

Anthropogenic Moisture Production and Its Effect on Boundary-layer Circulations over New York City

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ABSTRACT.—A heat and moisture excess over New York City is shown to exist by the analysis of helicopter soundings of temperature and wet-bulb depression. The magnitude of the temporal and spatial distribution of anthropogenic moisture emissions in New York City were estimated from fuel-usage data. The URBMET urban boundary-layer model was used to evaluate the effects on the dynamics of the urban boundary layer resulting from the observed urban moisture excess. Work is currently in progress to determine the fraction of the observed moisture excess over New York that is due to anthropogenic sources.

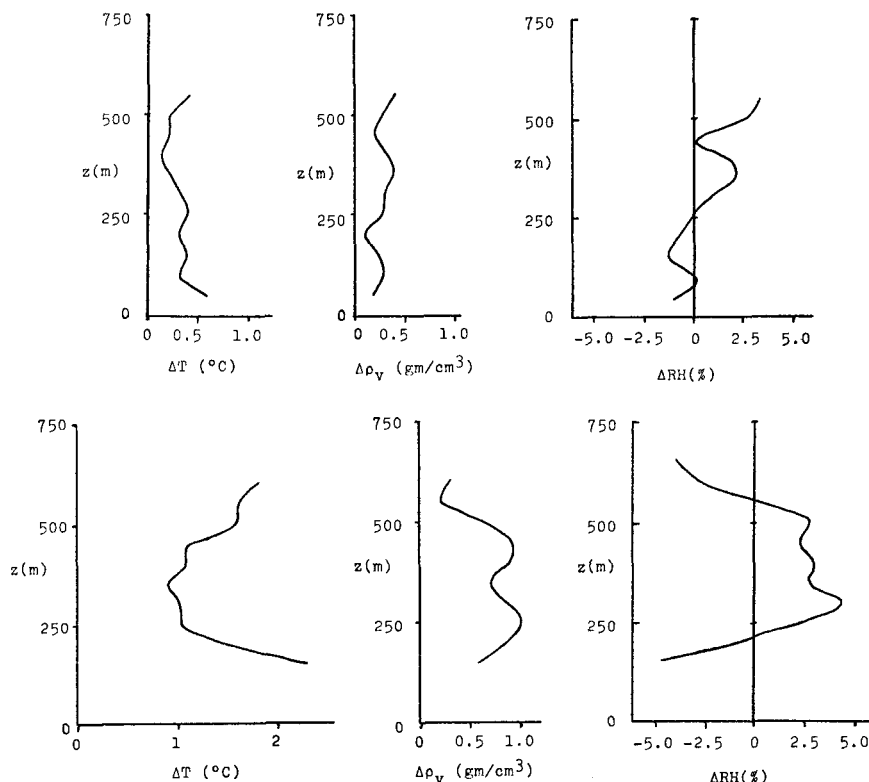
UNTIL RECENTLY, studies of the atmospheric moisture content at the surface in and around cities have shown that, on the average, cities are somewhat drier than their rural surroundings. Average relative humidities have generally been found to be several percent lower in cities than in nearby rural areas; also, absolute humidities were found to be slightly lower in the built-up areas. The main reason given for these humidity differences was the lower evaporation rates in the city than in the country. This reduction occurs because rainfall is retained by vegetation-covered rural surfaces, while rapid runoff occurs in asphalt- and concrete-covered cities (Peterson 1969).

Recently, Chandler (1967) obtained atmospheric-moisture data from a series of automobile transverse in and around London during three summer nights of low wind, clear skies, and well developed urban heat islands. He found that measured urban vapor pressures were higher than nearby rural vapor pressures, and found the reverse true for relative humidities. He attributed the higher nighttime urban absolute humid-

ity to the lower amount of dew formation in urban areas and to the addition of water to the urban atmosphere from anthropogenic sources.

Similar results were found by Ackerman (1971) in an analysis of seven years of dew-point data from urban Midway Airport in Chicago and from rural Argonne National Laboratory, 125 miles southwest of Chicago. Results showed: (1) an urban moisture excess when all of the data were considered, (2) an urban moisture excess for the nighttime data, (3) an urban moisture deficit for the daytime data, and (4) an urban moisture excess for the winter daytime data. Thus during the times when combustion was a major source of moisture, the urban atmosphere was more moist than the rural atmosphere. These results are consistent with those of Auer and Dirks (1974), who found that the air over St. Louis was drier than that over its nearby rural areas during summer daytime periods. Urban moisture excesses have also been found by Kopec (1973) and Goldreich (1974), while Hage (1972) showed that anthropogenic moisture emissions can enhance the forma-

Figure 1.—Average vertical distribution of urban minus rural values of temperature ΔT , absolute humidity $\Delta \rho_v$, and relative humidity ΔRH for daytime periods (upper curves) and nighttime periods (lower curves).



tion of low-temperature fog in the city of Edmonton.

Vertical and horizontal moisture distributions in and around New York City were studied by Lorenzen (1972) and Bornstein *et al.* (1972) to determine the vertical extent of urban-rural moisture differences. Sixty-two helicopter soundings of temperature, wet-bulb depression, and pressure height were obtained during three early-morning periods and during one late-afternoon period in 1964.

Results from the analysis of the above data (fig. 1) showed that the following values are larger at night than during the day: (1) urban heat-island values, (2) urban excesses in absolute humidity, (3) urban relative humidity deficits below 250 m, and (4) urban relative humidity excesses at heights between 250 and 500 m.

The data used by Bornstein *et al.* (1972) were collected from 1964 to 1969 as part of a U.S. Public Health Service sponsored grant to the late Ben Davidson of the Department of Meteorology and Oceanography at New York University. As described by Davidson (1967), the main goal of the project was to develop a sophisticated model for the prediction of the distribution of SO_2 in the New York City metropolitan area (Shieh *et al.* 1969).

Though the data obtained by the NYU project were used in various studies of the urban boundary layer over New York City, the original data set was never published, due to the untimely death of the project's principal investigator. In the belief that NYU/NYC data set is unique, and that it could be extremely useful to persons interested

in the urban boundary layer over New York City, much of the original data has recently been published by Bornstein *et al.* (1975b) under a grant from the U. S. Environmental Protection Agency and is on file with its Meteorology Laboratory at Research Triangle Park. An important component of the NYU/NYC data is an area and point-source emission inventory for the production of SO_2 , heat, and moisture from anthropogenic sources within the New York City metropolitan area during 1965.

