measurements on 21 September 1973 plotted as a function of time and space across the Los Angeles Basin. Upper entry is the turbidity coefficient (B) and lower entry (in parentheses) is the wavelength exponent (α). The decimal point of B marks the space-time location of each measurement.

numbers of small particles. In addition to these spatial variations, changes with time are also evident. Locations west of El Monte had their highest turbidities during the 1000–1100 traverse. From El Monte to Upland, highest readings occurred later in the day (1200–1300). Little diurnal variation was measured east of Upland.

During the morning traverses to the east, very low α values (0.0, 0.2) were measured at the intersection of I-10 and Milliken Ave., just east of Upland. On both occasions, the observer noted strong, gusty northeast winds and blowing dust from highway construction to the east (the present intersection of I-10 and I-15). Evidently, the low α values were caused by numerous large particles of windblown dust with few small particles originating from atmospheric pollutants.

Direct measurements of atmospheric aerosols in the Los Angeles region by Whitby *et al.* (1972) and Hidy *et al.* (1975) have shown that most of the aerosols caused by anthropogenic activity originate from gaseous emissions and subsequent gas-to-particle reactions within the atmosphere. Moreover, these are generally small particles in the submicron size range. Clean air advected into the Basin from the east was shown to have relatively few aerosols <1 μm diameter.

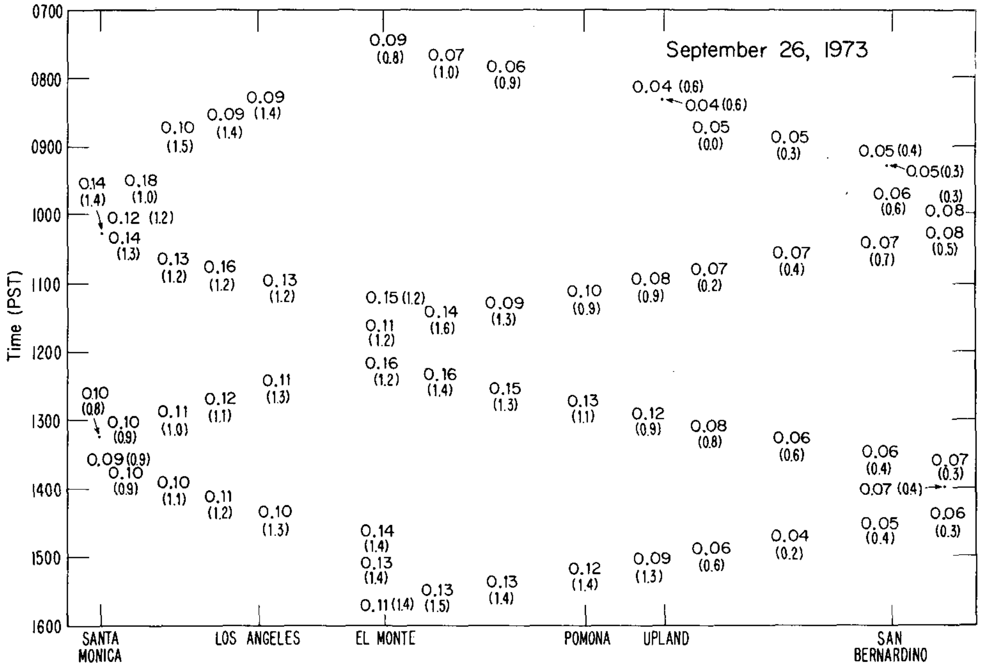

FIG. 9. As in Fig. 8 except for 26 September 1973.

Thus during days with restricted pollutant dispersion and high turbidity, one would expect the largest α values.

b. Aerosol concentrations

The turbidity coefficients discussed above refer to the aerosol extinction integrated vertically through the entire atmosphere. Surface aerosol concentrations were continuously measured at El Monte and MTD as part of LARPP. These data obtained with integrating nephelometers are shown in Figs. 10 and 11, respectively. The aerosol extinction coefficient (b_{scat}), determined by this light-scattering instrument, are plotted versus time of day for both experimental days. At El Monte, the readings were high all day on the 21st as a result of the overall smoggy conditions. After 0800 on the 26th, markedly reduced extinction coefficients were measured. However, at 0730 the high nephelometer reading in conjunction with the low turbidity values (Fig. 9) suggests the presence of a shallow atmospheric layer at the surface with high particle concentrations. The rise of b_{scat} readings from late morning to afternoon also agrees with the turbidity measurements. According to the nephelometer manufacturer's literature, b_{scat} values of 2×10^{-4} and 6×10^{-4} m^{-1} correspond to visibilities of 23.2 and 7.7 km, respectively, which concur well with the FAA observations of prevailing visibility at the nearby El Monte airport.

