Observations and Modeling of Downward Radiative Fluxes (Solar and Infrared) in Urban/Rural Areas

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ABSTRACT

Pollutants (gaseous and aerosol) contained in urban atmospheres alter radiative fluxes at the surface. Numerous radiative models have been developed, and while few experimental data are available, results are often contradictory. We have taken measurements, over several weeks, of downward radiation (solar and infrared) over the city of Toulouse and a rural reference site. The downward IR flux was larger at the urban site by day and night (increase between 15 and 25 W m^{-2}). Attenuation of the incident solar radiation at the urban site was observed (30 W m^{-2} in the middle of the day). A radiative model enabled us to show that the IR flux increase is mainly due to higher air temperature associated with the urban "heat island." The emissivity increase due to the addition of absorbing constituents in the urban area was very weak. The attenuation of solar radiation was due to absorption by urban aerosol. Total incoming radiation (solar + infrared) was similar at the two sites by day and was slightly higher at the urban site during the night.

1. Introduction

Numerical models and experimental measurements have illustrated the effects of an urban site on the atmospheric structure (temperature and wind profiles, surface energy budget, etc.). The incoming fluxes at the surface are important parameters of the radiation budget in urban atmospheres. This paper considers only the modification of the downward fluxes at the surface of an urban area, and disregards its consequences on the thermodynamic aspects of the urban atmospheric layer.

Several urban radiative models have been developed, but their results are more or less speculative because they involve assumptions regarding overall optical properties, size distribution and concentration of the urban aerosol. The radiative flux measurements at the surface of urban areas are rather scarce, sometimes contradictory and cannot be generalized because of local conditions. Our paper presents solar (direct and diffuse) and atmospheric radiation measurements taken in the urban area of Toulouse and also at a rural reference site. Our measurements are analyzed taking into account the different parameters which can influence the radiative fluxes. We also used a radiative model in order to interpret the experimental data.

2. Radiative fluxes in an urban atmosphere

a. Incident solar radiation (0.3–4 μm)

The attenuation of the direct solar radiation is due to absorption and scattering by aerosol and gases present in the atmosphere. The amount of energy which does not reach the surface is partly used to heat the polluted layer, the remaining part being scattered into space. A strong decrease of 12% of the global radiation was observed by Rouse *et al.* (1973) over the industrial site of Hamilton, Ontario. The attenuation is lower over other urban areas: 6 to 8% in Los Angeles, California during cloudless periods (Peterson and Flowers, 1978); 1 to 4.5% in St. Louis, Missouri (Bergstrom and Peterson, 1977; White *et al.*, 1978; Peterson and Stoffel, 1980; Method and Carlson, 1982).

Some radiative models have been developed to study the modification of solar radiation by an urban atmosphere. It is important to know the aerosol parameters introduced in these models. The early radiative model of Atwater (1971) predicts absorption in a polluted atmosphere as a function of the optical properties of the aerosol. Bergstrom and Viskanta (1973) in their radiative dynamic model assume an urban atmosphere containing 100 to 300 μg m^{-3} of aerosol, 20% of which consists of carbon; they use a modified gamma size distribution (Deirmendjian, 1969) with a maximum at ~1 μm. These conditions are characteristic of strong pollution and a very absorbant aerosol; their results show an attenuation of 10–30% according to zenith angle for the total solar flux during both winter and summer periods. Welch and Zdunkowski (1976) took into account relative-humidity-dependent size distributions and refractive indices. The top of their polluted layer reached 400 m and the aerosol mass load is 700 μg m^{-3}; the size distribution is of the Junge type: $dn/dr = ar^{-\alpha}$ (with

$\alpha = 4$), the limiting radii are 0.04 and 20 μm; here again, the conditions are of heavy pollution; their results show an attenuation of solar radiation varying from 12% (for a relative humidity of 40%) to 48% (for a humidity of 95%) assuming a solar declination angle of 45°. Finally, it is interesting to compare the simulations of Bergstrom and Peterson (1977) with measurements made in the St. Louis, Missouri area. The urban layer contains aerosol, the size distribution of which follows a power law ($\alpha = 4$); the concentration is parameterized in terms of the measured optical depth at 0.5 μm. Under clear atmospheric conditions, the simulations are in good agreement with the observations. On the other hand, when haze is present, the predictions can agree with the observed values if the aerosol parameters (size distribution and refractive indices) are modified.

