# Urban-Rural Humidity Differences

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## ABSTRACT

Urban and rural airport surface weather observations in a 13-year period of rapid city growth are used to document city effects on absolute and relative humidity in a dry climate at fairly high latitudes. The city is found to be dry at all hours (relative humidity) and dry by day but moist at night (absolute humidity) in all but winter months. Some but not all of the major features of the humidity differences conform to those found by Ackerman for Chicago. In winter, relative and absolute humidities are high in the city at all hours because of vertical mixing and combustion sources. Maximum differences in absolute humidity at night occur in March and August. The former is attributed primarily to urban snowmelt on occasions when rural temperatures are below freezing. The August peak occurs near sunrise and is attributed mainly to rural dewfall. The times of maximum cooling and maximum absolute humidity in the city on clear hights in summer are strongly dependent on wind speed. For this reason it is argued that interaction of advection processes and vertical flux divergence (radiative plus turbulent) seems to be essential for realistic simulation of urban cooling rates at night. Moisture differences appear not to play a crucial role in heat island development.

## 1. Introduction

The urban heat island and other manifestations of the influence of an urban area on atmospheric properties have been described at length for many different cities by many authors in recent years and one may ask whether or not such extensive study is justified. What purposes are served by achieving a better understanding of minor urban effects on weather and climate? References have been made by some authors to possible biological effects and it may happen that significant biological effects will be found and that such effects in themselves will justify the effort. However, it is not difficult to identify other reasons for urban climatology.

One compelling reason for such studies is the fact that cities appear to initiate complex interactions between advective, diffusive and radiative processes following local changes in boundary conditions. The problem of urban weather and climate is a problem of unsteady airflow over inhomogeneous surfaces and as such is an example of a major class of unsolved problems in micrometeorology. The data are almost always inadequate for a comprehensive study of all important physical processes that are taking place. Nevertheless, continuous data from multiple surface weather stations and towers in cities, and special studies utilizing automobile traverses, mobile sounding units, and helicopters have shed light on the structure and properties of airflow over cities. One hopes that continued observational and theoretical studies will lead to a much better understanding of the interactions that occur and that such knowledge will be useful in other problems of nonstationary flow over complex terrain.

Some knowledge of urban climatology is needed for other quite different reasons. In central Alberta, as in many other areas, urban observations are the only observations of temperature, wind and humidity that are available for relatively long time periods for regional and local water balance studies, and for climatic change studies. Some understanding of urban effects is needed if one is to adjust past observations to rural equivalents for use in long-term estimates of evaporation and evapotranspiration. Similarly, trend estimates derived from long-term smoothed temperature data are quite sensitive to systematic variations caused by urban effects and should be adjusted accordingly.

Urban influences on absolute humidity are not yet well understood or documented even though the literature on urban climatology in general has increased very rapidly in the past several years. It is generally agreed that, in terms of relative humidity differences, cities tend to be dry at all hours of the day in most months of the year. However, for certain purposes such as studies of radiative fluxes, and of the role of water vapor in air pollutant reactions, absolute humidities and their differences are needed.

Perhaps the most comprehensive survey of urban effects on air moisture has been given by Ackerman (1971) in the form of a comparative study of 20 years of hourly dew points at Argonne National Laboratory and Midway Airport in Chicago. In other cities helicopter or surface traverse measurements have been used to map humidity fields on selected days (Bornstein *et al.*, 1972; Chandler, 1967; Kopec, 1973). From these studies have emerged the concepts of an urban vapor dome (Bornstein *et al.*, 1972) and of large diurnal changes in absolute humidity differences, particularly in the warm season. The city has been found to be moist at night and dry by day relative to the surrounding countryside. However, the pattern of hourly and seasonal differences is very complex and contains some unexplained anomalies. In speculating on the reasons for some of the largest differences Ackerman (1971) attributed high city moisture at night in the warm season to dewfall in the country. She argued that evaporation of dew and the onset of transpiration in the early morning led to a rapid reversal in the sign of the differences. In the cold season combustion sources of water vapor in the city and, possibly, dessication over rural snow cover were thought to be responsible for urban excess moisture.

## 2. Data

Humidity and temperature data from 13 years of observations (1961–73) at the Atmospheric Environment Service stations at Edmonton International Airport (rural) and Edmonton Industrial Airport (urban) were studied in an attempt to evaluate urban effects in a dry climate at relatively high latitudes. Principal site characteristics and a map of the region were given in an earlier report (Hage, 1972a).