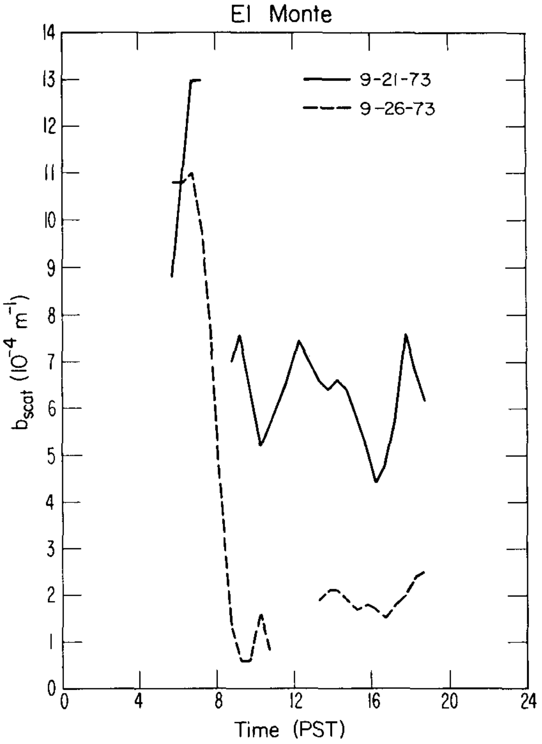

FIG. 10. Aerosol extinction coefficient (b_{scat}) versus time (PST) measured with an integrating nephelometer at El Monte on 21 and 26 September 1973.

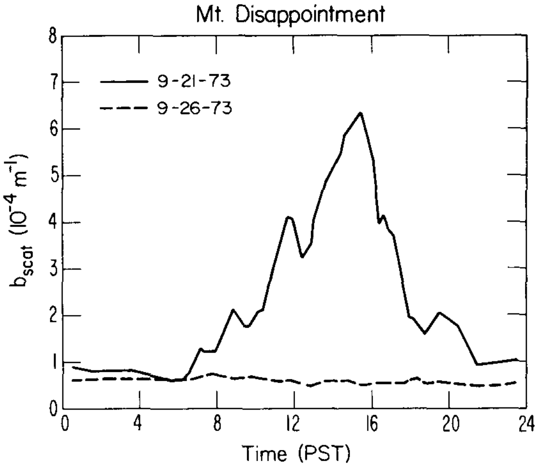

FIG. 11. As Fig. 10 except for Mt. Disappointment.

The nephelometer measurements from Mt. Disappointment also fit the overall contrasting atmospheric patterns on the two experimental days. On the 26th b_{scat} values were consistently low all day. On the 21st, however, the low early morning readings changed to markedly higher values during the daylight hours. This pattern was typical of many days during LARPP. Mt. Disappointment at 1820 m elevation has a south-facing slope extending into the Basin (see Fig. 1). On sunny days, air adjacent to this slope is heated and rises up the mountain. Consequently, smoggy air flows out of the Basin and is advected to the north and east over the San Gabriel Mountains. As the solar heating waned during late afternoon the nephelometer readings rapidly decreased.

c. Solar radiation measurements

The turbidity or aerosol extinction measurements showed a marked contrast between 21 and 26 September 1973. In addition, on the 26th there was some notable variation of turbidity throughout the Basin. In this section, these aerosol extinction values will be compared to measurements of incident total and UV global solar irradiance.

The UV measurements at the fixed sites are shown in Figs. 12 and 13 for 21 and 26 September, respectively. Ten-minute average irradiance values were plotted as points and connected to give the continuous lines for each location. Stratus clouds were present over much of the Basin during the early morning of the 21st but were mostly dissipated by 1100. Thereafter, the four urban sites received substantially less UV energy than did MTD. The greatest urban irradiance was measured at LAX, where the sea breeze was evidently advecting cleaner air from the ocean over the coastal area. The more transparent atmosphere