Finally, it can be observed that the strongest measured attenuation of the solar radiation occurs at an industrial site; over urban areas without industrial pollution, the attenuation does not exceed a few percent. The calculated attenuations depend critically on the aerosol parameters used in the models. Thus, it is important to measure simultaneously the attenuation of solar radiation and the urban aerosol parameters.

b. Incident infrared radiation (4–100 μm)

The downward longwave radiation in an urban area depends on atmospheric temperature and emissivity. Measurements taken in Montreal, Quebec during clear nights (Oke and Fuggle, 1973) show an urban–rural difference in the downward longwave flux of 7–40 W m^{-2} (2–25%). The authors explain that this increase is a result of the urban heat island. Similar results were observed by Aida and Yaji (1979) in Tokyo where the increase of the downward IR flux is ~6–10%. The measurements taken by Rouse *et al.* (1973) over the industrial site of Hamilton, Ontario and a control site showed an increase of the downward IR flux over the polluted site reaching 30% during daylight periods, with little nighttime difference.

Various authors have developed numerical simulations of the effect of the urban atmosphere composition on IR fluxes. Bergstrom and Viskanta (1973) (under the above described pollution conditions) showed an increase of ~10–20% in the surface IR flux due to aerosol. Ackerman *et al.* (1976) in considering a 1000 m thick polluted layer used the particle size distribution measured over Los Angeles, California (Whitby *et al.*, 1972). A concentration of 10^5 particles per cm^3 (measured average at Los Angeles) was found to cause an increase of 14% in the downward IR flux. An increase of 60% was obtained for a much larger pollution of 10^6 particles per cm^3. Finally, Welch and Zdunkowski (1976), with the aerosol model described above, obtained an increase in the downward IR flux from 10% (for a relative humidity of 40%) to 35% (for a relative humidity of 90%).

Thus, experimental measurements are rather scarce and essentially taken by night. These measurements have shown an increase from 5 to 20% in the downward IR flux which has been attributed to the urban heat island effect. On the other hand, the radiative models show an increase in the downward IR flux in the presence of strongly polluted layers. Thus, it appears very important to obtain measurements of downward fluxes over an urban site during both daytime and nighttime periods and to distinguish thermal effects from pollution effects on the modification of these fluxes at the surface.

3. Sites and instrumentation

Measurements presented in this paper were simultaneously taken over two sites during cloudless days. First, the urban site was located in the center of Toulouse, in a heavily populated area. The buildings' average height is ~15 m. Toulouse houses about 400 000 inhabitants in an area of 18 km^2. Second, the reference site was located in a rural area with a sparse population. Previous studies have been performed at the urban site, on vertical stability (Guedalia *et al.*, 1980) and on various pollutant sources (Lopez *et al.*, 1982) showing that: 1) the most important sources of urban aerosol are traffic and to a lesser extent combustion of heating fuel (the particle size distribution and the daily variation of concentration are shown in Fig. 1); and 2) the nighttime period is characterized by a weaker stability over the urban site due to lower surface cooling.

The measured radiative fluxes on each site are: 1) The downward solar fluxes (0.3 to 4 μm) (Kipp and Zonen pyranometers). A correction was brought to the diffuse radiation to account for the sunshield (Coulson, 1975). 2) The downward IR fluxes (4 to 100 μm) (Eppley pyrgeometers covered with silicon domes).

The instruments on both sites were compared with each other at two periods, May and October 1979. The accuracy of this calibration was ~0.2%. The largest error, due to reading the paper recordings, was ~5 W m^{-2} for the infrared radiation, 12 W m^{-2} for the shortwave global radiation and 8 W m^{-2} for the diffuse shortwave radiation. The measurements were carried out between May and July of 1979.

4. Radiation models

Two different models were developed involving infrared and solar radiation, respectively.

a. Infrared model

The model predicts the downward infrared flux in an atmosphere which contains gases (H_2O, CO_2 and

O_3) and aerosol particles. The spectral intensity I_ν is defined by the radiative transfer equation:

$$\mu \frac{dI_\nu}{dz} = -(K_\nu + \sigma_\nu)I_\nu + K_\nu B_\nu(z) + \frac{\sigma_\nu}{2}\int_{-1}^{1} P_\nu(\mu', \mu)I_\nu(\mu')d\mu', \quad (1)$$

where B_ν is Planck's constant; $\mu = \cos\theta$; K_ν, σ_ν are spectral absorption and scattering coefficients; and $P_\nu(\mu', \mu)$ is the scattering probability function from direction μ' to direction μ.

1) Gaseous absorption

The downward infrared flux was computed using the transmission functions of Moskalenko (1968–69) and Golubitskiy and Moskalenko (1968), which may be expressed as

$$t_\nu = \exp[-(\beta_\nu W^{m_\nu} \cdot P_e^{n_\nu})], \quad (2)$$

where W is the mass of absorbing gas, P_e is the efficiency pressure and β_ν, m_ν, n_ν are selective absorption coefficients. In the window region of the spectrum (8.5–13.5 μm), the transmission function of water vapor is given by

$$t_\nu = \exp[-(\beta_\nu W^{m_\nu} \cdot P_e^{n_\nu} + \beta_{K_\nu} W^{m_{K_\nu}} \cdot P_e^{n_{K_\nu}})], \quad (3)$$

where β_ν, m_ν, n_ν are the selective absorption coefficients and β_{K_ν}, m_{K_ν}, n_{K_ν} the absorption coefficients of the water vapor continuum. The spectral resolution is ~ 5 cm^{-1} up to 22 μm.