The limitations of point observations in any study of urban effects must be kept in mind. It is most unlikely that any single observation site within a city can be considered representative of the city under all weather conditions. In particular, one suspects that airport observations are influenced by the presence of a large open space with extensive asphalt and concrete surfaces. Nevertheless, the principal features of urban-rural temperature differences derived from an urban network of stations in Edmonton were found to be well reproduced by airport observations, though the magnitudes may have been exaggerated (Hage, 1972a). This is attributed in part to the fact that under clear skies at night, when differences are often large, winds were almost always from the south (WSW to SE). In such conditions air reached the rural airfield unaffected by the city, and reached the observation site at the southern boundary of the urban airfield before crossing the field itself. Both observing sites are least satisfactory for NE winds but such winds are infrequent. Rural airport minimum temperatures have been found to be lower (1°C on the average in all months) than nearby rural climatological stations. No adjustments were made for this.

In the 13-year period for which simultaneous observations were available from both airports the city of Edmonton increased in population from 280 000 to about 460 000. Humidity differences were computed separately for the years 1961–66 and 1967–73. In attempting to interpret these differences emphasis was placed on features that appeared in both samples and that showed clear indications of the influence of city growth.

## 3. Results

Mean absolute and relative humidity differences for the two sampling periods at night (0500 and 2300 LST) are shown in Fig. 1. The pattern of absolute humidity differences was similar to that reported by Ackerman (1971) for Chicago except for the occurrence of a secondary maximum in March. The city was found to be moist in all months with minima in midwinter and in the relatively dry months of April and May. Relative humidities were lower in the city than in the country except in midwinter. The effects of city growth were apparent in all major features.

The March maximum in absolute humidity differences was associated with melting snow. In Edmonton, unlike most cities at lower latitudes, extensive snow and ice cover exists even on streets and roofs throughout most winters. Melting occurs principally in March and, because of the urban heat island, it is not uncommon at night to have temperatures above freezing in the city and below freezing in surrounding rural areas. The effect on absolute humidity differences is dramatic (Fig. 2). Differences as large as 1 g m$^{-3}$ on some nights added to combustion source of water vapor in the city to produce the March maximum in Fig. 1. Normally, rural snow cover persists for some days after snow has left the city. However, as shown in Fig. 2, the reverse effect on such days (rural moisture source) was much smaller than the effect caused by freezing of the rural snow surface. In the absence of significant water vapor sources other than local or distant melting snow in early spring dessication over melting snow is rare in central Alberta.

Average daytime differences (1100 and 1700 LST) are shown in Fig. 3. In general the city was dry in summer and moist in mid-winter relative to the country. Anomalies occurred in May and September in both sampling periods. The pattern of differences in the warm season appeared to be related to the fact that precipitation and transpiration are both large in June, July and August but much reduced in May and September. A late summer anomaly similar to the one shown in Fig. 3 in September was found in Chicago data and attributed tentatively to a local rapid decrease in transpiration (Ackerman, 1971). A much more thorough investigation than is possible with the present data is needed if daytime warm season differences are to be accounted for.

According to Figs. 1 and 3 the city is relatively moist at all hours on the average in winter. Observations from a nearby rural radiosonde station at night in winter show that, on the average, mixing ratios in-