The main goals of the current research reported here are: (1) to determine the magnitude and variation in time and space of the anthropogenic moisture flux in New York City, (2) to determine the effects of the observed moisture excess on the dynamics of the urban boundary layer over New York City, and (3) to determine the fraction of the observed moisture excess over New York City that is due to each of the following: area-source emissions, point-source emissions, and reduced nighttime condensation rates in the urban areas, as compared to those in nearby rural areas.

The first of these goals has been carried out under a grant from the U. S. Environmental Protection Agency to the Department of Meteorology at San Jose State University, while the second part has been accomplished by use of the computer facilities at Lawrence Livermore Laboratory. The third section is currently being carried out under a grant from the National Science Foundation to the Department of Meteorology at San Jose.

In carrying out the second and third parts, the two-dimensional, nonsteady "URBMET" (for urban meteorology) urban boundary-layer model of Bornstein (1975) has been used to predict the temporal and spatial distribution of wind, temperature, and moisture within the urban boundary layer. The surface boundary condition for the absolute

humidity in these simulations is being obtained from the temporal and spatial distribution of the anthropogenic moisture production in New York City, as obtained from the fuel-use inventory compiled during the original NYU air-pollution project.

ANTHROPOGENIC MOISTURE EMISSIONS

Most of the study region (fig. 2) has an elevation that is close to mean sea level, but the northwestern 10 percent of the area consists of highlands that range in elevation from 250 to 500 feet above mean sea level. About 30 percent of the study area is water, while 60 percent is open country, and 10 percent has been built up for urban and suburban uses.

During the original NYU project, an unpublished inventory of the annual emission of SO_2 from the known area and point sources in the New York Metropolitan region was compiled. Point-source emission information was obtained through the use of questionnaires, while area-source emissions from both fixed and mobile sources were computed from fuel-use data obtained from the following sources: (1) the U. S. Bureau of Mines, which publishes an annual report on the shipments of fuel oil; (2) the New York Oil Heating Association; (3) the American Petroleum Institute; (4) the New York City Council Committee on Air Pollution; (5) the New York City Housing Authority; (6) the New York City Air Pollution Control Agency; (7) the NYC Fire Department; and (8) the New York City Licensing Agency, which controls the installation, registration, licensing, and insurance of each furnace or power plant in New York City. The seven main types of fuel consumed in the New York City area, the uses to which they are put, and their annual rates of consumption are listed in table 1.

Because fossil fuels are composed of carbon, hydrogen, sulfur, etc., the com-

Figure 2.—Topography of study area with values in feet above sea level. Also shown by the cross-hatched area are the built-up areas of New York City.

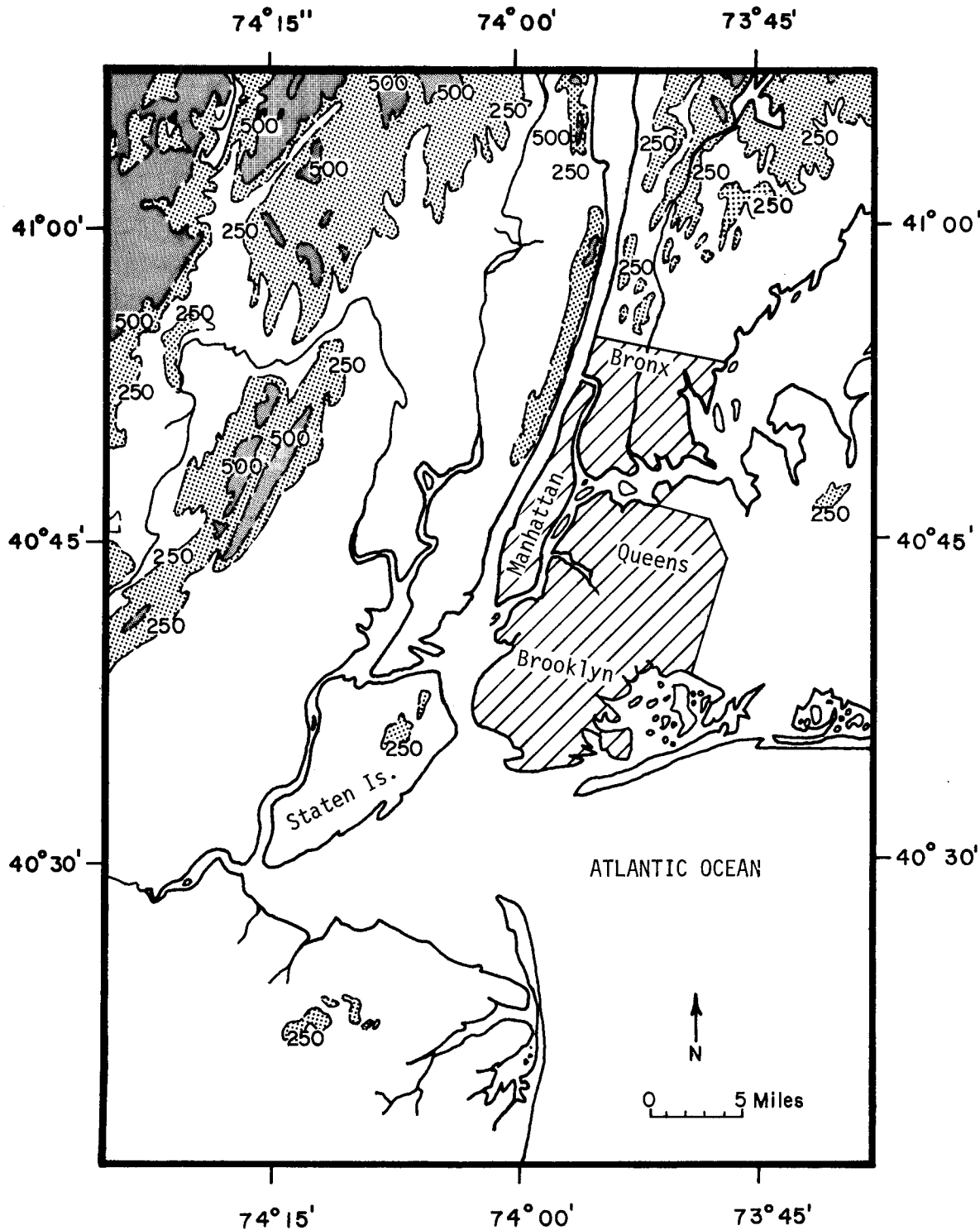


Table 1.—Fuel Consumption in New York City in 1965

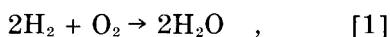
Fuel type	Uses	Annual consumption
Bituminous coal	Space-heating and firing of industrial boilers	5.4 x 10 ⁶ tons
Anthracite coal	Residential space-heating	0.72 x 10 ⁶ tons
Distillate oil #4	Space-heating of small apartment houses	1.5 x 10 ⁹ gal.
Residual oil #6	Space-heating of large apartment houses and operation of industrial plants and factories	2.6 x 10 ⁹ gal.
Natural gas	Fuel in power plants, energy for industrial plants, space-heating, and home cooking	1.67 x 10 ¹¹ ft. ³
Gasoline	Automobiles, trucks, and buses	1.1 x 10 ⁹ gal.
Diesel	Automobiles, trucks, and buses	66.6 x 10 ⁶ gal.