In order to reduce the computation time, the transmission functions of Goody (1964) were used between 22 and 100 μm with a resolution of 20 cm^{-1}.

2) Aerosol absorption and extinction

In the regions of the strong water vapor and carbon dioxide absorption bands, the effect of the aerosol may be disregarded. Thus the radiative treatment of the aerosol is confined in the 7–15 μm region.

Scattering by aerosol particles has often been neglected in the infrared spectrum. Other authors have used methods which allow the treatment of the radiative transfer equation with the scattering phase function (Ackerman *et al.*, 1976; Harshvardhan and Cess, 1978; among others). More recently, Carlson and Benjamin (1980) have proposed a simplified method which only takes into account the forward scattering peak. This method can be applied only for highly asymmetric phase functions (for example, the case of Saharan dust).

In the present study, the downward infrared radiation was obtained by ignoring the scattering integral in Eq. (1). It will be shown in the presentation of results that this simplification has little consequence on the accuracy of the computed flux. In these conditions, the downward infrared radiation at ground level is given by

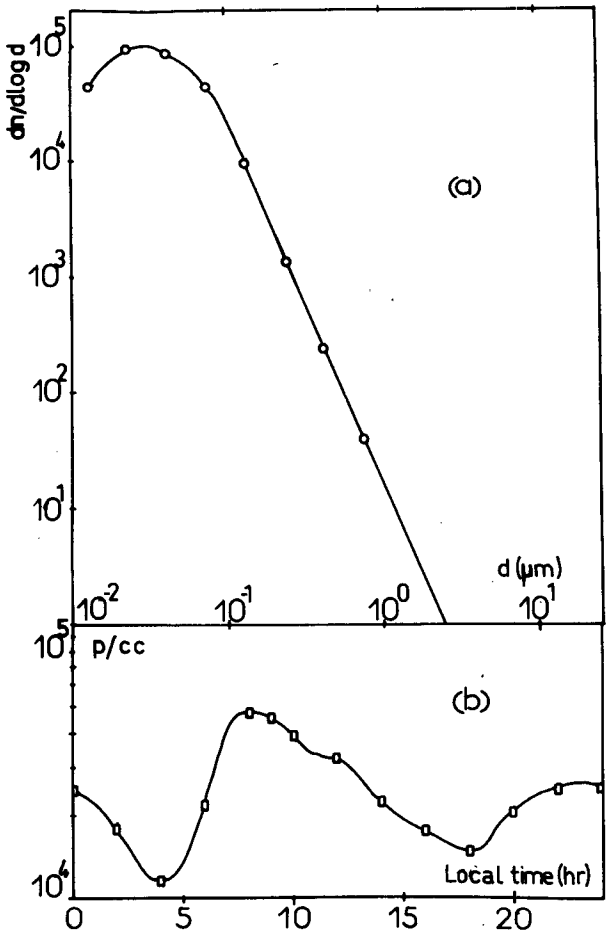

FIG. 1. Aerosol characteristics in Toulouse area: (a) Aerosol size distribution, (b) daily variation of aerosol concentration.

$$F_\nu\downarrow(0) = \int_0^\infty (1 - \omega_\nu)\pi B_\nu \frac{dT_\nu}{dz}\, dz, \quad (4)$$

where ω_ν is the single scattering albedo, and T_ν is the transmission of the atmospheric layer $(0, z)$ under an incidence arc $\cos(1/r)$; $r = 1.66$ is the diffusivity factor.

The spectral transmission of the aerosol is given by

$$t_\nu = \exp\left[-\int_0^z \int_{r_1}^{r_2} [Q_s(r) + Q_a(r)]n\pi r^2 dr dz'\right], \quad (5)$$

where Q_s and Q_a are scattering and absorption efficiency factors calculated from the Mie theory using the refractive indices discussed later; r_1 and r_2 are the limiting radii of the particle size distribution and $n(r)$ is the number of particles per unit volume at level z'.

