Effect of Urbanization on the Thermal Structure in the Atmosphere

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ABSTRACT.—An unsteady two-dimensional transport model was used to study the short-term effects of urbanization and air pollution on the thermal structure in the urban atmosphere. A number of simulations for summer conditions representing the city of St. Louis were performed. The diurnal variation of the surface temperature and thermal structure are presented and the influences of various parameters are discussed.

IT IS ESSENTIAL in air-pollution forecasting to understand how urbanization and the urban area modify the atmospheric environment not only in the immediate vicinity of the city, but also for a considerable distance downwind. Modification of the environment takes on many forms and includes alteration of the wind, temperature, and water-vapor profiles as well as the surface temperature and the injection of gaseous and particulate pollutants into the atmosphere.

During the past few years, many serious atempts have been made to observe and explain the microclimatic effects over and around urban areas. The best-documented and least-questioned climatic effect is the urban influence on temperature in the atmosphere. The urban heat-island phenomena is clearly a result of the modification of surface and atmospheric parameters by urbanization, which in turn leads to an altered energy balance. The possible causes of the heat island are well recognized *(Peterson 1969)*, but the individual effects such as physical and radiative property differences between urban and rural areas, flow changes caused by the roughness elements, man-made heat sources and radiatively participating pollutants have not been sufficiently studied, and their quantitative influences are not completely understood.

Observational programs and mathematical modeling are needed to gain understanding of the urban environment. Unfortunately, the very nature of the urban environment necessitates extensive measurements over large distances and long periods of time, which are not only difficult but also costly. Therefore mathematical models can be employed to advantage to help fill the observational gap by numerically simulating the transport processes in the atmosphere. To the extent that the mathematical model simulates the real atmosphere, it can then become a valuable tool for use in micrometeorological weather prediction, forcasting of pollution episodes, urban planning, interpretation of field data, and identification of pollutants by means of remote sensing methods.

In addition to the above, numerical simulations can also be used as a guide for observational programs such as the Regional Air Pollution Study (RAPS) sponsored by the U. S. Environmental Protection Agency (EPA) for the St.

Louis Metropolitan area. The main advantage of a numerical simulation lies in its ability to predict what will happen for any given changes in urban parameters, boundary, or initial conditions.

In this paper we will describe the short-term effects of urbanization on the thermal structure in the atmosphere of an urban area, using an unsteady two-dimensional transport model. The emphasis is on the potential effects of urbanization and air pollution on the thermal structure in the urban planetary boundary layer. As a specific example, results of numerical simulations of the city of St. Louis for summer conditions are discussed. Results of similar experiments have been reported *(Pandolfo et al. 1971, Atwater 1972, Bornstein 1972, Wagner and Yu 1972,* and *Atwater 1974).*

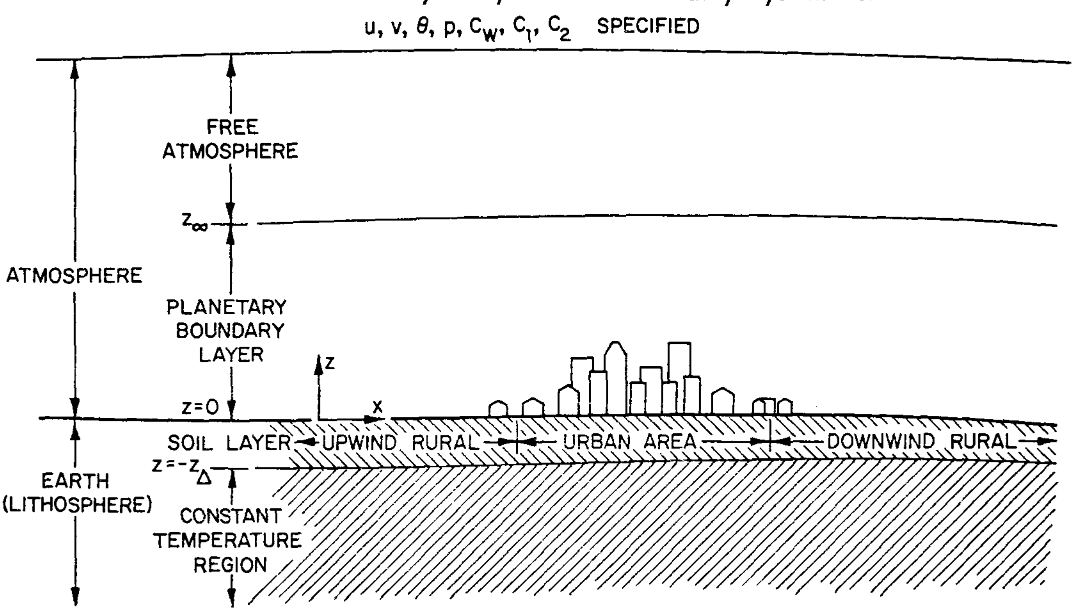
NUMERICAL MODEL

Physical Model and Assumptions

In the unsteady two-dimensional transport model (fig. 1), the earth-atmosphere system is assumed to be composed of four layers: (1) the free (natural) atmosphere where the meteorological variables are considered to be time-independent; (2) the polluted atmosphere (the planetary boundary layer, PBL), where the meteorological variables such as the horizontal, vertical, and lateral wind velocities, temperature, water vapor, and pollutant concentrations are functions of time, height, and distance along the urban area; (3) the soil layer, where the temperature is assumed to be a function of depth and time only (the soil and interfacial radiation properties are allowed to vary in the horizontal direction); and (4) the lithosphere, where the temperature is assumed to be constant during the simulation period. The atmosphere is assumed to be cloud-free, and no variation of topography is accounted for along the urban area.