Table 2.—Composition of natural gas

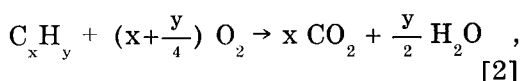
Paraffin hydrocarbon	Fraction of total mass	Water content
	<i>percent</i>	<i>percent</i>
CH ₄	93.45	186.90
C ₂ H ₆	3.67	11.01
C ₃ H ₈	1.78	7.12
C ₄ H ₁₀	0.65	3.25
Others	0.45	—
Total	100.00	208.28

bustion of these fuels produces oxides of sulfur, oxides of nitrogen, carbon monoxide, carbon dioxide, aldehydes, hydrocarbons, particulates, and water vapor. The quantities of these products put into the atmosphere depend on the rate of the combustion process, the content of impurities per unit mass, the equipment used for the combustion process, and the kinds of control devices that might have been installed. For example, in the steam boilers of Consolidated Edison power plants, 1.4 lbs. of steam are added per 100 lbs. of residual oil consumed. This is done in order to atomize the oil, so as to increase the efficiency of the combustion process. Thus the water-vapor emission rate from these stacks is greater than from other point sources.

The basic equation for the production of water from the combustion of coal (after the hydrocarbons have been broken down) is



while the general formula for the combustion of oil and gas is



where

$$y = 2x + 2 \quad [3]$$

if the hydrocarbon C_xH_y is saturated. Thus for coal, one gram of hydrogen produces 18 grams of water, while y grams of H₂ per mole of gas or oil produces 18Y/2 or 9Y grams of water per mole, where 18 is the ratio of the molecular weights of water and hydrogen.

The water production from each component of natural gas (table 2) was evaluated by multiplying the coefficient of the final term of equation 2; i.e., Y/2, by the percentages in the middle column of the table. Water-production factors for each of the seven fuel types used in New York City are shown in table 3, where the liquid water content of coal is determined by drying under standard conditions for 1 hour at 104 to 110 C.

The five boroughs of New York City (identified by name in figure 1) were gridded into 1 by 1 mile areas, and the following equation was used to evaluate

Table 3.—Composition by percent of total mass of the fuels used in New York City

Fuel type	H ₂ O (%)	Gaseous H ₂ O (%)	Liquid H ₂ O (%)	Total H ₂ O (%)	H ₂ O released per unit
Bituminous coal	5.14	46.26	2.0	48.26	0.4826 lb/lb
Anthracite coal	2.70	24.30	2.2	26.50	.265 lb/lb
Distillate oil	11.63	104.67	—	104.67	7.955 lb/gal
Residual oil	11.63	104.67	—	104.67	8.478 lb/gal
Natural gas	—	208.28	—	208.28	.11 lb/ft ³
Gasoline	15.00	135.00	—	135.00	9.315 lb/gal
Diesel	15.00	135.00	—	135.00	9.315 lb/gal

Table 4.—Percentage of SO₂ emitted from each fuel type in each Borough of New York City

Fuel type	Bronx	Brooklyn	Queens	Manhattan	Staten Island
Bituminous coal	1.45	8.61	32.53	37.26	70.80
Anthracite coal	2.16	1.34	.39	1.31	1.29
Distillate oil #4	8.60	13.91	10.26	1.13	5.99
Residual oil #6	87.18	75.69	56.05	59.88	21.53
Natural gas	.01	.01	.01	.01	.01
Gasoline	.39	.29	.48	.28	.22
Diesel	.21	.15	.28	.13	.16
Total	100.00	100.00	100.00	100.00	100.00

the magnitude of the annual anthropogenic moisture production M_A from each of the grid areas:

$$M'_A = \sum_{i=1}^7 \frac{S_A \cdot P_i \cdot M_i}{S_i}, \quad [4]$$

Definition and units for symbols are found at one end of this paper.

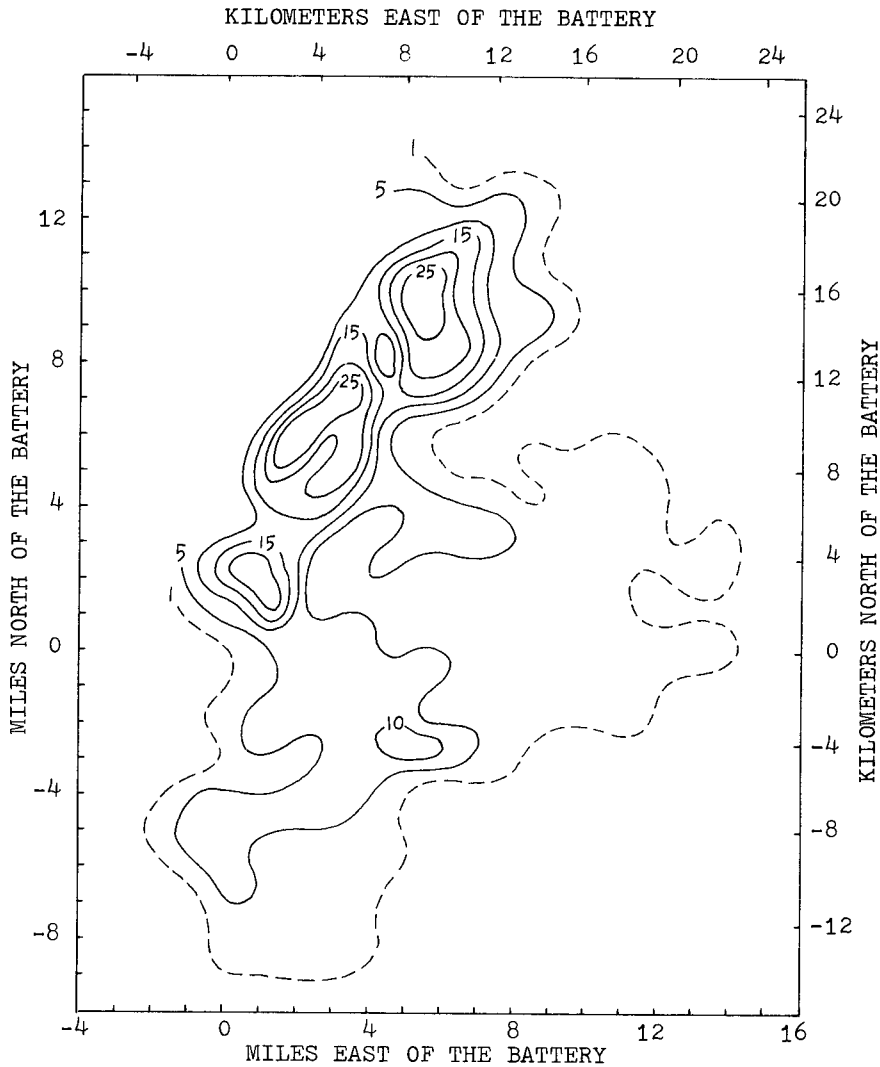
Note that the product of S_A (from the unpublished SO₂ inventory — now published by Bornstein *et al.* (1975b) — and P_i (table 4) gives the annual emission of SO₂ from the i -th fuel in a particular grid in tons per year. Values of P_i were kept constant in each borough because the use of each fuel in all of the grid areas was not available. Where the values were available, a random check showed that the magnitudes of P_i in a given borough were within ± 5 percent of the mean values used in Equation 4. The product of S_A times P_i divided by S_i (table 5) gives the annual use of the i -th fuel in the particular grids, while values of M_i (table 3) include the release of gaseous and liquid moisture.