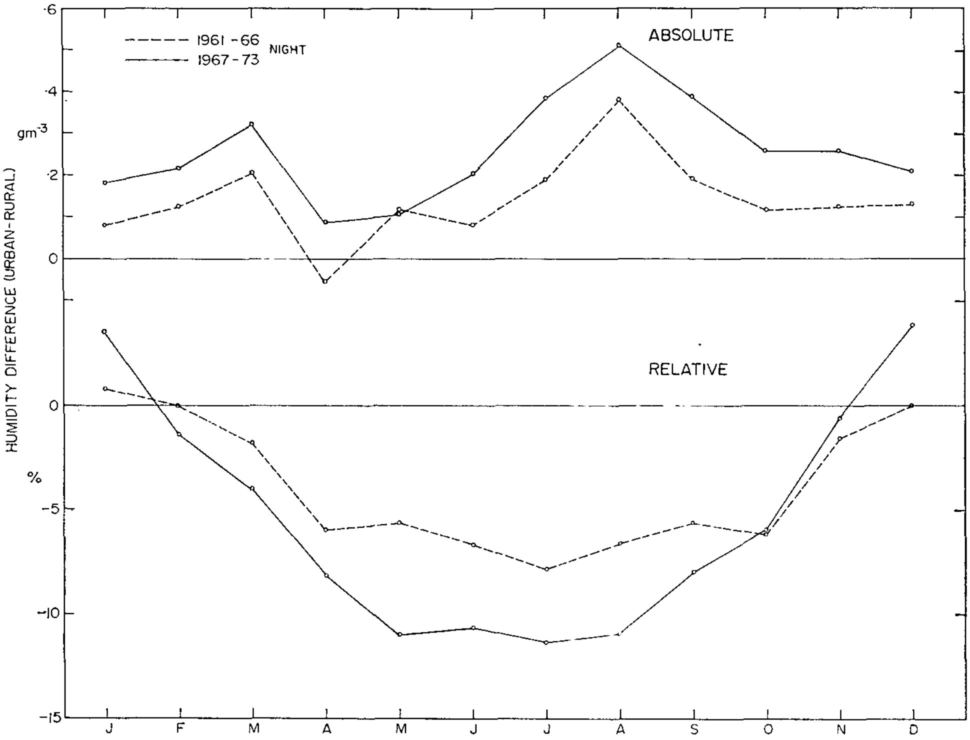

FIG. 1. Urban-rural absolute and relative humidity differences at night (average of data at 2300 and 0500 LST) from airport observations in Edmonton.

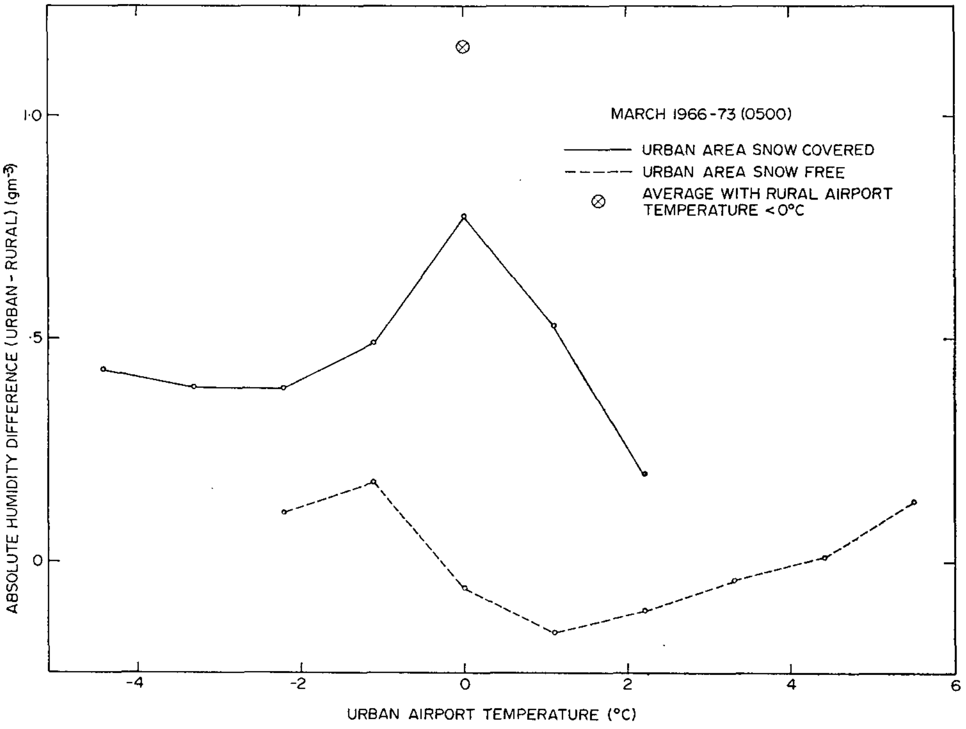

FIG. 2. Effect of melting snow on urban-rural absolute humidity differences in March from airport observations at 0500 LST at Edmonton.

