Trends in Attenuation Coefficients in Athens, Greece, from 1954 to 1991

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ABSTRACT

Unsworth and Monteith's attenuation coefficient T_{UM} was calculated from midday cloudless sky data in Athens, Greece, for the period 1954 to 1991. An interdependence between T_{UM} and the Linke factor T_{L} was found and is expressed as a mathematical function. It was also shown that the minimum turbidity levels occur during the winter and maximum levels occur during summer. An analysis of the long-term variation of the attenuation coefficients depicts the deterioration of air quality during the same period. The dependence of the ratio of diffuse to global radiation on the attenuation coefficient T_{UM}, is also presented.

1. Introduction

It is well known that aerosols considerably attenuate solar radiation. Airborne particulate and gaseous pollutants alter the solar radiation incident at the ground in two ways: by depleting the total radiation and by changing the proportions of direct and diffuse radiation (Peterson and Flowers 1977). At urban sites, high aerosol concentrations reduce the total incident energy and alter the diffuse/direct ratio (Jacovides et al. 1994). At rural locales, the decrease in the direct solar beam will be largely compensated by an increase in the diffuse flux. Furthermore, photochemical pollutants, which depend on ultraviolet radiation for their formation, drastically affect the amount of solar energy reaching the ground. The particles formed from photochemically induced gas to particle reactions, cause both absorption and scattering of the incoming radiation (Peterson and Flowers 1977).

Concern about possible changes in global climate has stimulated an increasing interest in the radiative effects of aerosol. Investigations on the aerosol's radiative effects using various turbidity parameters have been reported from several sites: Birdgman (1978), King et al. (1980), and O'Neil et al. (1993) from United States; Unsworth and Monteith (1972) and Unsworth and McCartney (1973) from British Midlands; Uboegbulam and Davies (1983) and Freud (1983) from Canada; and Louche et al. (1987), Karalis (1976), and Jacovides et al. (1994) from Mediterranean sites.

The study of atmospheric turbidity is important in meteorology, climatology, and for monitoring of atmospheric pollution. The atmospheric turbidity parameters are also required in order to determine the amount of spectral global irradiance, for the designing of photovoltaic cells, and for the selective absorbers for spectral thermal collectors (Bird 1989). With these diverse needs in mind, a series of measurements of direct solar beam irradiance between 1954 and 1991 are reported and analyzed in terms of aerosol amount.

The amount of atmospheric aerosol is represented by the various turbidity parameters. The most currently used are the Linke factor T_{L}, (Linke 1922) and the Angstrom turbidity coefficient β (Angstrom 1929). Less frequently, other parameters, such as α, the exponent of the extinction power law; β_0, the "true" turbidity coefficient; or $B_{0.5}$, the Schuepp coefficient, are used. An "integral optical depth" τ_a of the aerosols as proposed by Unsworth and Monteith (1972) may be served as a measure of the aerosol loading in the atmosphere.

The objective of this paper is to report data on the Unsworth-Monteith attenuation coefficient along with the well-known Linke turbidity factor, for an urban area. The Unsworth-Monteith factor is calculated from radiation observations in Athens, a city with air pollution problems. The trend of the time series of the attenuation coefficients is examined. Finally, the dependence on aerosol amount of the ratio of diffuse to global solar irradiance in the total waveband is discussed.

2. Evaluation of turbidity

a. Theoretical background

The aerosol attenuation coefficient of Unsworth and Monteith (1972) is used to measure turbidity in this study. It is derived from the Lambert–Bouguer law,

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which defines the spectral flux density of direct beam solar radiation $I(\lambda)$ after attenuation by the atmosphere as

$$I(\lambda) = I_0(\lambda)\exp\{-[\tau_R(\lambda) + \tau_O(\lambda) + \tau_W(\lambda) + \tau_\alpha(\lambda)]m\}, \quad (1)$$

where $I_0(\lambda)$ is the flux density at wavelength λ received at the top of the atmosphere by a plane normal to the solar beam; m is the optical air mass; and $\tau_R(\lambda)$, $\tau_O(\lambda)$, $\tau_W(\lambda)$, and $\tau_\alpha(\lambda)$ are spectral optical depths for Rayleigh scattering, ozone absorption, water vapor absorption, and aerosol attenuation, respectively. Equation (1) can be written as

$$I(\lambda) = I^*(\lambda)\exp[-\tau_\alpha(\lambda)m], \quad (2)$$

where $I^*(\lambda)$ is the flux density beneath an aerosol-free atmosphere. The Unsworth and Monteith aerosol attenuation τ_A is a weighted mean aerosol optical thickness defined by

$$\exp(-\tau_A m) = \frac{\int I^*(\lambda)\exp[-\tau_\alpha(\lambda)m]d\lambda}{\int I^*(\lambda)d\lambda}. \quad (3)$$