In the polluted urban planetary boundary layer the transport of momentum, energy, and species takes place by vertical and horizontal advection as well as by vertical and horizontal turbulent diffusion. In addition, radiative energy is transported in the solar (short-wave)

Figure 1.—Schematic representation of the urban environment and of influences analyzed by the urban boundary layer model.



and thermal (long-wave) portions of the spectrum. The interaction of both natural atmospheric constituents and gaseous as well as particulate pollutants with solar and thermal radiation is accounted for. The planetary boundary layer and soil layer are coupled by energy and species balances at the atmosphere-soil interface. The horizontal variation of the urban parameters such as man-made heat and pollutant sources, surface solar albedo (reflectance) and thermal emittance, surface roughness, thermal diffusivity and conductivity of the soil, and Halstead's soil moisture parameter are arbitrarily prescribed functions of position along the urban area. It has been observed *(Stern et al. 1972)* that the man-made heat and pollutant sources, for example, vary during the diurnal cycle. However, more realistic modeling of these sources during the diurnal cycle must await more complete observational data.

Model Equations

The numerical model is based on the conservation equations of mass, momentum, energy, and species. The equations used to describe the planetary boundary layer can be written in a general form as

$$\frac{\partial \phi_i}{\partial t} + u\frac{\partial \phi_i}{\partial x} + w\frac{\partial \phi_i}{\partial z} = \frac{\partial}{\partial x}\left(K_{xi}\frac{\partial \phi_i}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_{zi}\frac{\partial \phi_i}{\partial z}\right) + S_i(x,z,t) \quad [1]$$

where t, x, and z are the time, horizontal, and vertical coordinates; u and w are the horizontal and vertical velocity components; $\phi_i(x,z,t)$ is the dependent variable "conserved;" $S_i(x,z,t)$ is the appropriate source term; and K_{xi} and K_{zi} are suitable turbulent diffusivities. The independent variables and their corresponding sources are listed in table 1. A general discussion of the conservation equations was given by Plate *(1971)*, and Johnson *(1975)* presented a detailed derivation of the equations used in the model.

The boundary conditions prescribed at the edge of the outer flow (top of the PBL) and at the soil surface are the following: at the edge of the outer flow, ϕ_i is specified; at the interface, u = v = w = O; and the surface temperature (at any x) is predicted from an energy balance

$$[1 - r_s(x)]F_s(x,0) + e_t(x)F_t(x,0) - e_t(x)\sigma T^4(x,0) + \left(k + \rho c_P K_z^{\theta}\right)\frac{\partial \theta}{\partial z}\bigg|_0 + L\rho\left(D_w + K_z^{C_w}\right)\frac{\partial C_w}{\partial z}\bigg|_0 - k_g(z)\frac{\partial T_g}{\partial z}\bigg|_0 + Q = 0 \quad [2]$$

In this equation, the first two terms account for absorption of solar and thermal radiation, the third term represents thermal emission, the fourth and fifth terms account for sensible and latent heat transfer by molecular and turbulent diffusion, the sixth term rep-

Table 1.—Dependent variables and source terms

	ϕ_i		S_i
1	u	horizontal velocity	$f(v-v_g)$ geostrophic deviation
2	v	lateral velocity	$f(u_g-u)$ geostrophic deviation
3	θ	potential temperature	$\partial F/\partial z$, q radiative and man-made heat sources
4	C_w	water-vapor concentration	$\dot{C}_w$ water vapor emission
5	C_1	concentration of pollutant aerosol	$\dot{C}_1$ pollution emission
6	C_2	concentration of gaseous pollutant	$\dot{C}_2$ pollution emission

resents heat conduction into the ground, and the final term is the man-made surface heat flux. The water vapor concentration at the surface is prescribed by Halstead's moisture parameter *(Pandolfo et al. 1971)* by the expression

$$C_w(x,0) = M(x)C_{w,sat}[T(x,0)] + [1-M(x)]C_w(z_1,0) \quad [3]$$

where M is the moisture parameter, $C_{w,sat}$ is the water-vapor concentration at saturated conditions, and z_1 is the first grid point above the surface. For a prescribed pollutant flux at the surface, m_n, a species balance at the interface, yields the condition

$$m_n = -\left(D_n + K^{C_n}\right)\frac{\partial C_n}{\partial z}\bigg|_0 \quad , n=1 \text{ and } 2 \quad [4]$$

At the upwind boundary, the meteorological variables are predicted from the unsteady one-dimensional model of Bergstrom and Viskanta *(1973a)*. Initially, ϕ_i is specified everywhere and is assumed to be independent of the horizontal coordinate x.

Turbulent Diffusivities

Specification of turbulent diffusivities for an urban atmosphere in connection with numerical modeling of the PBL is a very difficult task and has been discussed in a recent review *(Oke 1973a)*. The semi-empirical equations developed by Pandolfo et al. *(1971)* were initially employed. The decay of turbulence in the upper part of the PBL was prescribed by following Blackadar's *(1962)* formulation. However, in the hours before sunrise, when the atmosphere became quite stable, unrealistically deep surface inversions resulted and the Richardson numbers were found to exceed the critical value.

In these situations the diffusivities predicted by Pandolfo's eddy diffusivity-Richardson number correlations were not applicable. Therefore, the cubic polynomial developed by O'Brien *(1970)* and used by Bornstein *(1972)* was employed for the prediction of the diffusivities in the transition layer under stable conditions.

Stable conditions were assumed to exist when the average Richardson number in the lowest 25 m of the atmosphere was greater than zero. Where this condition was reached, Pandolfo's model was used only near the surface, while the polynomial was employed in the transition layer. Otherwise, Pandolfo's model was used throughout the entire PBL. If the Richardson number exceeded the critical value, it was reset to this value so that unreasonable diffusivity values would not be predicted.

Radiative Transfer Model

The radiative transfer model used has been discussed in detail elsewhere *(Bergstrom and Viskanta 1973b)*, so only a summary of it is included here. The urban atmosphere is considered to be cloudless, plane-parallel, and consisting of two layers: (1) the free atmosphere, and (2) the urban PBL where the pollutants are concentrated. The earth's surface was considered to emit and reflect radiation as prescribed functions of wavelength. Since the atmospheric gases and particles absorb, emit, and scatter radiation, the radiative transfer between the free atmosphere and the PBL is coupled. However, no consideration is given to individual point sources of pollutants. Since multidimensional radiative transfer is complex, it is assumed that the transport of radiation can be approximated by a quasi-two-dimensional field based on the vertical temperature, water-vapor, and pollutant distributions at several predetermined horizontal positions. The radiative fluxes in the atmosphere are then evaluated at a few prescribed horizontal locations and linear or nonlinear interpolation is then used to determine the radiative fluxes between these locations.

