PARAMETERS OF ATMOSPHERIC TURBIDITY IN ATHENS AND THESSALONIKI

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The atmosphere over big Greek cities, especially Athens and Thessaloniki, has been recently burdened extensively by solid and gas aerosols. This has been the effect of the inadequate town planning and the climatological conditions in the area, in combination with the morphology relief surrounding these cities.

In Athens the Linke turbidity factor is less than 5 only during a few days around the year. In Thessaloniki the same factor has values greater than 5 at a very large percentage only during the warm semester. The picture of the Angström turbidity coefficient is the same. The Angström wavelength exponent shows that solid aerosols of small size are predominant in Thessaloniki, while large aerosols are predominant in Athens. The study of the Linke turbidity factor for specific spectral bands has led to the same conclusions.

1. INTRODUCTION

In recent years the atmosphere over highly populated Greek cities, such as Athens and Thessaloniki, has been significantly polluted by solid and gas aerosols. This has obviously been the effect of the large population living in narrow streets where the traffic is very heavy, and the fact that large and small industrial units are installed very near or even inside the cities. It should be mentioned here that the population of Athens and Thessaloniki are four millions and one million, respectively. The atmospheric pollution is also influenced by the morphology relief surrounding the cities, in combination with the climatological conditions predominant in the major city area.[1] The level of the pollution in Athens is so high that it is no longer possible for the atmosphere to clean itself.[2]

In the present paper an attempt is made to give an account of the atmospheric pollution in Athens and Thessaloniki by means of parameters whose values depend upon the direct solar radiation measured in the city centres. That is, based on the depletion of direct total and spectral solar radiation, we will give an account of the magnitude of atmospheric pollution, especially by solid aerosols.

2. DATA AND METHOD

The data used for the estimation of the appropriate parameters are essentially measurements of direct solar radiation taken at the National Observatory of Athens (λ = 23°43' E, φ = 37°58' N, and H = 107 m) and at the Solar Radiation Measuring Station of the Aristotelian University of Thessaloniki (λ = 22°57' E, φ = 40°37' N, and H = 47 m). Measurements refer to the 1986–1990 period. The Athens measurements were the ones taken at 11.20 local time, while the Thessaloniki measurements were the ones taken between 11.00 and 14.00 local time.

The estimation of atmospheric pollution, mainly by solid aerosols, was made using two parameters. These are the Linke turbidity factor and the Angström turbidity coefficient. The values of these parameters were estimated for the whole of the spectrum as well as for certain spectral bands of special interest. The spectral bands for which we estimated the Linke turbidity factor are the 300–525 nm, the 525–630 nm, the 630–710 nm, and the 710–2700 nm. For this purpose, we used values of direct solar radiation measured with filters: Quartz, OG1, RG2, and RGB. The first and the third spectral bands have also been used for the estimation of the Angström turbidity coefficient and wave turbidity exponent.

The estimation of the Linke turbidity factor was made based on the following background.[3,4] In a clear atmosphere, that is, one without water vapour, dust, haze, and other absorbers, the depletion of direct solar radiation is described by the Rayleigh scattering coefficient σ_λ given by the relation:

$$\sigma_\lambda = 0.00879\ \lambda^{-4.09}\ . \tag{1}$$

Therefore, direct solar radiation reaching the ground, travelling through optical mass m, is given by the relation

$$I_r = \int_0^\infty I_{0\,\lambda}\ 10^{-\alpha}\ d\,\lambda\ , \tag{2}$$

where $\alpha = \sigma_\lambda m$. On the contrary, in a really turbid atmosphere the direct solar radiation reaching the ground, travelling through optical mass m, will be given by the relation

$$I = I_0\ 10^{-m\,\sigma(m)\,T}\ , \tag{3}$$

where T is the Linke turbidity factor, $\sigma(m)$ the mean depletion coefficient of direct solar radiation throughout the spectral band. It follows that the turbidity factor T will be given by the relation

$$T = P(m)\ [\log I_0 - \log I - 2 \log D]\ , \tag{4}$$

where $P(m) = [m\,\sigma(m)]^{-1}$ which can be calculated from the relation[5]

$$P(m) = 22.64\ m^{-0.801}, \qquad \text{for } 1 \le m \le 4\ , \tag{5}$$

and D is the sun–earth distance at the moment of measurement, in astronomical units. The turbidity factor T

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shows the number of clear atmospheres causing the same decrease as the real atmosphere.