Table 5.—Fuel type, sulfur content by weight, and sulfur emission factors for the seven fuel types used in New York City

Fuel type	Sulfur content (%)	SO ₂ emission factor
Bituminous coal	1.875	75.0 lb/ton
Anthracite coal	.625	25.0 lb/ton
Distillate oil	.575	85.0 lb/10 ³ gal
Residual oil	2.450	390.0 lb/10 ³ gal
Natural gas	4 ppm	.6 lb/10 ⁶ ft ³
Gasoline	.030	5.0 lb/10 ³ gal
Diesel	.300	45.0 lb/10 ³ gal

Annual area-source (fixed and mobile) emissions of anthropogenic moisture in New York City in 1965 in 10¹⁰ gm per year (fig. 3) were obtained by the summation of the seven partial emission rates of Equation 4. The origin of the grid used in the figure is at Battery Park, which is at the southern tip of Manhattan. The annual emission data were converted into average hourly fluxes (fig. 4), which have the units of 10⁻⁵ gm cm⁻² hr⁻¹ and can be used as

Figure 3.—Isopleth analysis of anthropogenic moisture production from area sources in New York City, in 10^{10} grams per year.



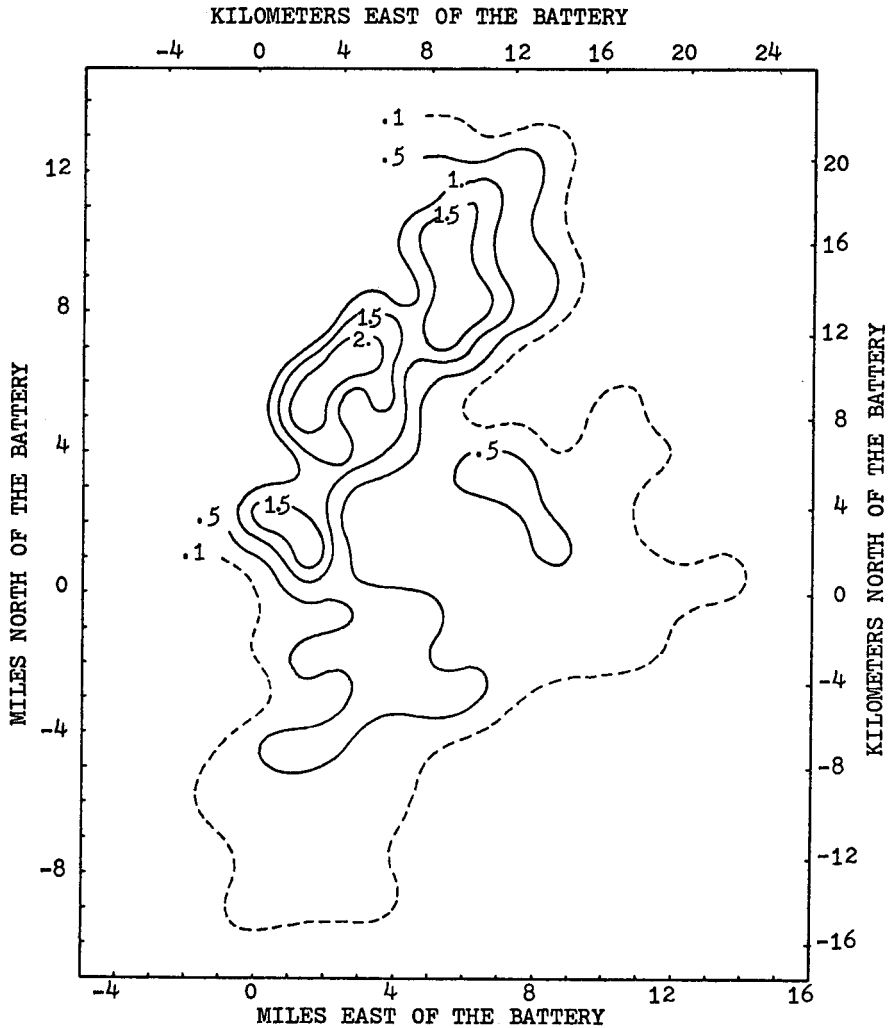
the lower (flux) boundary conditions in a numerical boundary-layer model of the urban atmosphere, as is being done by Tam (1975).

Because some areas in New York City are source-free (such as Central Park and rivers around Manhattan), the fluxes of the previous figure were recomputed in terms of emission intensities; i.e., the emission of H_2O per unit of production area per time. This increased the maximum emission from $2.2 \times 10^{-5} \text{ gm cm}^{-2} \text{ min}^{-1}$ to $4.3 \times$

$10^{-5} \text{ gm cm}^{-2} \text{ min}^{-1}$. The second value corresponds to a 22.6-cm-per-year annual evaporation rate, which is about 25 percent of the annual evaporation rate in the coastal Atlantic off of New York City (Jacobs 1951).

For studies requiring a more detailed emission pattern, the above computations were repeated on 0.5 by 0.5-mile area-source grid over Manhattan (Bornstein et al. 1975b), the region of maximum H_2O emission. In computing the emission rates for the finer grid, the

Figure 4.—Isopleth analysis of anthropogenic moisture production from area sources in New York City, in $10^{-5} \text{ gm cm}^{-2} \text{ min}^{-1}$.



emissions from the larger areas were assumed to be homogeneously distributed over the built-up areas of the city, while emissions from the rivers around Manhattan and from Central Park were taken to be zero.