The radiative fluxes and flux divergences are evaluated by dividing the entire electromagnetic spectrum into solar ($0.3 \leqslant \lambda < 4$ μm) and thermal ($4 \leqslant \lambda \leqslant 100$ μm) portions. The computational details can be found in Bergstrom and Viskanta *(1973b)*. Total emissivity data for water vapor and carbon dioxide were used, and scattering was neglected in predicting radiative transfer in the thermal part of the spectrum. It was assumed that the influence of gaseous pollutants could be confined to the 8 to 12 μm spectral region due to the relative opacity of the H_2O and CO_2 bands. Ethylene or sulfur dioxide were considered to be representative pollutants. The spectral absorption and scattering characteristics of the aerosol in a polluted atmosphere were taken from the model developed by Bergstrom *(1972)*.

Numerical Method of Solution

The alternating - direction - implicit (ADI) method *(Roache 1972)* was employed to solve the transport equations [1]. The selection of suitable grid spacing, appropriate finite-difference approximations for the spatial derivatives and the algorithm itself, and tests for convergence are discussed in detail by Johnson *(1975)*. To improve the resolution near the surface, a logarithmic-uniform grid spacing was chosen in the vertical direction. The logarithmic spacing extended to about 1 km from the earth surface, and from there to the top of the PBL (~ 2 km) the spacing was uniform. A uniform spacing was also employed in the horizontal direction and in the soil layer.

The number of grid points and their spacing in the vertical and horizontal directions can be varied. The results reported have been obtained by using 22 nodes in the vertical direction and 17 in the horizontal direction. The first vertical grid point was located at 5 m from the surface and the horizontal grid spacing was 1.5 km. The program required practically the entire high-speed memory capacity (138,000/150,000 bytes octal) of the National Center for Atmospheric Research CDC-7600 digital computer. The computational time was approximately 8 minutes for a 24-hour simulation period.

RESULTS AND DISCUSSION

Numerical Experiments

The numerical model has been tested, and a number of numerical experiments have been performed, using the city of St. Louis as an example. Because of the length and scope of the paper, it is possible to include only some selected results for the temperature in the atmosphere. The experiments were designed to simulate the thermal structure and pollutant dispersion in the urban atmosphere. The urban area was modeled by varying the appropriate surface parameters between rural and urban values in the horizontal direction. The value of these interface parameters are given in table 2. A horizontal distribu-

Table 2.—Numerical values of interface parameters for simulations (Johnson, 1975)

Parameter	Upwind rural	Urban Center
Solar albedo	0.18	0.12
Thermal emittance	.90	.95
Soil thermal conductivity (W/mK)	.1	.5
Soil thermal diffusivity (10^7 m^2/s)	1	2.5
Surface roughness (m)	.2	1.0
Moisture availability parameter	.1	.05
Lower soil boundary temperature (K)	295.5	295.5
Urban heat source (W/m^2)	2	20
Aerosol pollutant source ($\mu g/m^2s$)	0	2.5 or 5
Pollutant gas source ($\mu g/m^2s$)	0	2.5 or 5

tion was established by selecting the values of parameters at the rural and urban center locations and, for lack of any better data or information, a Gaussian distribution curve was then fitted between the urban and rural locations by specifying the standard deviation of a suitably chosen mean value. The data given in table 2 are representative values over the city.

The simulations were started at 1200 solar time and continued for a 24-hour period. The initial temperature profiles used were taken from Lettau and Davidson *(1957)* for 24 August 1954 and were imposed over the entire area (no x-variation). The initial horizontal and lateral velocity fields were either identical to or decreased by a factor of 2 of those given by Lettau and Davidson for the O'Neill Great Plains Turbulence Study. The pollutant-concentration profiles were initialized to a constant background value of 50 $\mu g/m^3$.

Components of the Energy Budget at the Surface

The surface temperature can be considered as the forcing function of the model. Thus it is important to understand the variation of the energy budget components along the urban area. These are presented in figures 2 and 3 at 2400 of the first day and 1200 of the second day. Inspection of figure 2 shows that the emitted (q_e) and the absorbed thermal (q_{at}) fluxes are the dominant components. The turbulent (q_t), the latent

Figure 2.—Variation of the surface balance flux components (q_t-turbulent, q_l-latent, q_e-emitted, q_{as}-absorbed solar, q_{at}-absorbed thermal, q_g-ground conduction, Q-urban heat source) at the surface at 2400 of the first day; Gaussian distribution, radiatively nonparticipating, u_g=6 m/s and v_g=4 m/s.

