Proc. Indian natn. Sci. Acad., Part A, Phys. Sci., **46**, No. 1, 1980, pp. 99–107.

Meteorology

RADIATIVE EFFECTS OF POLLUTANTS ON THE URBAN CLIMATE

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(*Received 30 May 1979*)

This paper describes the results of a numerical study which was aimed at evaluating the radiative effects of the pollutants on the urban climate. The numerical model developed for the purpose incorporates two-dimensional transport processes which are capable of providing the understanding of the most important urban effects.

The model has been applied to simulate the effects of radiative participation on the temperature excess in the urban areas as compared to rural surroundings. The urban temperature excess profiles obtained by numerical simulation show that solar heating during the day has a considerable influence on the magnitude of the temperature crossover at night. The results also indicate that the increased downward thermal radiation due to pollutants leads to an increase in heat island intensity by as much as 50 per cent in the early morning hours.

INTRODUCTION

THERE has been considerable speculation concerning the possible effects of pollutants on the large and short term changes in the thermal structure of the atmosphere and on the inadvertent modification of the urban climate. Rasool and Schneider (1971) and Schneider (1971) have concluded that the net effect of increasing numbers of aerosols is to cool the earth-atmosphere system. Using a one dimensional radiative-conductive model, Atwater (1970) showed that the cooling due to layers of pollutants could cause elevated inversions. Atwater (1971) has also shown that, within the aerosol layer itself, there may be some pronounced effects which can materially alter the thermal structure of the layer. Bergstrom and Viskanta (1973) studied the effect of pollutants using a one dimensional model which accounted for turbulence effects through semi-empirical eddy diffusivity correlations. Their results indicated that pollutants could be responsible for the destruction of the nocturnal surface inversion. They also showed the formation of elevated inversions due to pollutant induced cooling. Utilizing a boundary layer model developed by Pandolfo *et al.* (1971), the author (1976) investigated the thermal changes induced by pollutants and concluded that the major effect of pollutants was to cause the delay of the onset of unstable conditions after sunrise.

This paper describes the results of a study performed to improve the understanding of the possible effects of pollutants on the urban climate. As there is a general lack of consensus on the radiative effects of pollutants on urban-rural temperature differences, it is hoped that these results would shed some light on the controversial topic.

METHOD OF ANALYSIS

Nomenclature :

F : Total radiative flux in z^+ direction.

h : Thickness of constant-flux layer.
H^* : Height of the boundary layer in two-dimensional model.
K : Turbulent eddy diffusivity.
k : Thermal conductivity or Turbulent kinetic energy.
${}^{M}C_n$: Surface pollutant.
p : Pressure.
${}^{S}C_n$: Volumetric pollutant source strength.
T : Thermodynamic temperature.
t : Time.
u : Horizontal velocity along x-axis.
u_* : Surface frictional velocity.
v : Horizontal velocity along y-axis.
w : Vertical velocity along z-axis.
z_0 : Roughness length.
θ : Potential temperature.
κ : Von Karman constant.

Subscripts :

C_n : Species.
H : Heat.
M : Momentum.
o : Surface value.
s : Solar or Soil.
t : Thermal.

(*a*) *The Model Equations* — The transport processes are formulated for two-dimensional case which is capable of providing the understanding of the most important urban effects. With the standard assumptions (Estoque, 1973), the governing equations can be written as :

X-momentum :—

$$\frac{Du}{Dt} = fv - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K_M \frac{\partial \mu}{\partial z}\right) + \frac{\partial}{\partial x}\left(K_x \frac{\partial u}{\partial x}\right) \qquad \text{...(1)}$$

Y-momentum:—

$$\frac{Dv}{Dt} = -fu - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K_M \frac{\partial v}{\partial z}\right) + \frac{\partial}{\partial x}\left(K_x \frac{\partial v}{\partial x}\right) \qquad \text{...(2)}$$