Anthropogenic moisture production in New York City by borough (table 6) shows that Staten Island contributes only a small fraction of the total area-source emission in New York City (and hence it is not cross-hatched in fig. 1), while Queens contributes the maximum amount of any borough. Production by

fuel type (table 7) shows that residual oil produces more moisture in New York City than does any other fuel type, while production by source type (table 8) shows that domestic space-heating produces a larger amount of anthropogenic moisture than any other source type.

Estimates of the hourly emission rates of anthropogenic moisture from the fixed, but not mobile, area sources in New York City were made by using data obtained from timers attached to boilers located in selected buildings. The resulting data were used by Halpern

Table 6.—Anthropogenic moisture production in New York City by borough

Borough	Production (10 ¹² gm/year)	Percentage of total
Queens	10.13	33
Brooklyn	8.60	28
Manhattan	7.06	23
Bronx	3.99	13
Staten Island	0.92	3
Total	30.69	100

Table 7.—Anthropogenic moisture production in New York City by fuel type

Fuel type	Production (10 ¹² gm/year)	Percentage of total
Bituminous coal	2.35	7.7
Anthracite coal	.17	.6
Distillate oil	5.05	16.4
Residual oil	9.93	32.3
Natural gas	8.32	27.1
Gasoline	4.59	15.0
Diesel	.28	.9
Total	30.69	100.0

Table 8.—Anthropogenic moisture production in New York City by source type

Source type	Production (10 ¹² gm/year)	Percentage of total
Domestic	10.91	35.5
Industrial	1.78	5.8
Government & commercial	4.18	13.6
Power plants	8.95	29.2
Motor vehicle	4.87	15.9
Total	30.69	100.0

et al. (1971) to relate the number of minutes per day that the boilers were in operation to the degree-day value D computed as follows:

$$\text{or } D = 65 - \bar{T}, \quad \bar{T} \leq 65, \quad [5]$$

$$D = 0, \quad \bar{T} > 65,$$

where $\bar{T}$ is the average daily temperature of a given day in °F.

The boiler-timer data were then used by Halpern *et al.* (1971) to develop the

following equation, which relates the daily emission rate of H₂O from a particular area source to the annual emission rate from that area source:

$$M_D = \frac{0.7}{4871} D + \frac{0.3}{365} M_A. \quad [6]$$

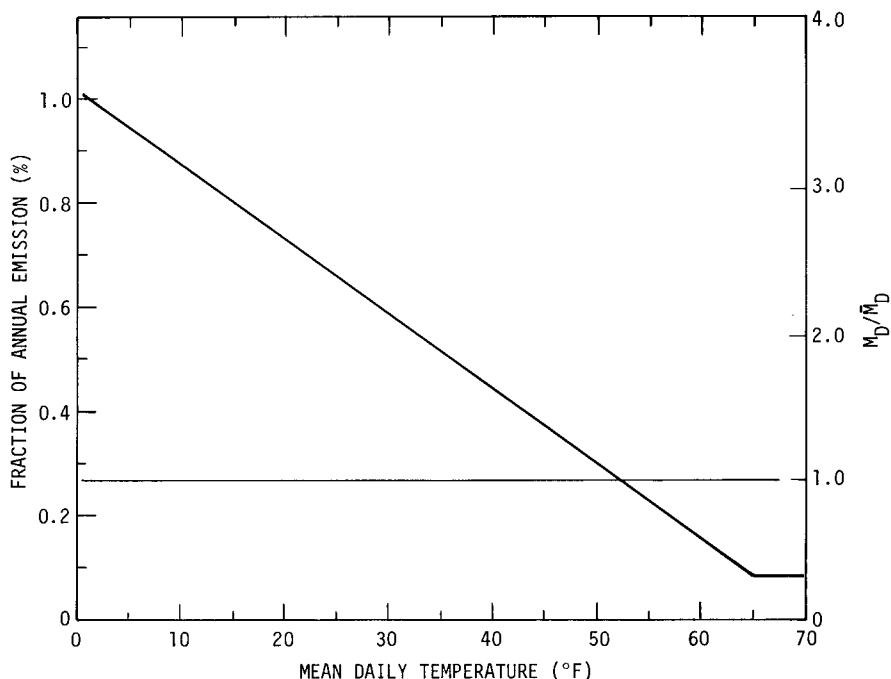
The above relationship shows that 30 percent of the annual emission of H₂O from each area source is due to the production of hot water at a uniform rate throughout the year. The remaining 70 percent is due to space-heating, which is dependent on the average daily temperature. Note that the annual sum of the daily degree-day values for New York City is the 4871 appearing in the equation.

If M_A were spread uniformly over the year, then on each day 0.27 percent of the total would be emitted. However, when Equation 6 is used to prorate M_A according to $\bar{T}$ (fig. 5), it is found that the value of $(M_D/M_A) \cdot 100$ percent varies linearly from 1.02 percent for a $\bar{T}$ of 0°F to 0.08 percent for a $\bar{T}$ equal to or greater than 65°F. Thus the emission on a cold day can be as much as an order of magnitude greater than that on a hot day.

The same boiler-timer data were used by Halpern *et al.* (1971) to develop curves showing the diurnal variation in winter, when most of the fuel is consumed for space-heating, and in summer, when most of the fuel is used for the production of hot water in the hours near sunrise and sunset. These results were used by Leahey and Friend (1971) to compute the spatial distribution of the annual and daily production of anthropogenic heat in New York from area sources due to fossil fuel use. They can be used to produce the same information for the anthropogenic moisture flux in New York City.

In the New York City area in 1965 there were 378 point sources of SO₂ that were found to have an annual emission rate of at least 100 tons of SO₂. The 205 point sources within the city emitted

Figure 5.—Fraction of annual area-source emission of moisture in New York City as a function of mean daily temperature. Also shown is the ratio of the daily emission M_D to the uniform daily emission $\bar{M}_D$ (shown as the horizontal line).



3.67×10^5 tons of SO_2 per year, or about one-half of that emitted by the area sources within the city.

In general, the rate of consumption by power plants, industrial processes, and automobiles changes only slightly throughout the year. However, the emission rates of some industrial and commercial sources do vary significantly over the year, and the emission rates of many point sources do have a diurnal variation. Where it was available, this information has been tabulated by Bornstein *et al.* (1975b), as has been the stack height and heat-emission data needed in plume-rise calculations. Thus the NYU/NYC data set contains the information needed to evaluate the area-source and point-source emissions of anthropogenic moisture in New York City for use as the surface flux boundary condition for moisture in an urban boundary-layer model of New York City.