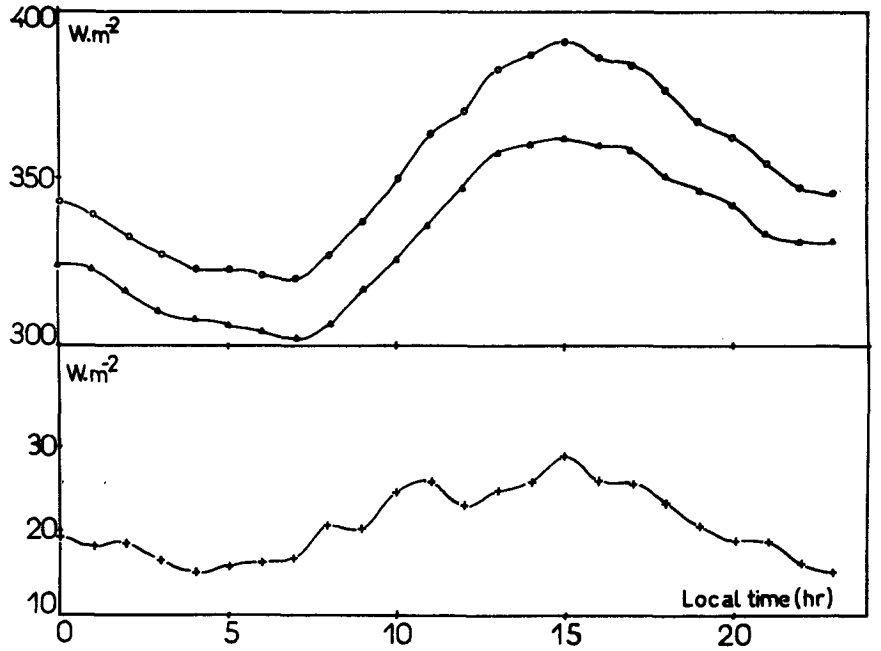

FIG. 2. Daily mean variation of measured surface downward IR fluxes: (a) circles, urban site; triangles, rural site; (b) urban–rural difference.

b. Solar model

In the visible part of the spectrum, our purpose was to obtain only the attenuation of the solar radiation induced by the urban aerosol. We considered identical amounts of gaseous absorption and Rayleigh scattering at both sites. The spectral intensity of the directly transmitted solar radiation at the surface can be written as

$$I_\nu = I_{0_\nu} \exp\left[-\int_0^{H_p}\int_{r_1}^{r_2} (Q_s + Q_a)\pi r^2 n(r) dr dz\right], \quad (6)$$

where H_p is the path length within the polluted layer (dependent on the zenith angle), and I_{0_ν} is the direct intensity at height H_p.

This computation has been made by dividing the visible spectrum (0.4–2.5 μm) into 12 intervals.

5. Experimental results (cloudless days)

a. Downward IR radiation

All measurements show that the downward IR radiation flux was greater over the urban than over the rural site for both daytime and nighttime periods. Fig. 2a plots the daily average variation of the IR flux at both sites (average of 10 measurement days). A daily variation of the downward IR fluxes appears at both sites following the temperature variation of the low atmospheric layers. The difference between urban and rural fluxes also shows a weak diurnal variation. The maximum of this difference occurred during the daylight hours and the minimum at night. The average increase of the urban IR flux was between 14 and 25 W m^{-2}.

b. Solar radiation

The directly transmitted radiation was slightly greater at the rural than at the urban site while the diffuse radiation was similar at both sites. Fig. 3 shows the daily variation of the rural–urban difference for the direct and diffuse radiation on 4 July 1979. It appears that the greatest difference in diffuse radiation between the two sites did not exceed 8 W m^{-2}, which is less than the measurement error. Directly transmitted radiation was always lower at the urban site, differing by $\sim$30 W m^{-2} ($\sim$3.5%) in the middle of the day.

Thus, the total radiation (IR + visible) is approximately equal at the two sites by day and slightly larger at the urban site by night. We investigated the different parameters which are able to modify the radiative fluxes at the urban site, using the radiative model.

6. Parameters inducing changes in the downward IR radiation

a. Urban atmosphere temperature

The measurements previously taken exclusively by night in Montreal, Quebec by Oke and Fuggle (1972) and in Tokyo, Japan by Aida and Yaji (1979) showed that the downward IR flux was increased by urban atmospheres. The authors explained this increase as