Z-momentum :—

$$\frac{\partial p}{\partial z} = -\rho g \qquad \text{...(3)}$$

Continuity :—

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad \text{...(4)}$$

Energy :—

$$\frac{D\theta}{Dt} = \frac{\partial}{\partial z}\left[K_H\left(\frac{\partial\theta}{\partial z} - \gamma_c\right)\right] + \frac{\partial}{\partial x}\left(K_x\frac{\partial\theta}{\partial x}\right) - \left(\frac{p_o}{p}\right)^{R/c_p} \cdot \frac{1}{\rho c_p}\frac{\partial F}{\partial z} + \dot{H}_p \qquad \ldots(5)$$

Water vapour :—

$$\frac{Dq}{Dt} = \frac{\partial}{\partial z}\left(K_c\frac{\partial q}{\partial z}\right) + \left(K_x\frac{\partial q}{\partial x}\right) + \dot{q} \qquad \ldots(6)$$

Pollutant species :—

$$\frac{DC_n}{Dt} = \frac{\partial}{\partial z}\left(K_c\frac{\partial C_n}{\partial z}\right) + \frac{\partial}{\partial x}\left(K_x\frac{\partial C_n}{\partial x}\right) + {}^{s}\dot{C}_n, \quad n = 1, 2, \ldots N, \qquad \ldots(7)$$

where

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + w\frac{\partial}{\partial z} \qquad \ldots(8)$$

Soil layer :—

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial z^2} \qquad \ldots(9)$$

In eqn. (5), γ_c is a small positive quantity which accounts for the counter-gradient heat flux often observed in the atmosphere. On the basis of Telford and Warner's observations, Deardorff (1967) recommends a value of 0.7×10^{-3} K/m for γ_c.

(*b*) *Boundary Conditions* — At the earth's surface ($z = z_0$), the boundary conditions are

$$u = v = W = 0,$$

$$T = T_0\,(x, t),$$

$$q = q_0\,(x, t),$$

$$C_n = C_{no}\,(x, t).$$

The ground temperature $T_0(x, t)$ is calculated from the standard energy balance equation at the earth's surface (Estoque, 1973). The surface water vapour concentration is calculated by postulating that the ratio of the actual evaporation rate to the potential evaporation rate is a constant (Halstead *et al.*, 1957).

The surface pollutant concentration is given by specifying the pollutant source ${}^{M}C_n$ as follows :—

$${}^{M}C_n = -K_c\,\partial C_n/\partial z \qquad \text{at } z = 0.$$

Elevated pollutant sources are modelled by source term ${}^{s}\dot{C}_n$ in the pollutant species equation.

At the bottom of the soil layer, the temperature is taken to be a constant. The boundary conditions at the top of the atmospheric layer ($z = H$) are specified by requiring the values of the atmospheric variables to remain constant over the time period of simulation.

The lateral boundary conditions were assumed to be periodic in X-direction, i.e., the atmospheric variables have the same values at the beginning and the end of the urban-rural system, Physically, this means that at distances far enough from the urban area, the atmospheric variables attain values which are not significantly different from those at large distances upwind of the urban complex. Obviously, the formulation of periodic boundary condition assumes that there are sinks of energy and pollutants between the end of the urban area and that of the rural area.

The imposition of periodic boundary conditions forces pollutant concentrations to build up over the urban-rural system which represents stagnating conditions during which pollution episodes occur. As the earth-atmosphere interface can absorb momentum as well as energy, the velocity and temperature fields are not expected to be affected by the conservation effects periodic boundary conditions tend to introduce. Thus, the numerical scheme accounts for advection effects on the velocity and temperature fields and at the same time avoids the difficulties associated with inflow and outflow boundary conditions.

(*c*) *Turbulence Model* — For the purpose of the turbulence model, the boundary layer was divided into two regions. Next to the air-soil interface, a 50 meter thick constant-flux layer was postulated in which the production and dissipation of turbulence was assumed to be in equilibrium. In this layer, the turbulent kinetic energy equation (Launder & Spalding, 1972) can be solved for k from the equation

$$k = \frac{l^2}{C_D}\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 - \frac{\alpha g}{T}\left(\frac{\partial \theta}{\partial z} - \gamma_c\right)\right]. \qquad ...(10)$$

Then, the eddy diffusivities K_M and K_H can be written as

$K_M = k^{1/2}.l$, $K_H = \alpha k^{1/2}.l$,

where α is assumed to be 1.35 (Businger, 1973). The mixing length, l, in the constant flux layer is given by $l = kz$.