NUMERICAL SIMULATIONS

In the basic URBMET model, finite difference solutions to the vorticity and energy equations are obtained in a vertical plane in the direction of a constant geostrophic wind. The vertical fluxes of heat and momentum are assumed to be constant with height in a lower, analytical, surface-boundary layer, while they generally decrease with height in an upper, numerical finite-difference, transition layer.

The transition layer is assumed to be hydrostatic and Boussinesq, the latter assumption implying incompressible flow. All lateral gradients are assumed to be zero, except for that of the undisturbed pressure, which corresponds to a constant geostrophic wind. Adiabatic motions are also assumed, while diffusion effects in the direction of the geostrophic wind are assumed to be insignificant as compared to advective effects. Initially,

adiabatic lapse rates are assumed, as the heat-island simulations are assumed to commence at 1800 LST. The eddy-exchange coefficients used in the transition layer in URBMET are computed from a third-order-polynomial. Details on the formulation of the model can be found in Bornstein (1975).

One modification of the original URBMET model in the current study was the inclusion of a continuity equation for water vapor, under unsaturated conditions, given by

$$\frac{\partial q'}{\partial t} = \frac{\partial(uq')}{\partial x} + \frac{\partial(wq')}{\partial z} + \frac{\partial}{\partial z} \left(K_q \frac{\partial q'}{\partial z} \right), \quad [7]$$

where K_q was taken equal to K_H . Because of this equality, the surface layer profiles for q' are identical to those for θ' , if q and q^* replace θ and θ^* , respectively, in the various surface boundary layer equations in B. In addition, the potential temperature θ is replaced by the virtual potential temperature θ_v . The two are related by

$$\theta_v = [1 + 0.61 q] \theta, \quad [8]$$

where each of the three variables, in the absence of any initial variations, can be given by the sum of a space average constant and a perturbation quality resulting from the urban induced circulations. If

$$\theta' \ll \theta_m, \quad [9]$$

it can be shown that

$$\theta_v' \approx \theta' + 0.61 \theta_m q', \quad [10]$$

and thus θ_v' replaces θ' everywhere in the model equations given in B. The second change in URBMET was concerned with the choice of the magnitude of the time step used in integration, and this is discussed in Bornstein and Robock (1975a).

An interlaced grid was used in this study, as it considers velocity components to be the average inflow and outflow rates on horizontal and vertical elements of a cube. Previous studies have discussed the superiority of vari-

Table 9.—Grid locations for θ , u and v grid points, with height above the surface z indexed by j , and distance from the center of the urban area x indexed by i

j/i	z (m)	x (km)
1	0	—30
2	12.5	—20
3	37.5	—12.5
4	62.5	— 7.5
5	87.5	— 5.0
6	125	— 2.5
7	175	0
8	225	2.5
9	275	5.0
10	325	7.5
11	375	10.0
12	450	15.0
13	600	22.5
14	850	32.5
15	1200	47.5
16	1650	67.5

able grid spacing in achieving high resolution near the surface and near discontinuities in surface characteristics. Accordingly, the 16 by 16 grid network used in the present study (table 9) possesses such a spacing near the surface, and in the vicinity of the city. A list of the boundary conditions on q' currently used is given below.

$$q' = a(x, t), \quad z=0, \quad [11]$$

$$\text{continuity of } q' \text{ and } \frac{\partial q'}{\partial z}, \quad z=h, \quad [12]$$

$$q' = 0, \quad z=H, \quad [13]$$

$$\frac{\partial(uq')}{\partial x} = 0, \quad \text{upwind boundary} \quad [14]$$

At each time step, following an initialization process described below, the following is performed: determination of the new values of θ_v' and q' at the surface; construction of the constant flux layer using the latest values of θ_v' , q' , and U at the surface, and at the lowest finite difference grid; and determination of the new q' , θ_v' , ζ , Ψ , u , w , v , and U fields, respectively, using the newest available values of all parameters and done in a

manner described in Bornstein and Robock (1975a).

The initial conditions were considered to be those at the beginning of an urban heat-island episode (at 1800 LST), and thus the following initialization procedure was carried out. First, the URBMET model was used to simulate the one-dimensional, neutral, dry planetary boundary layer over homogeneous terrain by assuming the following conditions

$$\frac{\partial}{\partial x} w = 0 \quad [15]$$

$$Y = \Gamma \quad [16]$$

$$\theta'_v = 0 \quad [17]$$

$$q = q_m = 0 \quad [18]$$

Justification of the assumption contained in Equation 16 for the hours near 1800 LST can be found in the observations obtained over cities (Bornstein 1968), as well as in those from rural O'Neill, Nebraska (Kuo 1968).

Simulations were carried for values of the surface roughness parameter z_0 of 1 and 3m, and for values of the geostrophic wind u_g of 3 mps. The values for z_0 were chosen to be typical of areas with buildings of one and six stories (Lettau 1969). The simulations were carried out using a constant value of 15 sec for the time step of integration, and were concluded when equilibrium conditions were obtained; i.e., when the final accelerations of the damping inertial oscillation were less than $0.1 \text{ cm sec}^{-1} \text{ hr}^{-1}$.

The resulting equilibrium wind profiles were then used as the initial conditions for simulations reproducing the two-dimensional equilibrium distributions of wind over a rough city under conditions of neutral stability. Thus, the conditions expressed in equation 15 were no longer used, but as the results of

these new simulations provided the initial conditions for the heat-island simulations discussed below, the conditions shown in equations 16 to 18 were still used.

Two-dimensional equilibrium wind distributions for the rough city cases were obtained after 3 hours of simulated time, using an equal advection and diffusion time step of 15 sec. The results of these simulations showed that the values of the total horizontal wind speed at the urban sites at heights up to several hundred metres were reduced in magnitude below those at corresponding heights at the upwind rural boundary. The maximum difference in speed occurred at the first grid point above the surface and over the downwind half of the city. The maximum upward and downward values of the corresponding vertical velocities were associated with the areas of maximum convergence and divergence at the upwind and downwind edges of the city, respectively.

Simulations were carried out to reproduce effects on the structure of the urban boundary layer, during the hours from 1800 to 1000 LST, resulting from higher urban than rural values of z_0 and surface temperature, but not q' . Hence, the conditions expressed by equations 16 and 17 were no longer used, but equation 18 was still applied.