It is calculated from

$$\tau_A = -\frac{1}{m}\ln\left[\frac{I(\lambda)}{I(0)}\right], \quad (4)$$

where $I(\lambda)$ is measured direct beam flux density for the whole spectrum and $I(0)$ is the spectrally integrated value of $I^*(\lambda)$. In the following, the attenuation coefficient τ_A will be referred to as T_{UM} for practical reasons.

b. Database and procedures

For the study of the attenuation coefficient in Athens, long-term pyrheliometric measurements for the period 1954–91 were used. The observations were performed at the National Observatory of Athens (NOA) at 0820, 1120, 1420, and 1720 LST (LST is 2 h ahead of UTC), whenever clouds were not present in the sight path. In the present analysis, only measurements of 1120 and 1420 were used, since measurements from 0820 and 1720 are scarce, especially during the winter months. In addition, the corresponding air masses at these hours are of the same order. This was done in order to avoid the effects caused by different air masses on the turbidity coefficient.

The instruments used were Linke–Feussner pyrheliometers equipped with Schott filters OG530, RG630 (formerly RG2), and RG695 (formerly RG8), measuring radiation above cutoff wavelengths of 0.525, 0.630, and 0.710 μm, respectively. A quartz filter was also used with a nominal cutoff wavelength of approximately 0.250 μm (Iqbal 1983). More details on the instrumentation and data used can be found in Jacovides et al. (1993). An Eppley PSP radiometer was used for measuring total global irradiance (GLOB). It must also be noted that the diffuse irradiance (DIF) was calculated from the difference between the corresponding values of the global and direct (DIR) beam component of solar irradiance on a horizontal surface under the restriction that this difference indicated a positive value of diffuse irradiance. In the following, the turbidity parameters and related quantities are considered on a daily and a monthly basis.

Furthermore, the normal incidence irradiance at the earth's surface through a dust-free atmosphere with a specified water vapor content—that is, $I^*(\lambda)$—is calculated following the Bird and Hulstrom (1981) formulation:

$$I^*(\lambda) = 0.975 S\tau_R\tau_O\tau_W\tau_G, \quad (5)$$

where S is the solar constant corrected for departure of the sun–earth distance from the mean value. For completeness, the various transmittances and other related quantities are listed below.

The transmittance by Rayleigh scattering τ_R is given by (Iqbal 1983)

$$\tau_R = \exp[-0.0903 m_\alpha^{0.84}(1 + m_\alpha - m_\alpha^{1.01})], \quad (6)$$

where m_α is the air mass, duly modified by the station pressure,

$$m_\alpha = m_r\left(\frac{P}{P_0}\right) \quad (7)$$

with m_r the relative optical air mass given:

$$m_r = [\sin h + 0.15(h + 3.885)^{-1.253}]^{-1} \quad (8)$$

(Kasten 1965), where h is the solar altitude. The transmittance by ozone is as follows (Hay and Darby 1984):

$$\tau_O = 1 - \frac{0.00212X}{(1. + 0.0042X)} - 0.013X^{0.195}, \quad (9)$$

where $X = 3.5\ m_r$. The transmittance by water vapor is given as (Hay and Darby 1984),

$$\tau_W = 1 - \left(2.03 + \frac{8.5}{W^{0.365}}\right)^{-1} \quad (10)$$

with

$$W = m_r\left(\frac{1013}{P}\right)^{0.75} W_C \quad (\mathrm{mm}), \quad (11)$$

where W_C is the sea level water content (mm), which is calculated through the equation (Linacre 1992)

$$W_C = \exp(2.25 + 0.0545 T_d), \quad (12)$$

where T_d is the surface dewpoint temperature.