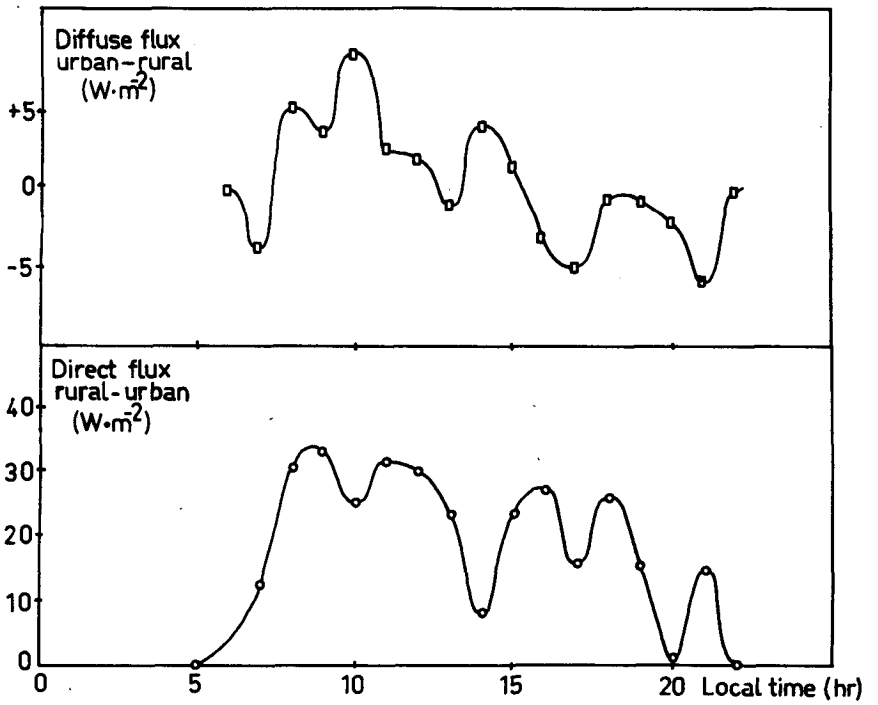

FIG. 3. Measured solar flux in Toulouse area on 4 July 1979: (a) diffuse urban–rural difference; (b) direct rural–urban difference.

being due to the nocturnal urban heat island. Our measurements show that this increase in the urban IR flux occurs during both daytime and nighttime periods with a maximum during the afternoon. We used our radiative model to compute the downward IR fluxes at the urban site.

Two kinds of temperature data were used in the model:

1) Air temperature measurements taken during a limited number of days at both sites showed that the difference between urban and rural air temperature near the surface was ~4–6°C by both day and night.

2) Aircraft measurements of thermodynamic parameters taken over both sites on 2 June 1978. These measurements were obtained during horizontal flights at different levels carried out by the Aerocommander of Institut National d'Astronomie et de Géophysique (INAG) (Ravaut, 1973). Air temperature and upward IR radiation at the 300, 500 and 1000 m levels are shown in Fig. 4. The urban–rural air temperature difference was only ~0.5°C at the 300 m level; the temperature increase was displaced downwind from the urban site; at the 500 and 1000 m levels, there was no difference in air temperature between urban and rural areas. It is likely that the observed increase of the upward IR radiation over the urban site at the three levels was due to the surface emission temperature being higher than that for the rural site. This increase was ~12 W m^{-2} at both the 500 and 1000 m levels, and is equivalent to a surface temperature of the urban site 5–6°C higher than that of the rural site. The IR flux measured at 300 m shows a second increase downwind from the urban site, possibly due to the emission of the warmer urban atmosphere out of the atmospheric window. This second maximum disappears at higher levels because of atmospheric opacity.

1) Model results

The radiative transfer model outlined in Section 4 was used to study the influence of temperature profile on the downward IR radiation. In each case we also computed the IR flux from the empirical relations of Brunt (1932) and Unsworth and Monteith (1975).

2) Daytime

The temperature profiles used for both sites are plotted in Fig. 5b. A 1000 m thick layer with an adiabatic lapse rate was assumed for the rural site. The air temperature near the surface of the urban site was taken to be 6°C higher than that of the rural site, based on *in situ* and aircraft temperature measurements. The temperature over the urban site was assumed to decrease linearly and merge into the rural profile at 300 m. This is felt to be a realistic hypothesis if aircraft measurements are taken into account. Bornstein (1968) also observed at New York an excess of temperature which vanished at 300 m. A specific