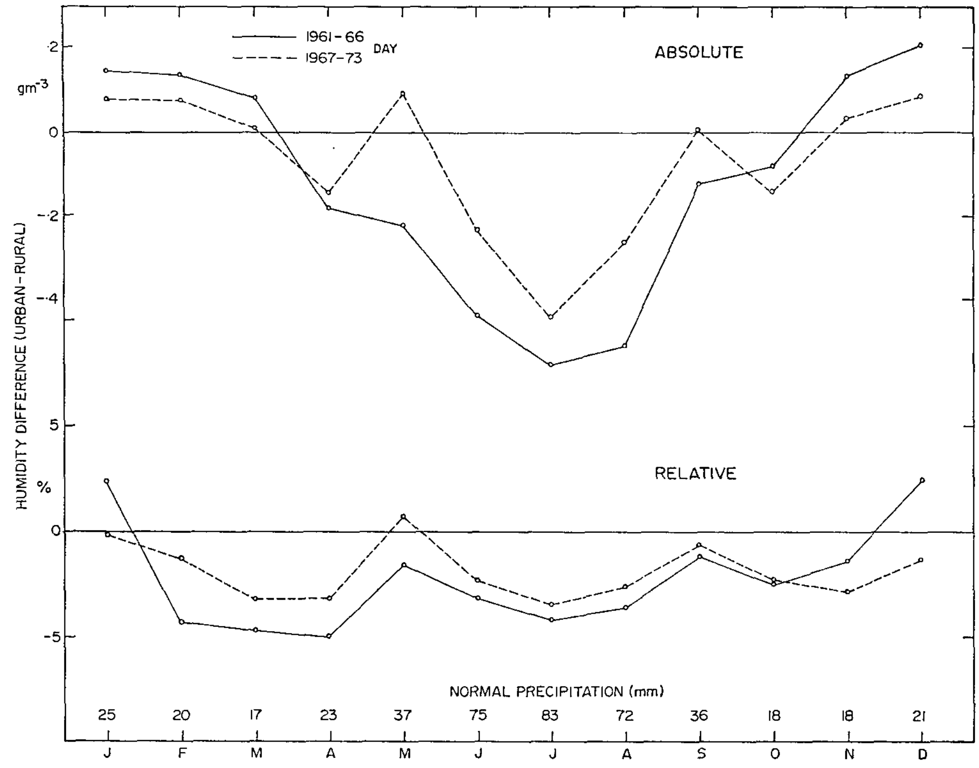

FIG. 3. Urban-rural absolute and relative humidity differences during the day (average of data at 1100 and 1700 LST) from airport observations in Edmonton.

creased with height in the lowest several hundred meters. Therefore, the absolute humidity of surface air as it passes over the city can increase both by vertical mixing and by the addition of water vapor from urban sources.

An attempt was made to estimate quantitatively the relative importance of these two processes using urban tower temperature profile data which became available in 1974. Temperatures at 1.2 m at the urban airport and at 10, 46 and 91 m on a nearby urban tower on strong heat island nights were found to be consistent with a temperature profile consisting of a well-mixed (dry adiabatic) layer of depth $h$ capped by an inversion having a linear vertical temperature gradient derived from the tower temperature at 43 m and the rural airport temperature at 1.2 m. Estimates of mixing-ratio contributions $\Delta r_c$ due to combustion were derived from a simple advection model for which

$$\Delta r_c = \frac{3Q_w x}{2\rho h U},$$

where $Q_w$ represents the mass of water added per unit area per unit time by combustion, $x$ is the distance from the upwind edge of the city to the urban airport, $\rho$ is air density, $h$ is the height of the mixed layer at the urban tower, and $U$ is the mean wind speed through the mixed layer. No assumption was made about the relative magnitude of radiation and combustion as heat sources for the production of a mixed layer. Instead, $h$ was derived from tower temperature data. Mixing-ratio contributions due to downward mixing of moist air ($\Delta r_m$) were estimated using vertical mixing-ratio gradients as observed in the rural air at 1200 GMT, and assuming constant mixing ratios in the layer of depth $h$. The results, including urban airport temperatures $T_u$ and observed rural-to-urban increases in maxing ratio $\Delta r_0$, on four mornings in December 1974 are listed in Table 1.

The required values of $Q_w$ were taken from daily non-industrial natural gas consumption data. Power

TABLE 1. Observed rural-to-urban mixing ratio increases ($\Delta r_0$) and computed changes due to combustion ($\Delta r_c$) and vertical mixing ($\Delta r_m$) at 1200 GMT on four days with strong heat islands in December 1974 at Edmonton, Alberta.

| Date | $T_u$ (°C) | $h$ (m) | Mixing-ratio differences (g kg⁻¹) $\Delta r_c$ | $\Delta r_m$ | $\Delta r_0$ | Residual |
|---|---|---|---|---|---|---|
| Dec. 3 | −7 | 44 | 0.16 | 0.14 | 0.59 | 0.29 |
| 9 | 1 | 33 | 0.06 | 0.08 | 0.26 | 0.12 |
| 10 | −4 | 30 | 0.10 | 0.08 | 0.51 | 0.33 |
| 11 | −8 | 26 | 0.20 | 0.07 | 0.34 | 0.07 |
| Means | | | 0.13 | 0.09 | 0.42 | 0.20 |