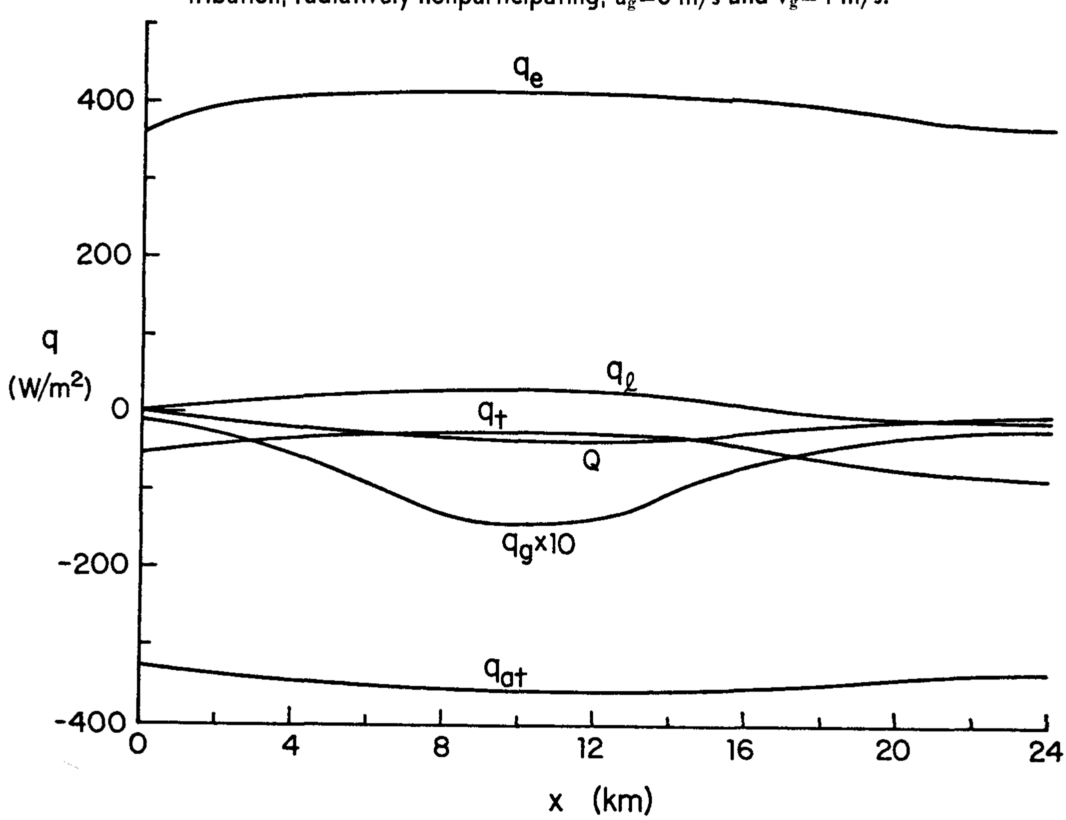
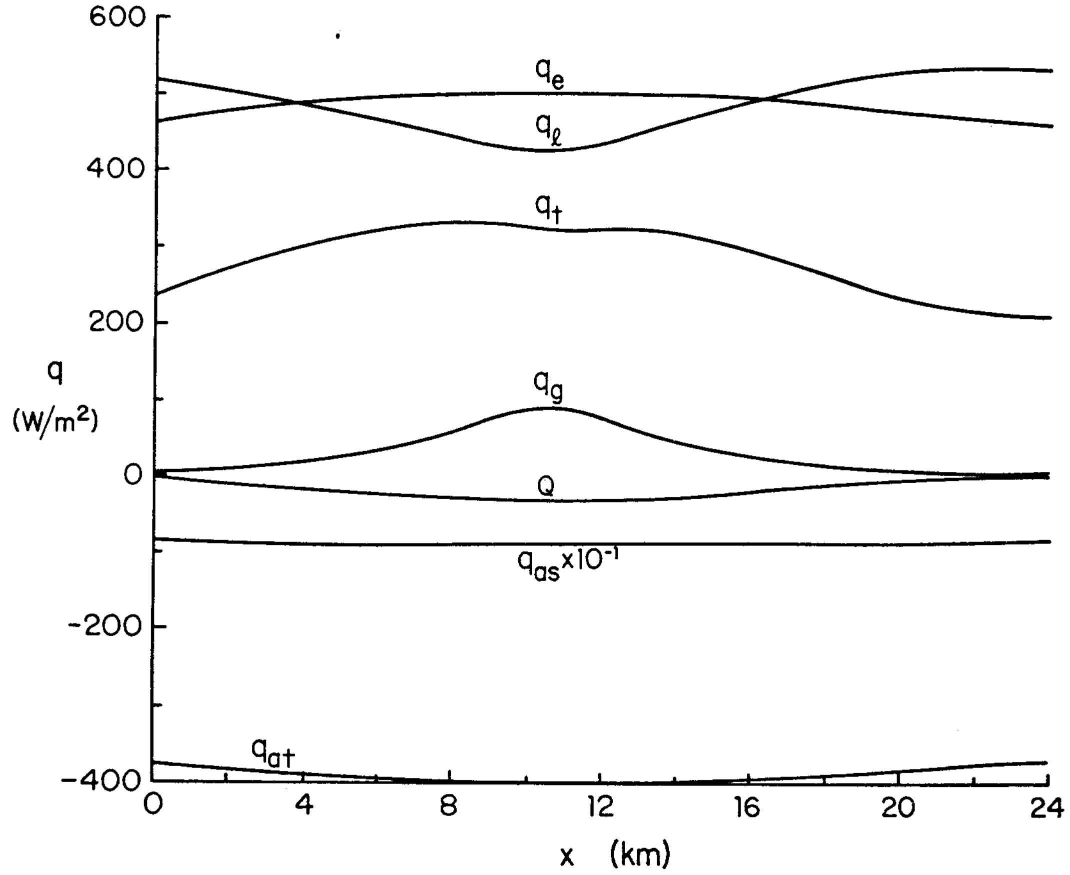


Figure 3.—Variation of surface energy balance flux components at 1200 of the second day; Gaussian distribution, radiatively nonparticipating, $u_g=6$ m/s and $v_g=4$ m/s.