The estimation of the Angström turbidity coefficient and the estimation of the wave exponent were also made based on the following background.[6,7]

An effective wavelength λ_{eff} corresponds to each spectral band. Therefore, the intensity I of the direct solar radiation for a spectral band recorded by a pyrheliometer for optical mass m can be expressed by the relation

$$I = I_0 \exp\left[-\frac{\beta_m}{\lambda^{-1.3}}\right], \tag{6}$$

where I_0 is the irradiance power at the upper boundary of the atmosphere, λ is the effective wavelength, and β is the Angström turbidity coefficient for the spectral band.

For the 300–525 nm band the effective wavelength is 455 nm and the irradiance power is 313 W/m^2. For the band 630–710 nm the effective wavelength is 669 nm and the irradiance power is 127 W/m^2. Based on relation (6) we estimated the coefficients β_1 and β_2 of the bands 300–525 nm and 630–710 nm, respectively. Finally, by the relation

$$\log(\beta/\beta_2) = 1.041 \log(\beta_2/\beta_1) \tag{7}$$

we estimated the true β coefficient of the atmosphere. Also based on coefficients β_1 and β_2, we estimated the wavelength exponent α from the relation

$$\alpha = 1.3 - 5.94 \log(\beta_2/\beta_1)\,. \tag{8}$$

Values of the wavelength exponent should vary between 1.0 and 2.0, according to Junge's theory. In practice though, we found values greater than 5.0 when the predominant size of solid aerosols in the atmosphere was very small. Negative values of the wavelength exponent have been found in the case of very large size of solid aerosols predominating in the atmosphere.

3. TURBIDITY COEFFICIENTS IN ATHENS AND THESSALONIKI

Using relations (4) and (5) we estimated the values of the Linke Turbidity Factor T (LTF) for the total spectrum as well as for the spectral bands 300–525 nm, 525–630 nm, 630–710 nm, and 710–2700 nm.

The annual variation of LTF is exhibiting its maximum during the warmer months. This fact is expected since during these months the climatological conditions predominant in the major geographical area of the Greek mainland, favour the accumulation of large quantities of solid aerosols in the atmosphere. The frequent anticyclonic situations or situations with very small horizontal temperature gradient are characteristic of the summer climate in Greece. Another characteristic fact is that rainfalls in Greece are very rare during the summer. The mean monthly values of the LTF are high both in Athens and Thessaloniki. The mean monthly values in Athens are, on average, higher than the corresponding values in Thessaloniki, by approximately 2 units. In Athens, the mean monthly values are higher than 5 during all months of the year. On the contrary, in Thessaloniki, the mean monthly values are greater than 5 only during the May–October semester (Table I). July is the month with the highest mean value of LTF, which reaches 9 in Athens and 6.5 in Thessaloniki. In Athens, during the winter, there are days with LTF values lower than 5 and there are no days with LTF less than 3. During the summer there are no days with LTF value less than 5 (Table II). In Thessaloniki, during the winter, 20% of the days have LTF values less than 3. From October to April though, the largest percentage of days have LTF values less than 5. It means that in Thessaloniki, during this period, there are 15 days per month with values of LTF less than 5. The most unfavourable day in Athens, during the studied period, appeared in May with LTF value 12.7. In Thessaloniki it appeared in July with value 10.5.

Comparing the mean monthly values of LTF in Athens during the 1963–1972 period[8,9] with the corresponding values of the period under study, we find that in Athens today, the values of LTF are increased by at least 2 units during the winter and by 3 units during the summer. The turbidity of the atmosphere in Athens during the 60s was slightly less than the one predominating today in Thessaloniki. There are no data showing the turbidity of the atmosphere over Thessaloniki before the period under study, so we cannot make comparisons as in the Athens case.

The coefficient of variation of LTF values in Athens is approximately 12–13%, while in Thessaloniki about 20% (Table I). It seems that atmospheric turbidity in Athens exhibits greater stability than in Thessaloniki.

TABLE I. Statistical analysis of the Linke turbidity factor (T) values.

	January	February	March	April	May	June	July	August	September	October	November	December
Mean Values												
Athens	5.67	6.38	7.58	7.86	8.21	8.11	8.85	8.41	7.98	7.33	6.15	5.64
Thessaloniki	3.88	4.64	4.98	4.74	6.07	5.84	6.53	6.14	5.70	5.02	3.64	3.49
Difference	1.79	1.74	2.68	3.12	2.14	2.27	2.32	2.27	2.28	2.31	2.51	2.15
Coefficient of Variation (%)												
Athens	12.3	12.4	16.9	14.2	15.4	12.0	12.4	12.9	12.6	16.7	14.8	9.4
Thessaloniki	23.6	18.6	20.3	24.3	16.4	20.0	20.1	19.8	17.8	21.0	22.0	14.8
Maximum Values												
Athens	7.7	7.8	11.5	11.3	12.7	10.5	11.7	10.9	11.1	11.5	9.4	7.1
Thessaloniki	6.2	6.9	8.0	7.8	8.9	10.3	10.5	9.2	7.4	7.1	6.1	5.1
Minimum Values												
Athens	4.6	5.0	5.7	6.2	6.3	5.7	6.2	5.6	5.8	4.9	4.6	4.6
Thessaloniki	2.0	2.7	2.3	3.2	4.2	4.2	4.3	4.0	3.1	3.1	2.5	2.1

Comments: coefficient of variation = standard deviation / mean value

TABLE II. Distribution (%) in classes of the Linke turbidity factor (T) values.