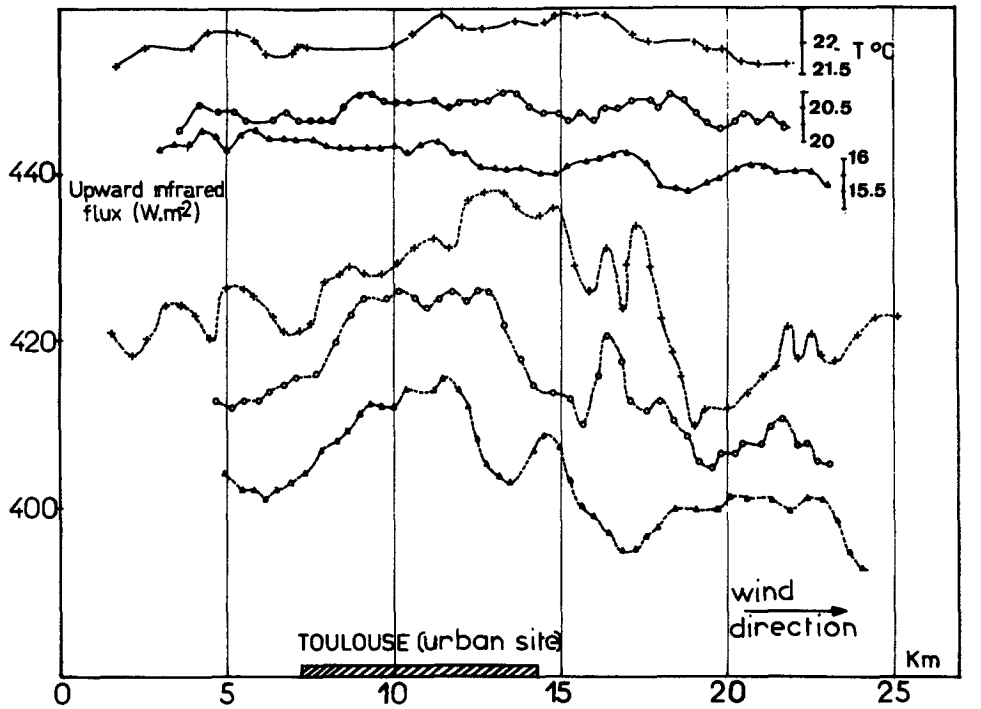

FIG. 4. Aircraft measurements of air temperature and upward IR flux in Toulouse area on 2 June 1978, at different altitudes: crosses, 300 m; circles, 500 m; triangles, 1000 m.

humidity of 6 g kg^{-1} was assumed for both sites. Table 1 shows the downward IR flux computed from our model and from empirical relations.

The empirical relations overestimate the downward IR flux for an urban site. Indeed, these relations only take into account the surface temperature assuming a standard profile above. This method cannot be used in urban sites since the surface temperature is not representative of the temperature profile of the whole atmosphere. The increase of the IR flux predicted by our simulation is ~15 W m^{-2} while our measurements showed a mean excess of the downward IR flux varying between 22 and 25 W m^{-2} in the middle of the day. Thus, it appears that most of the measured downward IR flux increase is due to an urban temperature excess, and that only 7–10 W m^{-2} should be explained by other factors (the accuracy of the IR radiation measurements was ~5 W m^{-2}).

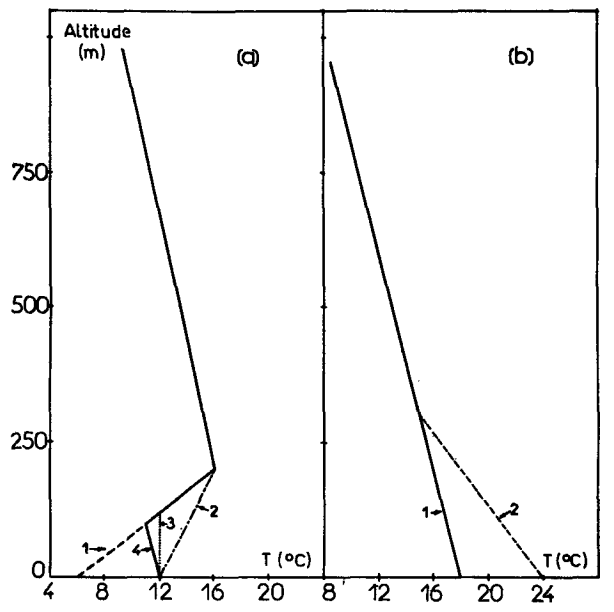

FIG. 5. Vertical temperature profiles used in the radiative model. (a) Nighttime: 1, rural site; 2, 3, 4, urban site. (b) Daytime: 1, rural site; 2, urban site.

3) NIGHTTIME

The temperature profile (Fig. 5a) used for the rural site exhibits a 200 m thick surface inversion layer

TABLE 1. Downward surface IR flux (W m^{-2}) for a daytime period computed from temperature profiles of Fig. 5b and from empirical relations. The last line denotes the IR flux increase (%) in the urban site with respect to the rural site.

	Present simulation	Brunt relation	Unsworth relation
Rural site	307	306.6	312
Urban site	322	331	345
Urban − rural	15 (4.9%)	25 (8.1%)	33 (10.5%)

TABLE 2. Downward surface IR flux (W m^{-2}) for a nighttime period computed from temperature profiles of Fig. 5a and from empirical relations. The last line denotes the IR flux increase (%) at the urban site with respect to the rural site.

	Present simulation			Brunt relation	Unsworth relation
		(Profile 1)			
Rural site		279		260	246
	(Profile 2)	(Profile 3)	(Profile 4)		
Urban site	292.2	290.6	290.3	280	279
IR flux increase	13.2 (4.7%)	11.6 (4.2%)	11.3 (4.1%)	20 (7.7%)	33 (13.4%)

(Profile 1). Three profiles were used for the urban site, corresponding to an adiabatic (4), isothermal (3) or inversion (2) urban layer. In the three cases the surface temperature was assumed to be 6°C higher than that of the rural site. The computed downward IR fluxes are presented in Table 2. The excess IR flux varies between 11 and 13 W m^{-2} according to the urban temperature model.