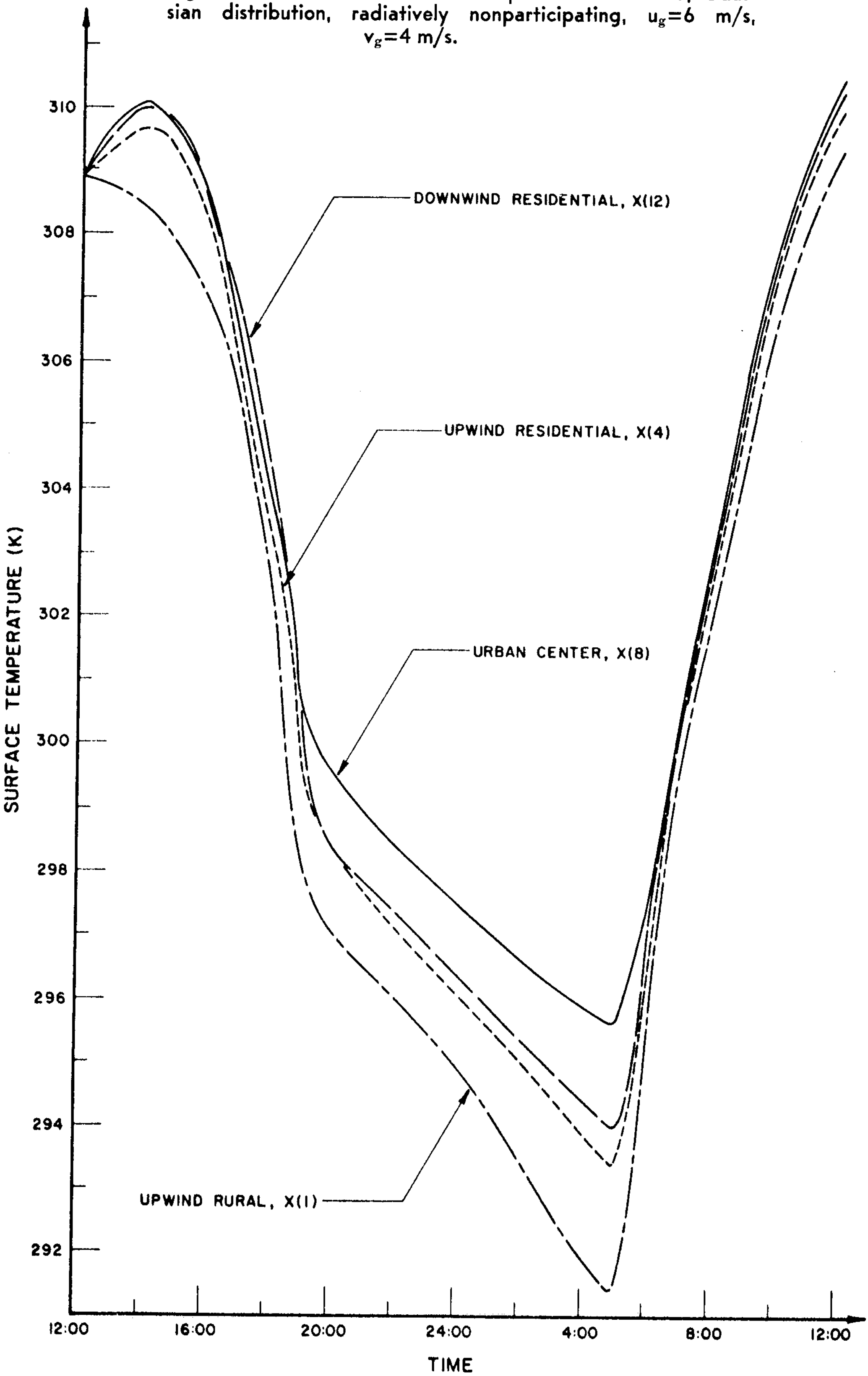


(q_l), the ground conduction (q_g), and the man-made urban heat (Q) fluxes are significantly smaller. However, at noon (fig. 3) the absorbed solar flux (q_{as}) is the largest term in the energy balance and the man-made heat source (Q) is the smallest. At the urban center (x = 10.5 km) the soil heat conduction term (q_g) amounts to only about 10 percent of the absorbed solar flux. The turbulent (q_t) and the latent (q_l) fluxes are quite sensitive to surface gradients and show significant variation along the urban area.

Surface Temperature

The diurnal variation of the surface temperatures at four positions along the urban area are shown in figure 4. The surface temperature drops sharply in the late afternoon, reaches a minimum just before sunrise (between 0500 and 0600), and rises sharply in the morning. During the first few hours of the simulation, an initial transient is noted in the surface temperature. This is due to the fact that the assumed initial velocity, temperature, and water-vapor concentration profiles were far away from the quasi-steady solution induced by the diurnal cycle, and it took about 2 to 3 hours for the system to adjust. The surface temperatures at the downwind residential location (node 12) are slightly higher than at the upwind residential (node 4) locations. This is attributed to the heating of the air as it flows over the warm city. The maximum surface

Figure 4.—Variation of surface temperature with time; Gaussian distribution, radiatively nonparticipating, u_g=6 m/s, v_g=4 m/s.



temperature difference (about 4°C) between the urban center and upwind rural locations occurs just before sunrise. On the other hand, for a simulation with higher wind speeds (u_g = 12 m/s and v_g = 8 m/s), the maximum difference occurs in the evening at 1900 and remains almost constant throughout the night *(Johnson 1975)*.

The effect of radiatively participating pollutants as measured by a local surface-temperature difference (temperature with participating pollutants/temperature without) is illustrated in figure 5. The temperature differences result from an interaction between many complex phenomena, and therefore individual influences are not easily identified. The surface temperature difference is largest during the night and reaches a maximum before sunrise 0500 and is smallest at noon. The differences between the surface temperatures are considerably smaller for higher wind speeds *(Johnson 1975)*.

A comparison of the surface temperatures for the Gaussian and rectangular distributions of urban man-made heat sources is illustrated in figure 6. The results show that the difference between the two results is only about 1°C, and the maximum occurs early in the morning (0500) when the man-made urban heat source is a significant component of the energy budget. At noon (1200) the surface temperatures in the city differ by only about 0.1°C, indicating the predominance of the radiant energy transfer in the interfacial energy balance.

Temperature Structure

The isopleths of the two-dimensional potential temperature fields at 6-hour

Figure 5.—Local surface temperature difference (simulation with radiatively participating pollutants minus simulation with radiatively nonparticipating pollutants) along the city; Gaussian distribution, ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, m_1=m_2=2.5 μg/m^{2}s.