The transmittance by uniformly mixed gases, essentially O_2 and CO_2, is defined by (Iqbal 1983)

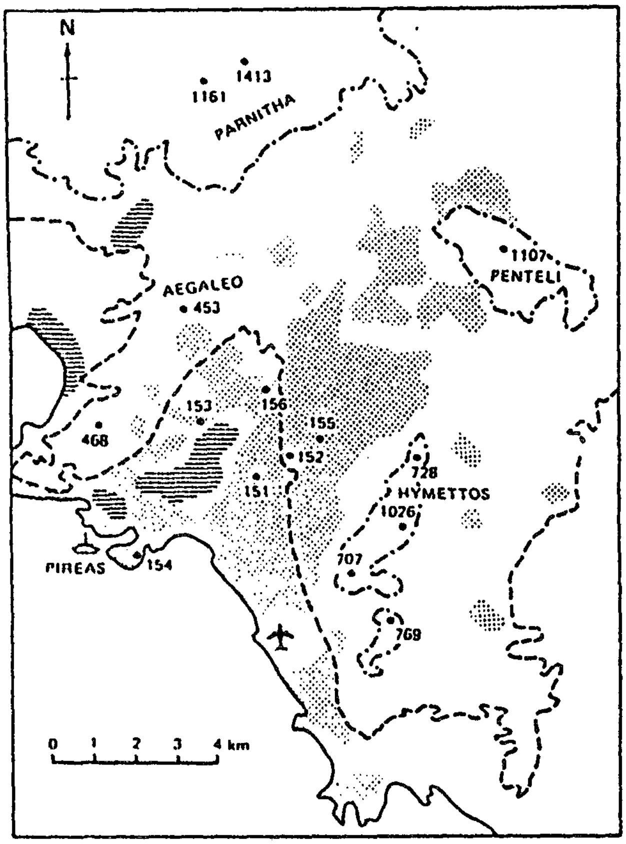

FIG. 1. Map of the Athens basin. Residential areas are indicated by stippling and industrial areas by cross-hatching. The peaks of major mountaineous areas and their elevations in meters as well as the 100-m (dashed line) and 500-m (dot–dash line) contours are also indicated.

$$\tau_G = \exp(-0.0127 m_\alpha^{0.26}). \qquad (13)$$

In the analysis of these data no T_{UM} values greater than 1 were found.

3. Results and discussion

a. Site's climatology

Before proceeding further with the results, it is desirable to discuss briefly the weather conditions and the air quality of the Athens basin. As shown in Fig. 1, the city of Athens (and its suburbs) is located in a basin surrounded by mountains from three directions and open to the sea from the fourth. The main axis of the basin is south-southwest to north-northeast and is approximately 27 km in length. Its width is approximately 17 km. There are three main mountains, Hymettus to the east, Pendeli to the north-northeast, and Parnitha to the north-northwest with elevations up to 1400 m. The opening of the basin to the sea is from south toward Saronic Gulf. The population of the urban areas within the Athens basin is approximately 3.6 million. The rapid expansion of the city during the last 30 years was not followed by the parallel development of the necessary infrastructure (road network, parks, etc.). The most important source of air pollutants is the heavy traffic (Kallos et al. 1993). More than 1 million registered vehicles operate in the region. The main industrial zones are located in the south-southwest edge of the city of Athens while a considerable number of industrial installations are also located north-northwest of Parnitha. Some other sources are located in the harbor of Pireus, while the contribution of air pollutants from ships, aircraft, and central heating during the cold months, cannot be negligible.

Regarding climate, the Athens basin has a typical Mediterranean climate with hot dry summers and wet mild winters. The daily mean temperature in the winter is 10°C and in summer 26°C. The annual mean rainfall is about 420 mm. The most usual rainfalls occur between October and May. The relative humidity varies from 43% (June) to 71% (December). Owing to the orientation of the Athens basin and the mountains surrounding it, the flow field shows a preference in two directions: one from the north or northeast (mainly during winter and late summer) and the other from the southwest (during spring and early summer). Northerly winds are usually strong and favor the ventilation of the Athens basin (Kallos et al. 1993).

b. Presentation of the results

Following Unsworth and Monteith (1972), the attenuation coefficient T_{UM} is correlated with the well-known Linke turbidity factor T_L. This is done for two reasons: (i) both of them can be determined from unfiltered pyrheliometric measurements of normal-incidence direct solar irradiance, and (ii) both are functions of air mass number. Figure 2 shows the variation of

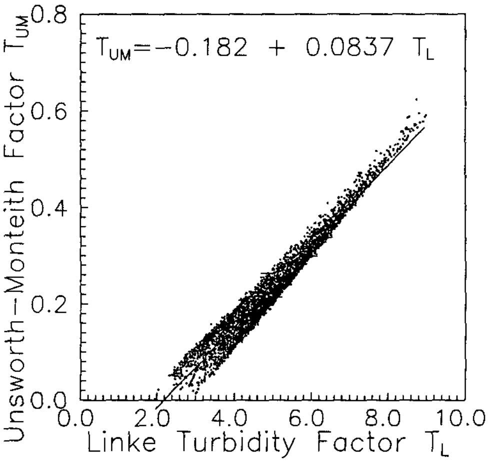

FIG. 2. Dependence of the attenuation coefficient T_{UM} on the Linke turbidity factor T_L.