						ATHENS						
T	January	February	March	April	May	June	July	August	September	October	November	December
3												
	10									1	3	9
5												
	84	75	30	27	16	13	5	8	18	48	91	89
7												
	6	25	57	49	58	70	50	62	67	42	3	2
9												
			11	22	23	17	41	30	14	8	3	
11												
			2	2	3		4		1	1		
						THESSALONIKI						
T	January	February	March	April	May	June	July	August	September	October	November	December
	19	3	3							1	25	18
3												
	67	65	51	64	19	30	14	20	31	54	69	81
5												
	14	32	45	29	60	52	49	53	52	43	6	1
7												
			1	7	21	17	35	25	17	2		
9												
						1	2	2				
11												

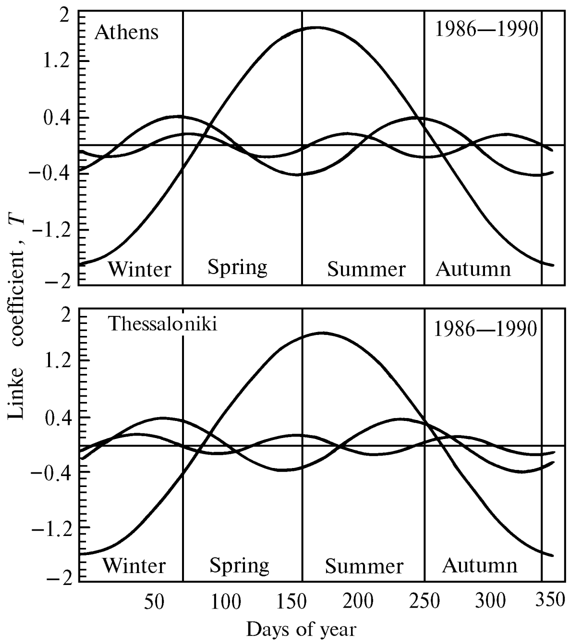

FIG. 1. Harmonic analysis of the annual variation of the Linke turbidity factor T (first three harmonics).

In order to discover more differences between values of the Linke turbidity factor, observed in Athens and Thessaloniki during the examined period, we have performed the harmonic analysis[10] of the mean values of LTF for the 73 five–day periods of the year for both cities. Five day periods were used because of some missing daily solar radiation values. An analysis has yielded the following information for the first three harmonics (Fig. 1). The amplitudes of the corresponding harmonics, for the two cities, are almost equal. In the Athens case, the first three harmonics accounted for the total variance of the LTF at 85%, 5%, and 1% percentages respectively for each harmonic. In the Thessaloniki case, these percentages were 81%, 5%, and 1%. In the Athens case harmonics reach their maximum values on the 2nd of July, the 17th of March and the 25th of March. The corresponding dates for Thessaloniki are the 5th of July, the 5th of March, and the 14th of February. These dates are within a five day approximation. Therefore, differences between LTF values observed in Athens and Thessaloniki mainly depend upon constant factors such as human activity and at a much smaller percentage upon interannual variations caused by factors such as atmospheric circulation in the Greek area.

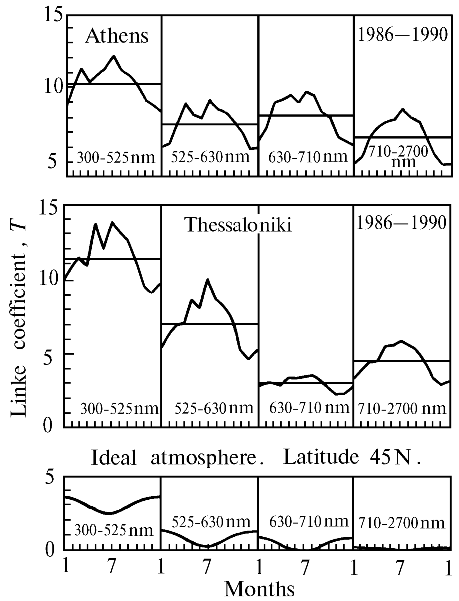

FIG. 2. Annual variation of the Linke turbidity factor T for four spectral bands.