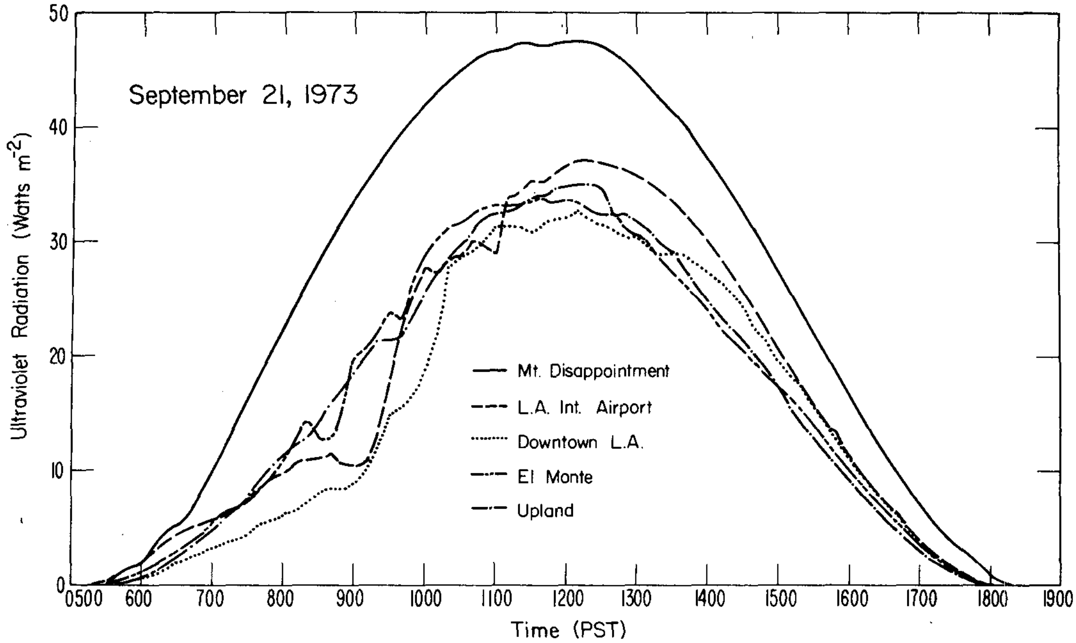

FIG. 12. Ultraviolet irradiance (W m^{-2}) versus time (PST) measured at five locations in the Los Angeles area on 21 September1973. The continuous traces for each location were formed by connecting points representing 10-min average values.

along the coast is not reflected in the turbidity cross section, although the coastal turbidity measurement was made at 1219 PST, just as the UV irradiance at LAX was beginning to significantly depart from the other urban site values. Throughout the afternoon the DLA, ELM and UPL UV irradiances were similar, as were the earlier turbidity observations. The quantity of radiation received, both UV and total solar, at all the fixed sites is given in Table 1 for the period 1200–1800 on the 21st. Thus, the comparisons are free of cloud influence. During that time the urban sites LAX, DLA, ELM and UPL received only 76, 69, 64 and 65%, respectively, as much energy as did MTD. The same general trend is evident from the total solar data where the same urban sites plus SBD received 88, 88, 85, 85 and 83% of the radiation incident at MTD.

TABLE 1. Quantity of radiation (J cm^{-2}) measured at six sites around Los Angeles, Calif., during the morning and afternoon of 21 and 26 September 1973, at UV (0.30–0.38 μm) and total (0.3–3.0 μm) solar wavelengths.

Date/ Time (PST)	Spectral interval	MTD	LAX	DLA	ELM	UPL	SBD
9-21-73	UV	55.8	42.5	38.3	35.9	36.4	—
1200–1800	Total	1050	926	919	896	891	867
9-26-73	UV	63.2	46.1	48.9	45.5	54.7	—
0600–1200	Total	1264	1093	1125	1136	1230	1229
9-26-73	UV	57.7	42.0	39.4	36.7	42.9	—
1200–1800	Total	1068	990	958	952	973	1012

The radiative pattern on the 26th (Fig. 13) shows more interstation variation and less overall depletion from the mountain measurement than that on the 21st. The low turbidities in the east corresponded to the most intense radiation. The UV irradiance at Upland was significantly higher than that at the other three urban sites until about 1300. The total solar measurements showed even higher irradiance at San Bernardino than at Upland (see Table 1). For the whole day SBD received about 7% more total solar energy than did the three westermost urban sites. After 1300 the turbidities at Santa Monica, DLA and UPL were similar and somewhat less than that measured at ELM. The corresponding UV irradiances showed good qualitative concurrence. The decreased UV irradiance at El Monte between 1000 and 1100 is also reflected in the nephelometer measurements, and suggests that a volume of relatively smoggy air moved east past the site at that time. Unfortunately, there were no coincident turbidity observations and the El Monte nephelometer was then out of service for calibration for several hours. For the 26th as a whole, however, El Monte received less UV energy than any other urban location. For the complete day, LAX, DLA, ELM and UPL received 73, 73, 68 and 81%, respectively, as much UV energy as MTD.