Above the constant-flux layer, the eddy diffusivity is specified by a cubic polynomial suggested by O'Brien (1970). The variation of eddy diffusivity is given by

$$K(z) = K(H^*) + \left(\frac{z - H^*}{H^* - h}\right)^2 \left[K(h) - K(H^*) + \left\{(z - h)\left(\frac{\partial k}{\partial z}\right)_h + 2\,\frac{[K(h) - K(H^*)]}{H^* - h}\right\}\right] \qquad ...(11)$$

As the mixed layer is usually capped by a stable layer in which there is virtually no turbulence, the boundary layer thickness, H^*, is defined as the lowest height at which the potential temperature gradient exceeds 4 K/km (Deardorff, 1967). Above the boundary layer the eddy diffusivity was assumed to be zero.

(*d*) *Radiation Model* — As is customarily done, the radiation spectrum was divided at 4 μm into the solar (0.3 μm $< \lambda <$ 4 μm) and infrared (4 μm $< \lambda <$ 100 μm) spectrum. In the solar spectrum, the emission term in the radiative transfer equation was neglected and it was assumed that the radiative properties of aerosols can be represented by spectrally averaged quantities. Other than aerosols, the only radiationally active constituent was water vapour. In order to avoid lengthy computations involving wavelength integration, a parameterized expression (Lacis & Hansen, 1974) for water vapour absorption was used to calculate the effective water vapour optical thickness. Assuming that most of the solar energy is contained in the direct beam, the optical thickness was defined by considering the absorption of the direct beam. Empirical methods (Paily *et al.*, 1974) were used to compute the directly transmitted and scattered (diffuse) solar radiation fluxes at the top of the boundary layer. Next, two-flux method was used to compute the radiative fluxes within the boundary layer. In order to facilitate an analytial solution of the two-flux equations, it was assumed that the radiative properties of the constituents of the atmospheric boundary layer can be represented by a mean single scattering albedo and a mean forward scattering factor.

Infrared absorption and emission of thermal radiation is a consequence of coupled vibrational and rotational energy transitions. A typical infrared spectrum consists of a few bands each of which would consist of hundreds of lines. For our study, the concept of band absorbance in the computation of infrared radiative fluxes was utilised and that the effect of inhomogeneity was taken into account by using the empirical emissivities. For water vapour, the emissivity correlation proposed by Atwater (1970) based on Kuhn's emission data were used. For carbon dioxide the emissivity correlation proposed by Shekter (1950) and subsequently revised by Kondratyev (1969) was used. The numerical scheme adopted to compute the infrared fluxes was similar to the one used by Jurica (1970).

Gaseous pollutants are important only when they absorb in the atmospheric window extending from 8 μm to 12 μm. Thus, a representative pollutant was required to be a strong absorber in the atmospheric window region. This study utilized the wide band parameters derived by Tien from the France-William's data (1966) on the infrared properties of Ammonia. Ammonia has its strongest absorption band (at 300 °K) centered at 10.5 μm and it absorbs strongly in the entire window region. Also, Ammonia seems to be becoming an incrasingly important air pollutant since it is associated with the presence of large populations.

Numerical Procedure

The urban-rural system was assumed to extend vertically upto 1.5 km which served as an upper limit for the boundary layer height. The city itself was taken to be 12 km long and the adjoining rural areas on each side of the city were assumed to be 4 km in horizontal extent.

Eleven uniformly spaced grid points were used in the horizontal direction (X-axis). The first 3 grid points represented the rural area, the next 5 points represented the urban area and the remaining 3 points were situated in the rural area. Variable grid spacing was used in the vertical direction.