The IR flux increase measured at the urban site (Fig. 2) was ~15 W m^{-2} at the end of the night. Therefore, it appears that most of the IR flux excess at the urban site is induced by the fact that the atmosphere is warmer than that at the rural site. As mentioned above, this heating cannot be explained by a modification of the downward radiative fluxes, but rather by the physical surface parameters of the built-up area (thermal conductivity and specific heat).

b. Emissivity of the urban atmosphere

The increase in the emissivity of the urban atmosphere depends on its composition, i.e., on the content of polluting gas and radiatively participating aerosol. CO_2, CO and hydrocarbons were chosen to simulate the radiative effects of the gaseous pollutants since these gases can be considered as representative of typical pollution caused by traffic and urban emissions. Measurements taken by McRae and Graedel (1979) in New Jersey showed that CO_2 concentration never exceeded 600 ppm. Our computations showed that a concentration of 600 ppm for CO_2 in a 1000 m thick urban layer increases the downward IR flux by 0.9 W m^{-2}. For CO and CH_4, the absorption coefficients of Green *et al.* (1963) were used. A concentration of 20 ppm for CO (maximum concentration measured in Toulouse) increases the downward IR flux by 1 W m^{-2}. A concentration of 4 ppm for methane results in an increase of 1.4 W m^{-2}. Therefore, the atmospheric emissivity increase due to the considered pollutants results in an IR flux increase of ~3 W m^{-2}.

1) URBAN AEROSOL

The urban aerosol size distribution used in the simulations was taken from measurements made in the Toulouse area (Lopez *et al.*, 1982). The refractive indices of water soluble aerosol (Volz, 1972) were adopted to represent this anthropogenic aerosol. Table 3 lists the calculated values of the downward IR flux for various aerosol concentrations.

A concentration of 10^5 p cm^{-3} (a value never exceeded in the Toulouse area) induces an increase in the IR flux of 0.5 W m^{-2}; a concentration of 10^6 p cm^{-3} would induce an increase of ~5 W m^{-2}. It is also important to know the influence of the refractive index. Assuming an index value of $1.8-1i$, i.e., higher than the generally used values, a 1000 m thick polluted layer containiing 10^5 p cm^{-3} leads to an increase in the IR flux of 3 W m^{-2} (instead of 0.6 W m^{-2} with Volz's indices). It is possible to show that the error engendered by neglecting the scattering source term is not significant. We have computed the downward IR radiation assuming that there is no attenuation by scattering processes. This method, which overestimates the downward IR flux, has given 310.4 W m^{-2} for a 10^5 p cm^{-3}. This should be compared with the value of 310.3 W m^{-2} (Table 3) obtained by ignoring the scattering integral. Thus, it can be seen that for the present aerosol properties, the contribution of the scattering source to the downward flux is negligible.

7. Attenuation of solar radiation

The attenuation caused by urban aerosol was computed from Eq. (7) using three values of the refractive index: $1/m = 1.5 - 0i$; $2/m = 1.5 - 0.05i$; $3/m = 1.5 - 0.1i$.

The direct solar radiation transmitted by a 1000 m thick atmospheric path was computed for various aerosol concentrations and is shown in Fig. 6. It may be noted that the refractive index has a weak influence for concentrations lower than 10^5 p cm^{-3}.

In order to compare this simulation with our ex-

TABLE 3. Surface downward IR flux (in W m^{-2}) computed from simulations for a 1000 m thick urban layer and various aerosol concentrations.

Aerosol concentration (particles per cm^3)	0	10^5	10^6
Downward IR flux (W m^{-2})	309.8	310.3	314.5

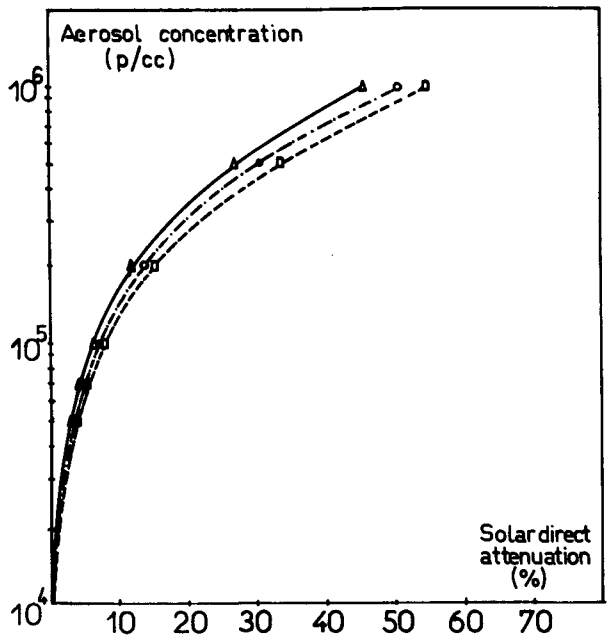

FIG. 6. Calculated attenuation of direct solar radiation through a 1000 m path length of polluted layer versus aerosol concentration. Aerosol refractive indices: triangle, $1.5 - 0i$; circles, $1.5 - 0.05i$; rectangles, $1.5 - 0.1i$.