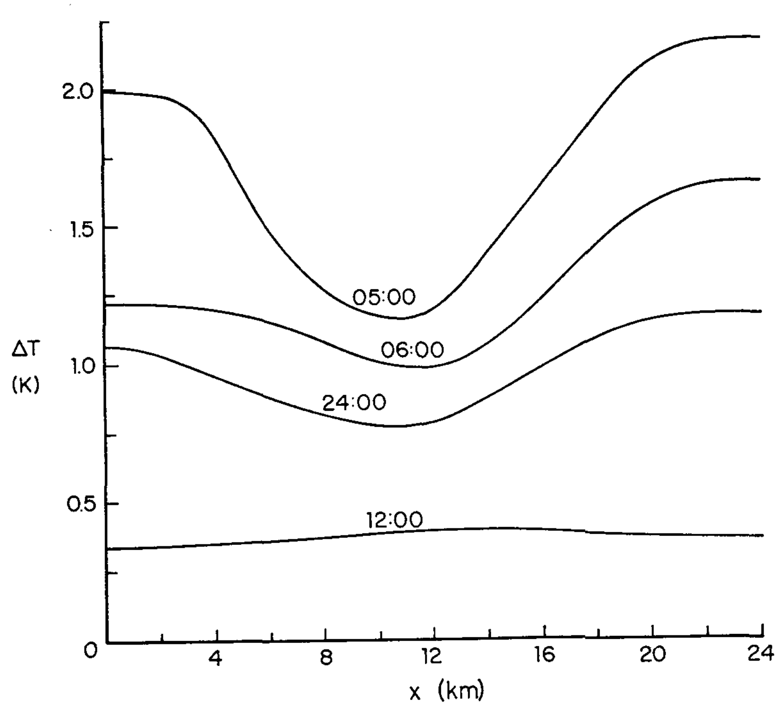
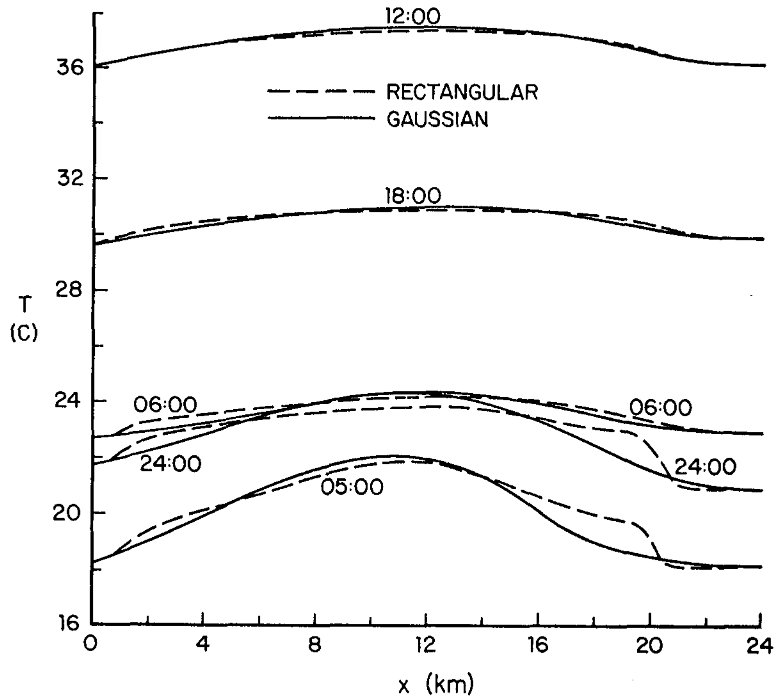


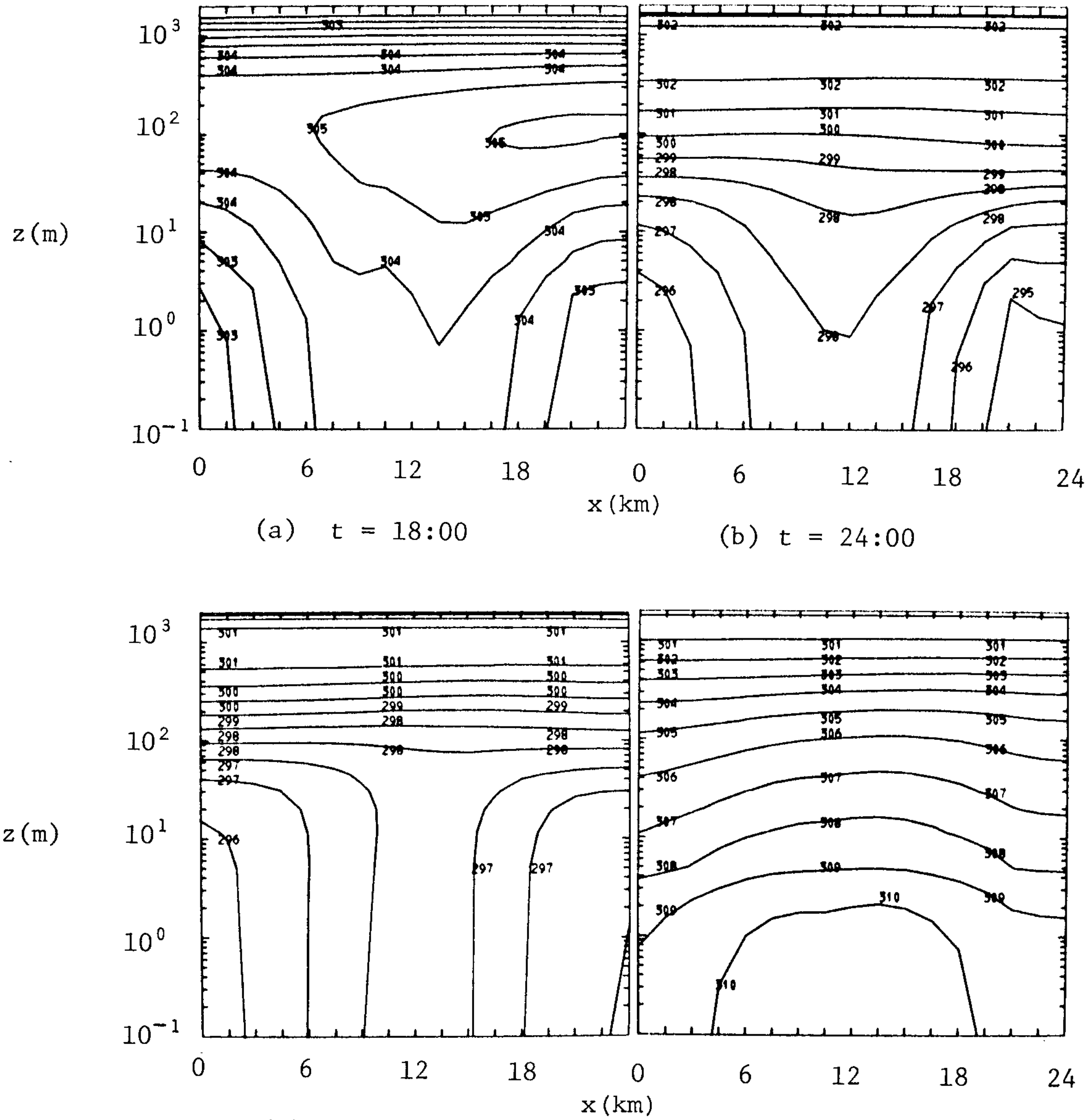
Figure 6.—Comparison of surface temperatures for Gaussian and rectangular distributions of urban heat and pollutant sources; radiatively participating, ethylene (C_2H_4)-pollutant gas, u_g=6 m/s, v_g=4 m/s, m_1=m_2=2.5 μg/m^{2}s.