The surface parameters used in the simulations were based on values suggested by Pandolfo *et al.* (1971) and Oke (1975) and are presented in Table I. It was assumed

TABLE I

Surface and pollutant parameters

(i) *Surface Parameters* :

Parameters	Rural	Urban
Surface albedo γ_s	0.25	0.15
Surface emissivity ϵ_t	1.00	1.00
Moisture parameters, H	0.10	0.05
Conductivity k_s, m^2/S	2.0	2.0
Diffusivity α_s, m^2/S	1.3×10^{-6}	1.3×10^{-6}
Surface roughness z_0, m	0.1	1.0
Heat production H_p, W/m^{2}s	0	40
Source strength $\dot{s}C_n$, g/m^{3}s	0	0.5

(ii) *Pollutant Parameters* :

Aerosol Properties :—

Single scattering albedo $\omega = 0.09$

Forward scattering factor $f = 0.84$

Extenction coefficient $\beta_{ex} = 10^{-6}$ m$^2\mu$g

that there was no variation in soil properties but they were different in rural and urban areas. Thus, heat island effects are produced primarily by the differences in evaporation rates and heat production between urban and rural areas.

The initial temperature field was representative of the early morning atmospheric conditions. The nocturnal inversion extended to 300 m and had a gradient of 0.02 °C/km. The stable layer above the inversion had a gradient of 0.01 °C/km. The initial velocity field was assumed to be uniform in the horizontal direction and the vertical profile was given by

$$u(x, z) = v(x, z) = u_* \{\ln (z + z_i)/z_i\}/\kappa \qquad \ldots(12)$$

where $u_* = 0.1$ m/s and $z_i = 0.1$ m

and κ is the Von Karman constant. The maximum velocity predicted by eqn. (12) was 2.5 m/s at the top of the atmospheric layer. The pollutant sources were placed at a height of 100 m along the urban area.

The conservation equations were numerically solved using a time splitting method (Marchuk, 1965). The 24 hour simulation started at 0600 hours. A series of four numerical simulations were conducted; in the first one the pollutants were not allowed to participate radiatively (simulation NP), in the second and third cases pollutant's radiative effects on the solar fluxes (simulation SP) and thermal fluxes (simulation TP) were considered individually, and in the fourth case the simulation was conducted with both solar as well as thermal participation (simulation P). The results of these simulations are discussed in the following paragraphs.

RESULTS AND DISCUSSIONS

The variation of the urban surface temperature excess as a function of time is shown in Fig. 1. It is seen that, for the case with no radiative participation (simulation NP),