Comparing the mean monthly values of the LTF factor for the above spectral bands, it is found that its values, in the 300–525 nm band (first band), are very high both in Athens and Thessaloniki, the latter being slightly higher than the former (Fig. 2). In the second and third bands, LTF values for Athens are almost the same or lower by 2 units than the corresponding values of the first band. On the contrary, in Thessaloniki, in the second spectral band, LTF values are lower than the corresponding values of the first band by 4 units, and higher by 4 units than the values observed in the third band. It should be mentioned that the values of the LTF in the third spectral band are very small (2.5–3.5 units), compared to the LTF values of other bands and LTF values of the same band in Athens.

Concerning LTF values of the 4th spectral band, we observe that between Athens and Thessaloniki there is a 2.5 unit difference, which is probably due to the solid aerosols only, since the mean value of precipitated water in the two cities is almost the same.

From the study of LTF values it is found that, in Athens, they appear to have a slight decreasing order from the first to the last spectral band. That is, in Athens, the atmosphere has a uniform behaviour at least for the visible band of the solar spectrum. On the contrary, in Thessaloniki, LTF values exhibit an intense decrease going from the first to third band. This means that in the atmosphere of this city, most solid aerosols have very small size. In Athens the situation is reverse. In Athens, the coefficient of variation of LTF values exhibits uniformity in the visible band of the solar spectrum (Fig. 3) with maximum value in March. In Thessaloniki, in the visible part of the spectrum, we observe a continuous increase of the variation coefficient going from small to large wavelengths. Highest values are observed in April (coefficient of variation is the fraction: standard deviation/mean value). Values of LTF are also given in a Rayleigh atmosphere (Fig. 2) to give another measure of atmospheric pollution.

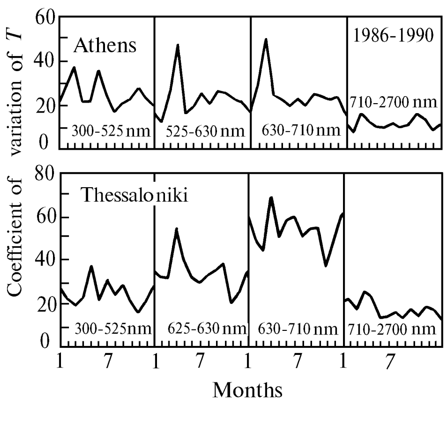

FIG. 3. Annual variation of the coefficient of variation of the Linke turbidity factor T for four spectral bands.

4. THE ANGSTRÖM TURBIDITY COEFFICIENTS

Using relation (6) we have estimated the turbidity coefficients β_1 and β_2 which express the turbidity of the atmosphere for the 300–525 nm and 630–710 nm bands, respectively. Using relation (7) we estimated the true AngstrЧЫm turbidity coefficient β for the 300–710 nm band. Finally, using relation (8) we estimated the wavelength exponent α for the same band.

An analysis of the results shows that values of β_1 in Thessaloniki are slightly larger than the values of β_1 in Athens, especially during the warm semester. On the contrary, β_2 values in Athens are double the ones in Thessaloniki during the cold semester and three times greater during the warm semester (Fig. 4). The same fact is confirmed by the values of LTF in the first two spectral bands.

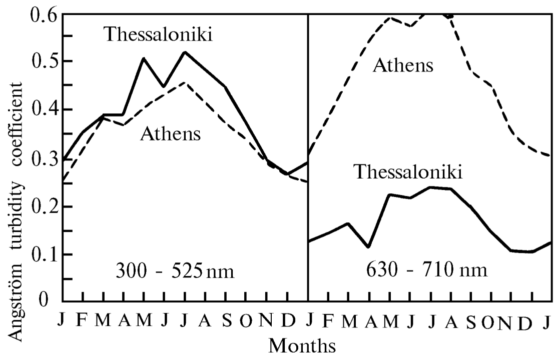

FIG. 4. Annual variation of the Angström turbidity coefficients β_1 and β_2.

The true Angström coefficient of turbidity β in Thessaloniki exhibits generally low values, almost throughout the year (Fig. 5). In Athens, this coefficient has much greater values which, during the summer, become double the ones during the winter. In Thessaloniki, the values of β vary between 0 and 0.2 (Table III) at a percentage greater than 80%. In Athens, the β values exhibit a very large dispersion. Therefore, during the winter, they vary between 0.2 and 0.6, while during the summer vary beyond 0.8 at a percentage greater than 50%.