The urban and rural surface cooling rates were estimated from the observations in and around urban Montreal by Oke and East (1971). These observations indicated that the rural atmosphere near the surface cooled rapidly in the evening hours before midnight, while the urban atmosphere near the surface was maintained at a nearly constant temperature during the same period. After midnight both regions cooled at about 50 percent of the rate found at the rural site before midnight. Therefore, the magnitude of the heat island near the surface increased with time in the early evening and then remained constant until morning. Thus

the following surface cooling and warming rates were assumed:

Period (LST)	Urban (C hr ⁻¹)	Rural (C hr ⁻¹)
1800-2400	0.0	-1.0
2400-0600	-0.5	-0.5
0600-1000	1.0	3.0

These simulations were carried out by using a variable time step for both the advective and diffusive processes (*Bornstein and Robock 1975*). The cooling rates prescribed above caused formation of a surface-based inversion in the rural areas, and the advection of cool rural air over the uncooled urban surface during the first 6 hours of the simulations caused formation of a slightly unstable layer near the urban surface. During the second 6 hours of simulation, the decreased surface-cooling rates slowed the rate of increasing stability at rural sites, while the urban cooling was unable to completely overcome the effects of advection, and thus Richardson numbers in the city remained slightly negative.

The horizontal wind field resulting after 6 hours of simulated time showed a region of decreased wind speeds, as compared to those at the upwind rural boundary. This region was found upwind of, and above, a region in which speeds are higher than those at the upwind boundary. A smaller region of decreased speeds was also seen downwind of the city near the surface. The corresponding vertical velocity field showed a region of sinking air over the city, sandwiched between two regions of upward motion.

The final simulations were carried out to reproduce the effects of an anthropogenic source of moisture on the structure of the urban boundary layer. Thus, the conditions expressed by equation 18 are no longer used; instead the background level of moisture q_m was arbitrarily set equal to 10 gm kg⁻¹. In addition, it was assumed that the surface value of q' at the urban grid points increased by 0.25 gm kg⁻¹ hr⁻¹.

Figure 6.—Distribution of the perturbation specific humidity q' in gm km⁻¹ after 12 hours of simulated time; i.e., at 0600 LST, for the flow over a warm, rough, wet city; values represent the deviation from those at the upwind boundary. Parameters include a geostrophic wind of 3 mps, a rural z_0 of 1 metre, and an urban z_0 of 3 metres.

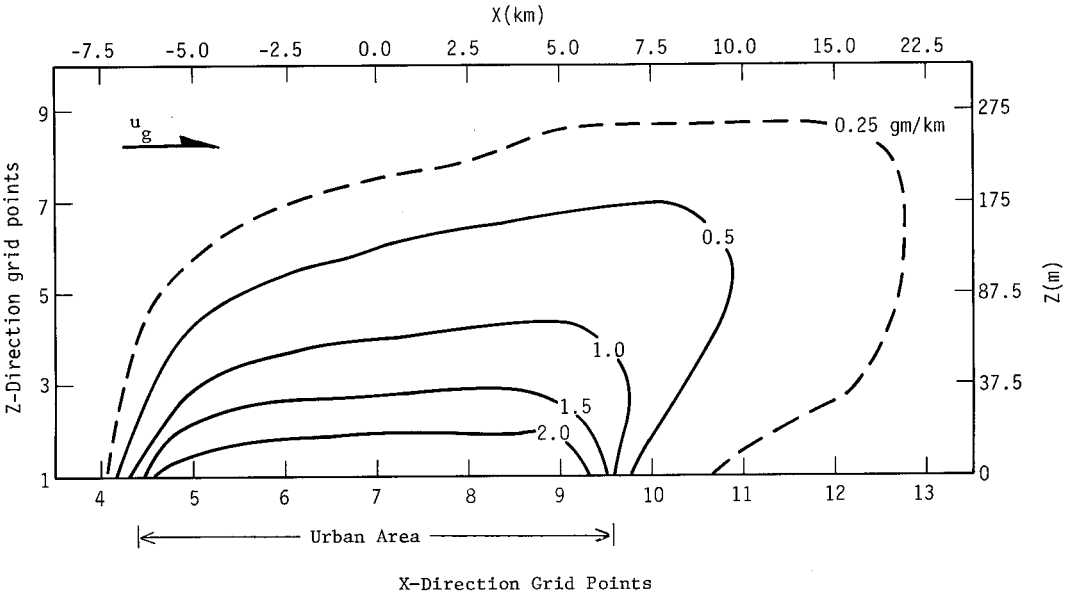
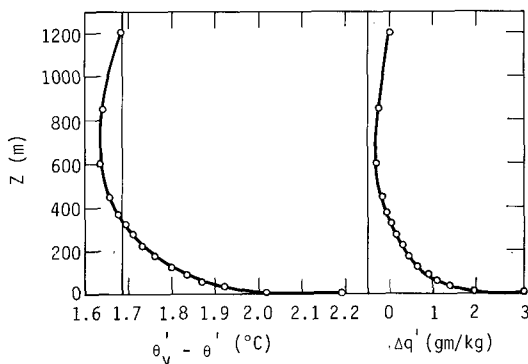


Figure 7.—Vertical variation of $\Delta q'$, the difference between the values of q' over the downwind urban edge and those at the upwind model edge, at 0600 LST for the run discussed in figure 6. Also shown is the vertical variation of $\theta'_v - \theta'$ at the upwind model boundary (thin vertical line) and at the downwind urban edge (thick curve).



The excess moisture thus placed into the urban atmosphere was advected and diffused vertically and/or horizontally, as expressed by equation 7. A typical distribution of q' after 12 hours of simulated time at 0600 LST (fig. 6) shows the effects of the advection and diffusion.

The vertical variation of the difference between the values of the perturbation specific humidity q' over the downwind urban edge and those at the upwind model edge at 0600 LST (the righthand half of figure 7) produces a buoyancy effect, as wet air is less dense than dry air. This enhances the buoyancy produced by the urban heat-island effect. At the same height above the surface, the magnitude of the buoyancy produced by the urban moisture excess at any point is given by the difference between the value of $\theta'_v - \theta'$ at the upwind model boundary and that at the point (fig. 7). From these values, and from the values of the total predicted buoyancy due to the heat-island effect was computed. The results (table 10) indicate that, near the surface, the additional buoyancy due to the moisture excess is about 10 percent of that due to the heat-island effect.

However, observations of the moisture excess over New York City by Bornstein *et al.* (1972) indicate that the moisture excess of the urban atmosphere in the present simulation could be increased by a factor of two. Even with the amount of anthropogenic moisture currently specified, there is a noticeable increase in the magnitude of the urban breeze effect (fig. 8) at the center of the urban area. The maximum increase of ΔU in the case of an urban moisture excess (case 2) over those from the case of no urban moisture excess (case 1) is about 8 cm sec^{-1} , or about 15 percent.