the Unsworth–Monteith coefficient T_{UM} with the Linke factor T_{L} for all the air masses encountered and for all the data points. The straight line is a regression line with equation

$$T_{\mathrm{UM}} = -0.182 + 0.0837T_{\mathrm{L}} \qquad (14)$$

or

$$T_{\mathrm{L}} = 2.32 + 11.44T_{\mathrm{UM}}. \qquad (15)$$

Equation (14) has a correlation coefficient $R^2 = 0.989$. Unsworth and Monteith (1972) gave a diagram (Fig. 1 in their paper) with T_{L} against T_{UM} for $m = 1, 3, 5$, from which the following equation can be derived (for $m = 1$):

$$T_{\mathrm{L}} = 2.85 + 11.50T_{\mathrm{UM}}. \qquad (16)$$

Comparing (15) and (16) it is seen that the slopes and the intercepts compare well. This is due to the fact that the data used in the present analysis, midday observations, correspond to an air mass ≤ 2, as can be seen from Table 1.

Mean monthly values of T_{UM} and T_{L} and their standard deviations (SD) are given in Table 1. An annual cycle is evident for both coefficients, with minimum and maximum values in winter and summer, respectively. The annual variation of turbidity parameters in Athens is related to weather conditions around the year. During winter, frequent rains remove from the atmosphere a considerable amount of aerosols by rainout and washout. The steady decrease of turbidity coefficients toward the end of late summer period is attributed to the diffusion mechanisms, whose effectiveness increases with velocity (Lalas et al. 1983). During late summer (August–September), the prevailing winds (Etesians) increase in frequency and intensity (Karalis 1976). The abrupt reduction of turbidity in September is due to the rains observed at the end of this month after a long period of dryness. Generally, throughout the year T_{UM} levels in Athens are higher than those reported by Rawlins and Armstrong (1985) for various locations in Britain. Similar cycles of the attenuation coefficient T_{UM} in various locations have been reported in the past (Peterson et al. 1981; Flowers et al. 1969). From Table 1, it can also be seen that the values of SD are relatively high compared to the mean values. These high deviations can be attributed not only to the influence of the local climatic conditions or astronomical factors and other natural phenomena, but also to the rapid development of the city of Athens. In a previous study, Jacovides et al. (1993) reported that the various spectral wavebands under clear skies showed a pronounced decline through the period 1966–90, which was attributed to the degradation of air quality of the city. This implies that the T_{UM} and T_{L} must have increased during the same period. Therefore, it becomes obvious that the determination of the long-term variation of T_{UM} and T_{L} as an indication of the increase of the aerosol concentrations in the atmosphere of the Athens basin is of particular interest. In Figs. 3a–d, the time series of the monthly mean T_{UM} and T_{L} values are shown as they are estimated from monthly data for the period 1954–91. The dataset was broken down in four periods in order to detect some characteristics related to the rapid development of the city of Athens. In addition, smoothing the data by using a simple moving average for both turbidity factors is also shown. The salient features of these figures are the following.

(a) Both the turbidity coefficients increase gradually from the beginning of the examined period, 1954, until approximately 1978, remaining constant until 1985; a slightly decreasing tendency seems to exist for the remaining period. These long-term variations of the attenuation coefficients in Athens might be due to the rapid increase of the number of circulating vehicles and industrial activity in this period.

TABLE 1. Monthly statistics of Unsworth–Monteith factor T_{UM}, Linke factor T_{L}, and airmass numbers.

Month	T_{UM}	SD*	T_{L}	SD*	m (1120 LST)	m (1420 LST)
Jan	0.149	0.078	3.64	0.906	2.079	2.287
Feb	0.163	0.086	3.83	0.959	1.729	1.831
Mar	0.219	0.107	4.48	1.108	1.355	1.456
Apr	0.205	0.102	4.69	1.151	1.175	1.266
May	0.237	0.108	5.13	1.139	1.090	1.180
Jun	0.250	0.111	5.39	1.150	1.066	1.138
Jul	0.265	0.113	5.47	1.212	1.109	1.168
Aug	0.247	0.107	5.44	1.138	1.139	1.214
Sep	0.192	0.088	4.55	1.031	1.259	1.410
Oct	0.234	0.101	4.95	1.039	1.482	1.763
Nov	0.185	0.074	4.05	0.846	1.859	1.987
Dec	0.144	0.056	3.59	0.624	2.162	2.576
Annual	0.209	0.095	4.90	1.271	1.458	1.606

* Standard deviation.