The contrast between the 21st and the 26th is most evident at the eastern urban stations for both turbidity and incident radiation. During the afternoons, when comparisons can be made for cloudless conditions, SBD received nearly 17% more total solar energy on the 26th than on the 21st while Upland

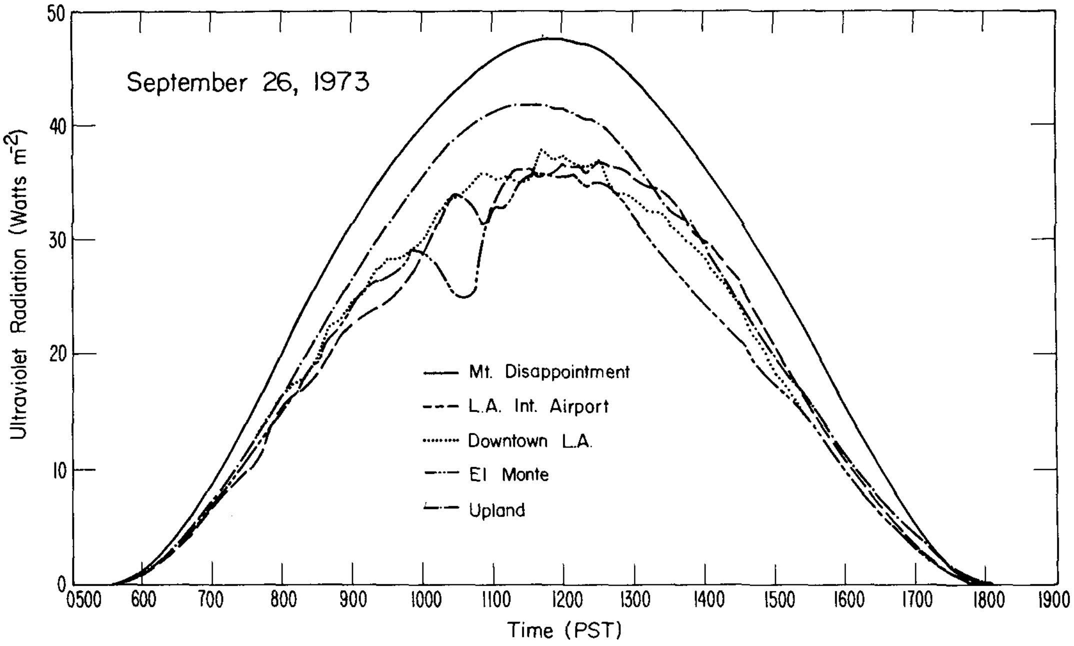

FIG. 13. As in Fig. 12 except for 26 September 1973.

received 18% more UV energy. Interestingly, at LAX the afternoon UV energy was actually slightly greater on the 21st, although the total solar energy was 7% less on that date. A possible explanation is that while the radiatively important pollutant concentrations were similar on both afternoons at LAX, the drier air on the 26th allowed more longer wave solar radiation to pass through the atmosphere than on the more humid 21st.

5. Summary

On two days during September 1973 atmospheric turbidity was measured across the Los Angeles Basin with sunphotometers. Meteorological conditions were distinctly different on the two days leading to hazy conditions on the 21st and warm, dry, haze-free easterly Santa Ana wind flow on the 26th.

Atmospheric turbidity measurements on the 21st showed quite high, but uniform values across the Basin. Remarkably little overall difference was evident across 100 km of metropolitan area. In contrast, on the 26th, turbidity varied significantly from west to east and the time of the daily maximum varied with location. Although the measurements on both days primarily reflected large urban-scale contrasts, turbidity anomalies, presumably due to local aerosol sources, were identified.

Nephelometer measurements of aerosol concentrations at El Monte and Mt. Disappointment also reflected the different atmospheric conditions on the two experimental days. Much higher values were measured at both places on the 26th. Moreover, the El Monte data agreed with nearby FAA visibility observations and the Mt. Disappointment record showed evidence of smoggy urban air flowing out of the Basin and over the mountains during mid-day.

Incident global total and UV solar irradiance measured at six sites around Los Angeles responded to the day-to-day and spatial aerosol variations detected by the sunphotometers and nephelometers. During the afternoon of the 21st the urban sites only received 64 to 76% as much UV, and 83 to 88% as much total solar energy as did Mt. Disappointment. On the 26th San Bernardino received 7% more total solar energy than the three sites in the western end of the Basin. A large contrast was found between the two days at the eastern locations. With easterly Santa Ana wind flow, San Bernardino received 17% more total solar energy while Upland received 18% more UV energy than on the hazy day.

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