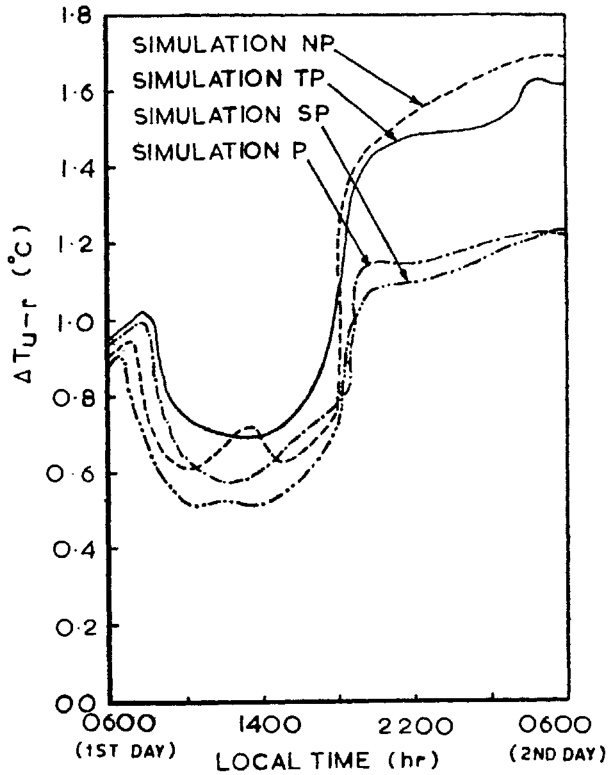

FIG. 1

the temperature excess is about 0.6 °C during the day and it increases sharply to about 1.1 °C at 1800 hours. The heat island reaches a maximum of 1.2 °C at 0600 hours of the second day. Further, the radiative participation by pollutants affects the heat island intensity to an appreciable extent. Thermal participation (simulation TP) increases the daytime temperature excess by about 0.1 °C and the night time heat island intensity by as much as 0.3 °C (25%). Solar participation (simulation SP) decreases the urban temperature excess by less than 0.1 °C during the day. These trends can be explained in terms of pollutant induced changes of the thermal and solar fluxes at the surface. The higher pollutant concentrations over the urban area lead to a greater increase of downward thermal radiation as compared to that over rural area. This explains the increase in the heat island intensity due to thermal participation. Solar participation on the other hand decreases the solar flux reaching the surface. This reduction is accompanied by a decrease in the surface temperature. It is noted that the urban surface temperature excess is the largest for simulation with both solar and thermal participation (simulation *P*). This is to be expected as the atmosphere is warmer in simulation *P* than in simulation *TP* due to solar heating during the day.

The vertical profiles of urban temperature excess/deficit at 1100 and 2300 hrs are shown in Figs. 2 and 3 respectively. It is seen from Fig. 2 that, in the simulation

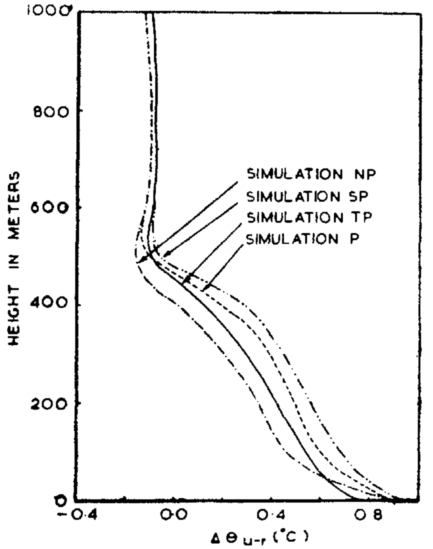

FIG. 2

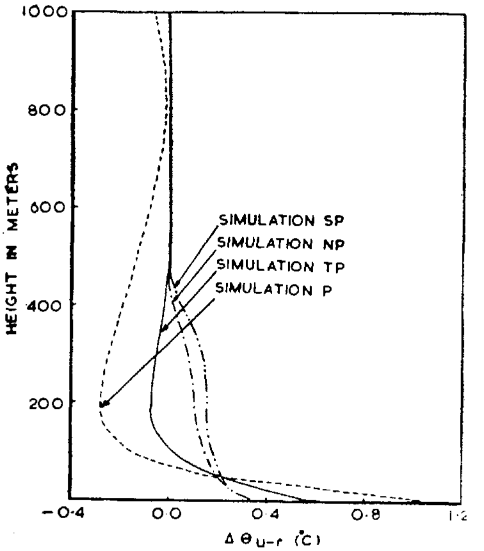

FIG. 3

with no radiative participation, the maximum temperature deficit of the order of 0.2 °C occurs at the top of the mixed layer which is about 500 meter thick at 1100 hrs. The effects of radiative participation on the daytime temperature crossover are small. Thermal participation increases the crossover effect while solar participation decreases it slightly.

Radiative participation has more noticeable effects during nighttime. As is evident from Fig. 3, at 2300 hrs no temperature crossover occurs for the simulation with no radiative participation. It is also interesting to note that solar heating during the day has a considerable influence on the magnitude of the temperature crossover at night. The maximum crossover of about 0.25 °C occurs for the simulation with solar as well as thermal participation at a height of about 200 meters.

CONCLUSIONS

The foregoing results indicate that the increased downward thermal radiation due to pollutants led to an increase of the heat island as much as 50 per cent in the early morning hours. Solar participation by aerosols decreased the urban temperature excess during the day while thermal participation increased the heat island intensity throughout the day. It is demonstrated that pollutants are an important contributing factor to the urban-rural temperature excess during the night. While no temperature crossover occurred in the simulation with non-participating pollutants, radiative cooling in the simulation with participating pollutants induced a temperature crossover of 0.3 °C.

ACKNOWLEDGEMENTS

This research was performed under auspices of the Air Pollution Section of the India Meteorological Department, Poona.

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