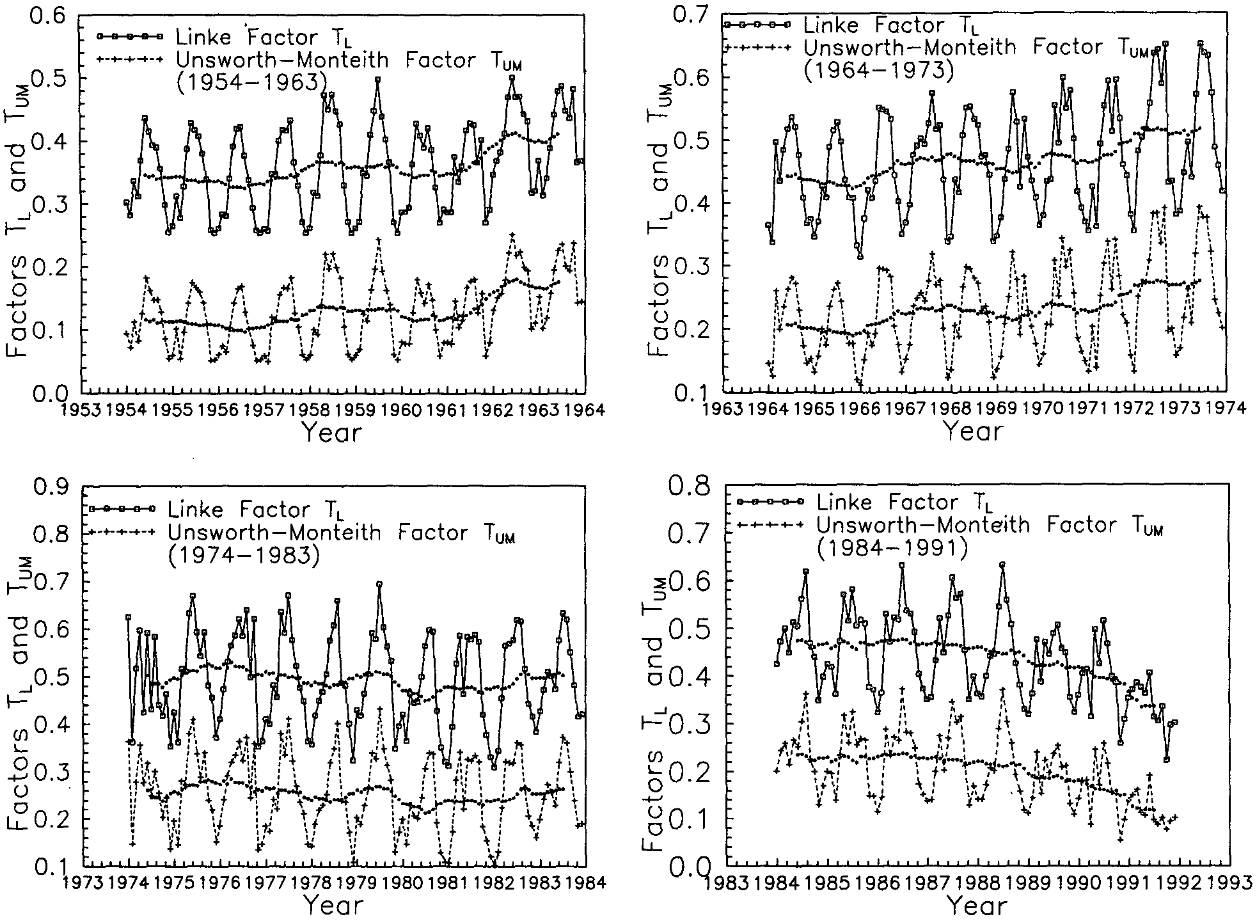

FIG. 3. Time series of the monthly mean values of the turbidity coefficients T_L (solid line) and T_{UM} (dashed line) together with the moving window average values (dot lines). The window extends 11 points leftward and rightward, for a total of 23 points. Here, T_L values have been divided by 10: (a) for the 1954–63 decade; (b) for 1964–73 decade; (c) for 1974–83 decade; and (d) for 1984–91 period.