perimental results, the variation of the measured attenuation on 4 July 1979 and the attenuation computed for a 1000 m thick layer are plotted in Fig. 7. It can be seen that the measurements and the simulations for a concentration of 3×10^4 p cm^{-3} are in good agreement. On the other hand, the experimental attenuation is greater than the computed attenuation for the morning period (0900 LST). This is probably provided by an increased concentration of aerosol particles at the beginning of the day.

8. Conclusion

Previous studies of the modification of radiative fluxes by an urban atmosphere show differences between the few experimental results and models in the literature.

Measurements of downward radiative fluxes were made simultaneously over the Toulouse urban site and over a rural site. The urban site is a middle-sized city (400 000 people), the most important pollution sources being traffic and urban emissions. These measurements show: 1) a downward IR flux excess of the urban over the rural site during both daytime and nighttime periods (~ 15 W m^{-2} at the end of the night and 25 W m^{-2} in the afternoon); and 2) an attenuation (3.5%) of the direct solar radiation at the urban site without an appreciable increase in the diffuse radiation.

A radiative model was used to identify the effects of various parameters on radiative downward fluxes in an urban atmosphere. The nocturnal and most of the diurnal IR flux excess can be explained by the

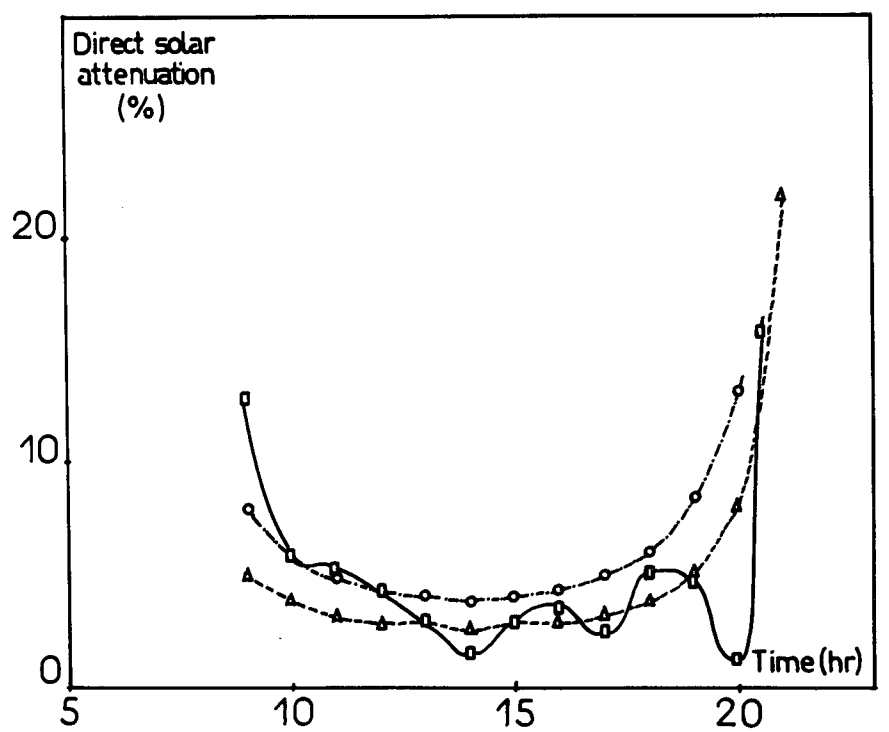

FIG. 7. Attenuation of the direct solar radiation by the polluted urban layer. Rectangles, measured on 4 July 1979; circles, calculated with 5×10^4 p cm^{-3}; triangles, calculated with 3×10^4 p cm^{-3}.

warmer urban atmosphere. On the other hand, the emissivity of the urban atmosphere is only slightly altered by the presence of aerosol particles. Thus, the heat island of the urban site is not due here to downward fluxes, but is likely to be the result of differing ground parameters. The aircraft measurements show a difference of 5–6°C between the surface temperatures of both sites. The presence of urban aerosol explains the attenuation of the solar flux. Therefore, measurements and simulations are in good agreement.

Finally, it is important to point out the necessity of obtaining measurements of radiative fluxes as well as the characteristics of the aerosol and the concentration of the polluting gases over various urban sites. Indeed, results of radiative models will be less speculative if they use experimental data which influences the radiative fluxes.

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