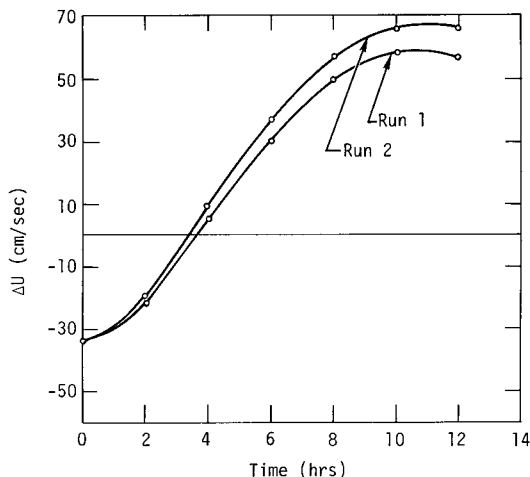
SUMMARY

A heat and moisture excess over of New York City has been shown to exist by use of helicopter soundings of temperature and wet-bulb depression. For three early morning flights, the moisture excess was about 0.9 gm m^{-3} , which represented an increase of about 10 percent over values at nearby rural sites. The humidity and moisture excesses were generally highest over the central part of the city, and then decreased over the peripheral urban areas, implying the existence of a heat and moisture dome over New York City.

Table 10.—Height variation of the temperature difference due to the urban moisture excess $\Delta\theta_1$, and due to the urban heat island $\Delta\theta_2$, at a site located at the downwind urban edge.

z (m)	$\Delta\theta_1$ (°C)	$\Delta\theta_2$ (°C)
0	0.5	5.8
12.5	.3	4.7
37.5	.2	2.5
67.5	.2	2.0
87.5	.1	1.7
125.0	.1	1.4
175.0	.1	1.0
225.0	.1	.8
275.0	.0	.7
325.0	.0	.6
375.0	.0	.4
450.0	.0	.3
600.0	.0	.1
850.0	.0	.0

Figure 8.—Time variation of the horizontal wind speed at a height of 125 m. Values represent the differences in cm sec^{-1} between the values at the upwind model boundary and those at the downwind urban edge for the two cases discussed in the text. The values of u_g and z_0 are those given for figure 6.



The magnitude of the temporal and spatial distributions of anthropogenic moisture emissions in New York City from fixed and mobile area sources were estimated using fuel-use data collected during the NYU/NYC urban air-pollution dynamics project of 1964-69. The maximum annual emission rate from a particular square mile in Manhattan was found to be equal to about 25 percent of the annual evaporation rate in the coastal Atlantic off of New York City.

The URBMET urban boundary-layer model was used to evaluate the effects on the dynamics of the urban boundary layer resulting from the buoyancy associated with an observed urban moisture excess. Results indicated that the buoyancy produced by the moisture excess was about 10 percent of that produced by the urban heat-island effect. This excess buoyancy enhanced the strength of the urban-breeze effect by about 15 percent over what had resulted due to the heat-island effect alone.

Work is currently in progress to determine the fraction of the observed

nighttime moisture excess over New York City that is due to each of the following: area-source emissions of moisture, point-source emissions of moisture, and reduced nighttime condensation rates in the urban areas, as compared to those in nearby rural areas. In this work, the flux of anthropogenic moisture into the atmosphere is used as a surface boundary condition for the URBMET boundary-layer model.

There is no completely satisfactory method of incorporating area and point-source emissions of moisture into a boundary-layer model. In previous models area sources of heat have been included in surface energy balances, even though some of this energy enters the atmosphere through the sides and tops of buildings. In addition, point sources cannot be represented in two-dimensional finite difference boundary-layer models, which can only treat line and area sources. Thus work remains to be done in order to accurately represent the effects of anthropogenic heat and moisture on the structure of the urban boundary layer.

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LIST OF SYMBOLS

Variables and Constants—

Roman Alphabet

$a(x,t)$	Specified variation of the surface specific humidity
h	Top of constant flux layer, equal to 25 m
H	Top of transition layer, equal to 1900 m
i	Horizontal index for horizontal wind and temperature grid
j	Vertical index for horizontal wind and temperature grid
K	Generalized eddy transfer coefficients in $\text{cm}^2 \text{sec}^{-1}$
K_H	Eddy transfer coefficient for heat in $\text{cm}^2 \text{sec}^{-1}$
K_q	Eddy transfer coefficient for moisture in $\text{cm}^2 \text{sec}^{-1}$
M'_A	Annual emission of moisture from a particular area source, in gm per year
M_A	Same as M'_A , but in $\text{gm cm}^{-2} \text{sec}^{-1}$
M_D	Daily emission of moisture from a particular area source grid, in $\text{gm cm}^{-2} \text{sec}^{-1}$
M_i	Moisture emission factor for the i -th fuel
p	Atmospheric pressure in dynes cm^{-2}
p_m	Constant space average of pressure in dynes cm^{-2}
p_0	Variation of pressure in absence of perturbation motion in dynes cm^{-2}
p'	Fluctuation of pressure due to perturbation motion in dynes cm^{-2}
P_i	Percent of total SO ₂ emission in a grid from use of the i -th fuel
q	Specific humidity in grams of moisture per grams of moist air

q_m, q_o, q'	See pressure definitions
q^*	Friction specific humidity in grams of moisture per grams of moist air
S_i	SO ₂ emission factor for i-th fuel
t	Time in sec
T	Temperature in K
T_m, T_o, T'	See pressure definitions
u	Horizontal component of wind in the x-direction in cm sec ⁻¹
u_g	Geostrophic wind in x-direction in cm sec ⁻¹
u^*	Friction velocity in cm sec ⁻¹
U	Total horizontal wind speed in cm sec ⁻¹
v	Horizontal component of wind in the y-direction in cm sec ⁻¹
w	Vertical component of the wind in cm sec ⁻¹
x	Horizontal coordination in direction of geostrophic wind in cm
y	Horizontal coordinate in direction perpendicular to the geostrophic wind in cm
z	Vertical coordinate for vorticity in cm
z_o	Aerodynamic roughness length in cm

Variables and Constants— Greek Alphabet

Γ	Dry adiabatic cooling rate, equal to 9.8 K km ⁻¹
ζ	Modified y-component of vorticity in sec ⁻¹
θ	Potential temperature in K
$\theta_m, \theta_o, \theta'$	See pressure definitions
θ_v	Virtual potential temperature in K
θ'_v	Perturbation virtual potential temperature in K
θ^*	Friction potential temperature in K
Ψ	Stream function in cm ² sec ⁻¹
Δ	Difference operator

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