intervals for a simulation with radiatively nonparticipating pollutants are shown in figure 7. At 1800 the atmosphere is nearly adiabatic, especially in the upwind rural area, with a thermal plume having a temperature of about 305 K forming at a height of about 100 m downwind of the city center (node 8, x = 10.5 km). Note that the last digit denoting the temperature of the isotherm at 1800, 2400, and 0600 hours has been truncated. However, the plume is not felt downwind, and the upwind and downwind surface temperatures are nearly identical. A surface temperature inversion develops at night and is seen to be deeper over the rural area than over the city. This is indicative of the nocturnal heat island, which decreases the stability of the atmosphere. The magnitude of this heat island is larger at night than during the day. This type of behavior is well documented *(Peterson 1969, Oke 1973b)*. Just after sunrise (0600) the breakup of the stable layer was noted. The surface inversion breaks up rapidly after sunrise due to heating of the surface by absorption of solar radiation, and by 0900 all traces of the inversion have disappeared. Similar types of diurnal variation of thermal structure have been found for other simulations under different conditions *(Johnson 1975)*.

The maximum temperature difference between simulations with radiatively participating and nonparticipatng pollutants occurs at the urban center late at night (fig. 8). The temperature differences are seen to be largest near the surface and are confined to the lowest 600 meters of the PBL. When the pollutant gas is assumed to have the radiative properties of sulfur dioxide (SO_2), the temperature structure predicted is practically the same as that for the

Figure 7.—Isopleths of potential temperature (in K); Gaussian distribution, radiatively nonparticipating, u_g=6 m/s, v_g=4 m/s.



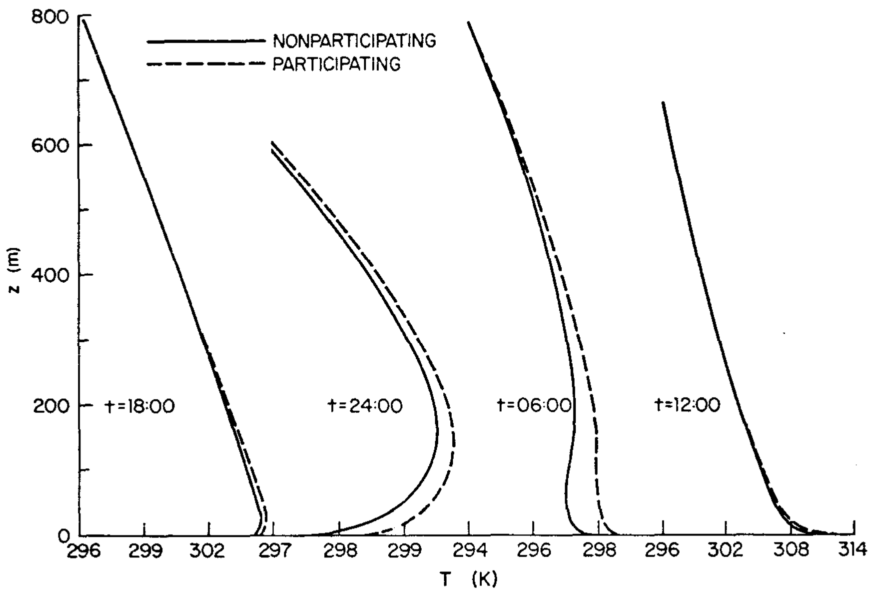
(a) t = 18:00

(b) t = 24:00

(c) t = 06:00

(d) t = 12:00

Figure 8.—Comparison of thermodynamic temperatures at the urban center; Gaussian distribution, ethylene (C_2H_4)-pollutant gas, $u_g=6$ m/s, $v_g=4$ m/s, $m_1=m_2=2.5$ $\mu g/m^2s$.



radiatively nonparticipating pollutant gas. This is due to the fact that SO_2 is a weakly radiating gas. The results are consistent with those obtained with the one-dimensional model *(Bergstrom and Viskanta 1973a)*. The net effect of the city and the human activity on the temperature distribution is illustrated in figure 9. The results show that the presence of radatively participating pollutants dampens the amplitude of the diurnal temperature variations and that for a relatively short (24-hour) simulation the effects are confined primarily below 600 m.

Urban Heat Island

The urban heat island is a well-known and accepted fact *(Peterson 1969, Oke 1973b)*. The urban heat-island itensity (maximum difference between upwind rural and highest urban surface temperature, Δt_{u-r}) predicted is shown in figure 10. For the assumed Gaussian distribution of man-made heat sources, the maximum surface temperature difference occurred at the urban center, whereas for the rectangular distribution during the night it occurred downwind of the center. The results presented in the figure show that there is a double peak in ΔT_{u-r}. The first peak is noted at about 2000. It arises due to the more rapid cooling at the upwind rural area than in the city. The maximum heat-island intensity occurs just before sunrise and has a magnitude of about 4°C. For the population of the urban area and wind speeds of the simulation this value is in good agreement with the observations and empirical correlation of Oke *(1973b)*. For a simulation with lower wind speeds ($u_g \simeq 2.4$ m/s and $v_g \simeq 1.6$ m/s), which are not reported here, the maximum heat-island intensity reached about 10°C. This is also in good agreement with the nighttime and daytime observed temperature excesses between the urban and rural locations *(Oke 1973b, DeMarrais 1975)*.