(b) From the individual points of the turbidity factors, one can see their annual trend for each individual year. In addition, it is clear that the attenuation coefficients tend to decrease slightly after the mid-eighties. This fact is probably due to the restrictions that were imposed on the sources of emission. For instance, restrictions on the circulating vehicles were imposed in the downtown area of Athens during the working day. Additionally, a gas producing unit, about 2 km from the center of the city was removed in 1985. This unit was located in approximately 1 km from the NOA station.

(c) Intercomparison between the figures reveals that the turbidity levels of the second period are higher than those of the first one. This increase in turbidity levels can be attributed to the urbanization of the city of Athens during the 1960s. The levels of the third decade are higher than that of the second period. During this decade, new industrial units in the western and northern vicinities of the city were established. This fact resulted in increasing atmospheric turbidity levels. Finally, in case of the period 1984–91, the turbidity levels become lower than the previous two decades. However, the levels are still higher than those of the first decade. This decade is characterized by the increasing number of air pollution episodes.

Viewing the figures, it is obvious that the air quality of the atmosphere has deteriorated in the period 1960–85. Due to the actions taken during the last decade, slight improvement started to appear during the last few years. The T_{UM} and T_L values decreased throughout the 1985–91 period. There is a need for further investigation of this feature.

Furthermore, some additional conclusions should be drawn from the correlation between the attenuation coefficient T_{UM} and the ratio of diffuse to global solar irradiance (DIF/GLOB). There is evidence that this fraction depends both on solar zenith angle and on atmospheric turbidity (Dogniaux and Doyen 1968;

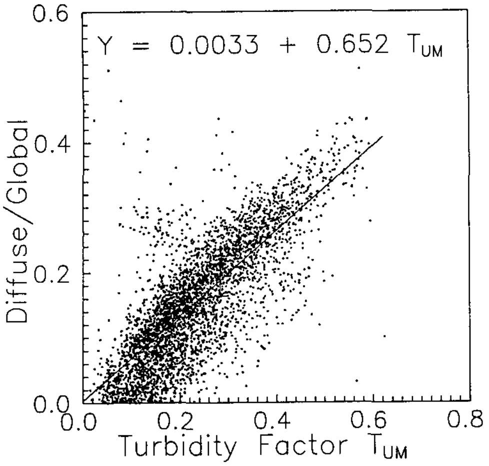

FIG. 4. Variation with T_{UM} of the ratio DIF/GLOB, on cloudless days.

Unsworth and Monteith 1972). Dogniaux and Doyen, showed that the fraction of diffuse to global solar radiation could be linearly related to Linke's turbidity factor T_L at fixed air masses. Unsworth and Monteith showed that for zenith angles less than 60°, the relationship between DIF/GLOB and the attenuation coefficient T_{UM} was well fitted by a straight line. The ratio DIF/GLOB was calculated from midday observations made under clear skies. Figure 4 shows this ratio, and the points were fitted by the regression line

$$\frac{\mathrm{DIF}}{\mathrm{GLOB}} = 0.0033 + 0.652T_{UM} \tag{17}$$

with a correlation coefficient $R^2 = 0.856$.

The scatter of points may reveal differences in aerosol size distribution. Equation (17) predicts that as the aerosol content tends to zero, the ratio DIF/GLOB should tend to 0.0033. The corresponding theoretical ratio is 0.072 for a model atmosphere containing 2 cm of precipitable water. A similar relationship was reported by Unsworth and Monteith (1972).

4. Concluding remarks

There is a growing worldwide interest in atmospheric turbidity as this is related to air pollution studies and because of its wider significance in tropospheric chemistry, climate studies, and in solar energy applications. From the overall analysis the principal conclusions are as follows.

1) The Unsworth and Monteith attenuation coefficient T_{UM} was obtained from spectral measurements of radiation. It has shown that minimum turbidity levels occur in the winter and maximum levels in the summer. This is attributed to the synoptic conditions (stronger winds, rain), which have a cleansing effect on the atmosphere. A similar cycle is observed for the Linke turbidity factor T_L.

2) The relation between T_{UM} and T_L was found to be linear with a correlation coefficient of the order of $R^2 = 0.989$. This relation is almost similar to that of Unsworth and Monteith (1972) for the British Midlands.

3) From the long-term variation of the atmospheric turbidity coefficients, some interesting information on the time evolution of the air quality for a longer period in the past can be drawn indirectly.

4) Finally, the variation of the ratio of diffuse to total global radiation (DIF/GLOB) is investigated and the results agree with that reported in Unsworth and Monteith (1972).

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