The wavelength exponent α has very small values in Athens and very large values in Thessaloniki. In Athens the wavelength exponent is negative in many occasions (Table IV). In January, the percentage of days with negative wavelength exponent values is 5%, while in June 32%. In Thessaloniki, days with negative exponent values are very rare.[11] The largest percentage of values of the wavelength exponent is between 0 and 2 for Athens and 2 and 6 for Thessaloniki.

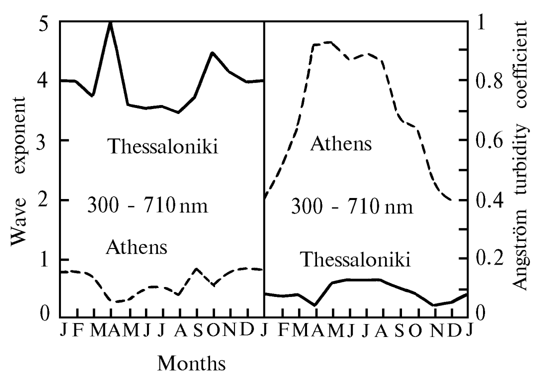

FIG. 5. Annual variation of the true Angstöm turbidity coefficient β and the Angström wavelength exponent α.

TABLE III. Distribution (%) in classes of the true Angström turbidity coefficient β values.

ATHENS												
β	January	February	March	April	May	June	July	August	September	October	November	December
	10		11			3	4		4		6	4
0.2												
	44	42	7	9	2	5	1	2	7	14	29	50
0.4												
	38	38	22	9	11	13	8	7	22	40	59	38
0.6												
	8	10	33	33	27	17	23	36	43	21		8
0.8												
			22	27	27	18	29	24	15	19		
1.0												
		10	4	21	33	43	35	30	9	7	6	
THESSALONIKI												
β	January	February	March	April	May	June	July	August	September	October	November	December
	92	95	95	99	86	85	83	87	92	96	100	93
0.2												
	3	3	4	1	10	10	14	9	7	3		7
0.4												
	4	2	1		3	3	2	4	1			
0.6												
					1		1					
0.8												
						1						
1.0												
	1					1				1		

TABLE IV. Distribution (%) in classes of the Angström wavelength exponent α values.

ATHENS												
α	January	February	March	April	May	June	July	August	September	October	November	December
	5	10	22	30	29	32	16	16	10	14	6	4
0												
	87	85	67	64	69	62	79	84	84	84	94	92
+2												
	8	5	11	6	2	3	4		3	2		4
+4												
						3	1		1			
+6												
									1			
THESSALONIKI												
α	January	February	March	April	May	June	July	August	September	October	November	December
	1					1				1		
0												
	6	5	6		7	8	5	6	6	5		10
+2												
	41	62	58	30	62	65	72	77	62	51	55	39
+4												
	45	25	30	45	29	18	19	13	24	28	36	41
+6												
	7	8	6	25	2	8	4	4	8	15	9	10

The different values of β and α observed in Athens and Thessaloniki are justified by the fact that both β coefficient and α exponent depend upon the ratio β_2/β_1. In Thessaloniki, this ratio is lower than unity, while in Athens it is greater. Therefore, the decadic logarithm is negative in Thessaloniki and positive in Athens. The very large values of the wavelength exponent α in Thessaloniki are due to the fact that most solid aerosols in the atmosphere of this city have very small size. This is also confirmed by technical reports of public institutions. In Athens, the very small values of α are due to the fact that solid aerosols in this city have very large size (e.g., carbon dust).

5. CONCLUSIONS

The atmosphere over Athens is characterized by large concentrations of solid aerosols, and therefore the Linke turbidity factor T has very large values. Only few are the days of the year during which T has a value less than 5. In Thessaloniki, the situation is slightly better. In this city, during the cold semester, the percentage of days with T values greater than 5, is generally small. The picture is reversed during the warm semester with this percentage exceeding 70%. In Thessaloniki, solid aerosols create large depletion of solar radiation of the short wavelength spectral band, and small depletion in the red band of the spectrum. In Athens, the depletion of solar radiation is almost the same for all spectral bands. This is probably due to the size of solid aerosols predominant in the atmosphere of the two cities, that is, large size in Athens and small size in Thessaloniki.

The values of the true Angström turbidity coefficient β in Athens are generally high and quite dispersed, especially in summer, when 50% of the β values exceed 0.8. On the contrary, in Thessaloniki the values of β are low and 80% of them is less than 0.2. The Angström wave exponent α has small values in Athens and large values in Thressaloniki. This is also due to the different size of solid aerosols over Athens and Thessaloniki.

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