CONCLUSIONS

As a result of a limited number of numerical simulations that have been

Figure 9.—Comparison of perturbation potential temperatures (temperature in the city minus the temperature at the upwind rural location) at the urban center for radiatively nonparticipating (a) and radiatively participating (b) simulations; Gaussian distribution, ethylene (C_2H_4)-pollutant gas, $u_g=6$ m/s, $v_g=4$ m/s, $m_1=m_2=2.5$ $\mu g/m^2s$.

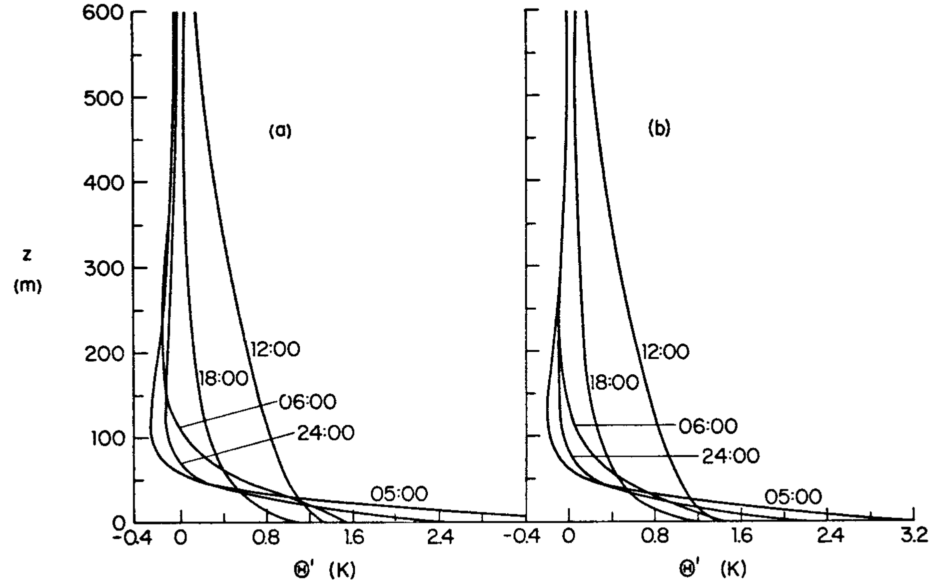
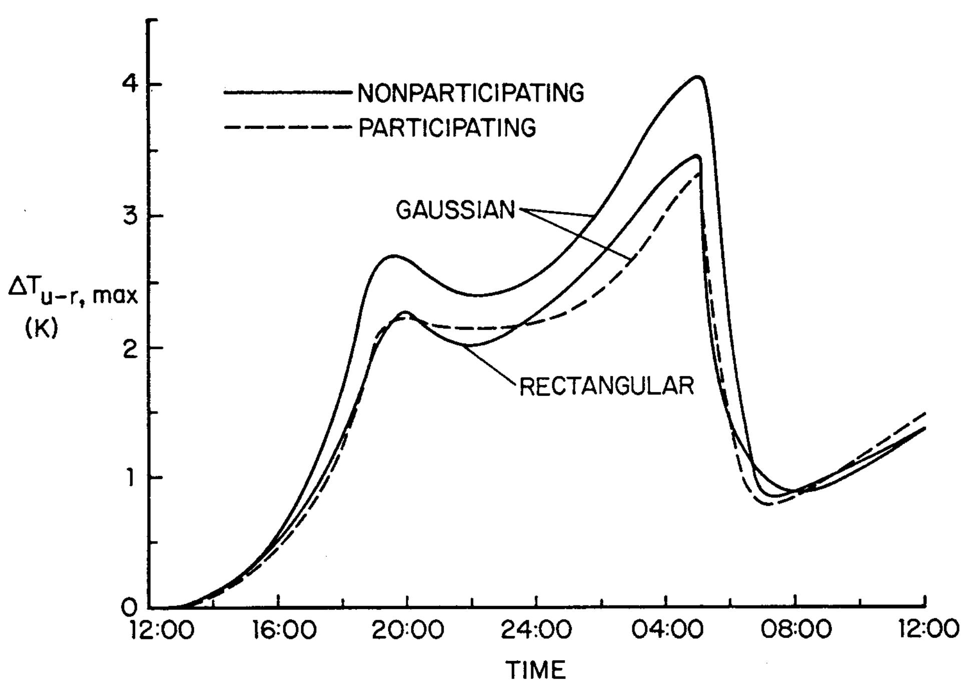


Figure 10.—Comparison of maximum urban upwind rural surface temperature differences; ethylene (C_2H_4)-pollutant gas, $u_g=6$ m/s, $v_g=4$ m/s, $m_1=m_2=2.5$ $\mu g/m^2s$.



performed for selected meteorological conditions during the summer, the following generalizations can be made:

1. The unsteady two-dimensional transport model predicts an urban heat-island intensity that is sensitive to wind speed and latent energy transport through Halstead's moisture parameter. The intensity of the urban heat island reached a magnitude of about 4°C near sunrise and about 1.4°C at noon.
2. For the conditions studied, the radiatively participating pollutants are relatively unimportant in forming the urban heat island compared to other factors. During the night, air pollution does increase the surface temperature by about 1.25°C at the urban center.
3. The role of radiatively participating pollutants in the formation of the thermal structure is relatively small and it is greatest late at night. The largest effect of pollutants was to decrease the stability at night and hence increase turbulent transport near the surface particularly at heights below 500 m.
4. The feedback mechanism between pollution, thermal structure, stability, and dispersion has the potential of being significant in modifying pollutant concentrations under more stable conditions and higher pollutant loadings. However, the magnitudes of the changes are dependent on the coupling between the radiative properties of air pollution and the buoyancy-enhanced turbulence. Due to the uncertainties involved in predicting either of these two quantities, the magnitude of these changes is uncertain.

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