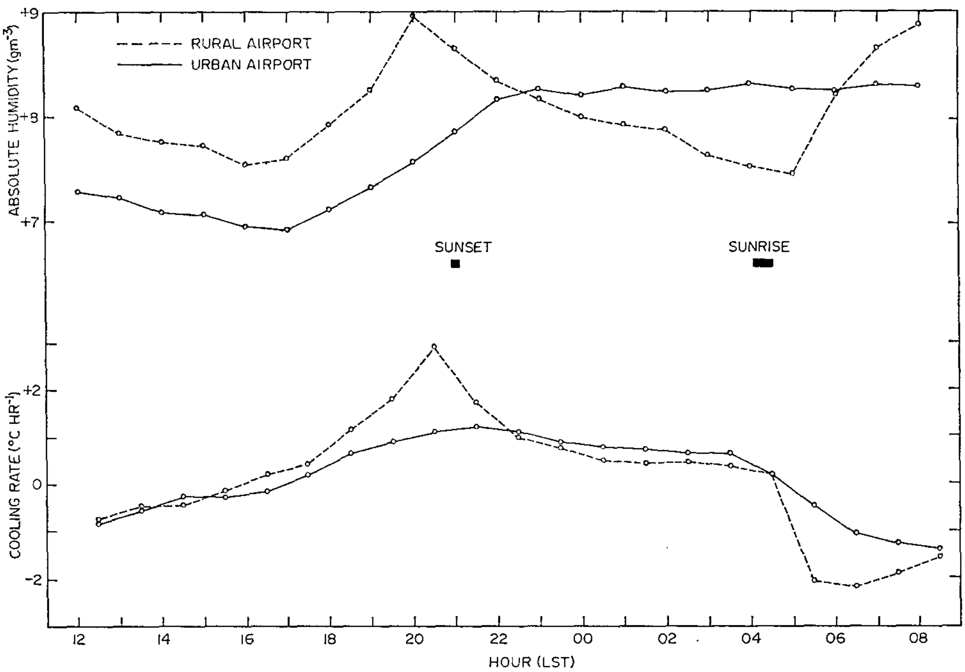

FIG. 4. Diurnal variations in urban and rural absolute humidities and cooling rates on clear nights in June and July from airport observations in Edmonton.

plants and large industries are located in the central, eastern and northern sections of the city and would not be expected to contribute to urban airport moisture in the S to SW winds that occurred on the dates listed in Table 1. A conversion factor of $2.3\times10^4$ J $g^{-1}$ for water-vapor production from pure methane was used. This represents an error of less than 5% for the natural gas used as fuel in Edmonton. Vehicle combustion rates would be negligible for the hours under study (0200 to 0400 local time).

According to Table 1 combustion products accounted for about 30% of the observed increase in mixing ratios at temperatures near 0°C on strong heat island nights in December. Vertical mixing contributed an additional 20%, leaving about one-half of the observed increase unaccounted for. The most probable reason for the discrepancy was that the contributions due to vertical mixing were underestimated because of the assumed linear gradient of mixing ratio between the surface and the lowest reported moisture level from the radiosonde (146 m). Vertical gradients of absolute humidity such as those illustrated by Geiger (1965) for the lowest tens of meters at night in dry climates are quite nonlinear with large magnitudes near the earth's surface.

As temperatures drop moisture contributions due to combustion increase and those due to vertical mixing decrease. In an earlier study (Hage, 1972b) it was shown that water vapor produced by combustion alone was sufficient to saturate air reaching the urban airport in Edmonton from the south and to produce fog at temperatures of about −30°C or lower. At normal winter temperatures (−15°C for December, January, and February) it appears that both combustion and vertical mixing contribute significantly to excess urban moisture.

In summer the diurnal variations in absolute humidity are large and complex. On clear days in rural locations in dry climates absolute humidities exhibit a pronounced double wave (Geiger, 1965). Maxima occur before sunset near the time of maximum surface cooling and after sunrise following the time of maximum rate of increase of temperature at screen level. The time of maximum cooling is also the time of maximum intensification of the urban heat island at screen level on such days and it is of interest to examine diurnal humidity variations in more detail.

Mean diurnal variations in absolute humidities and cooling rates for 30 sunny days in June and early July 1971–1973 (sunset within 10 min of 2100 local time) are shown in Fig. 4. The governing equations for potential temperature $\theta$ and specific humidity $q$, assuming no condensation in air, are

$$\underset{1}{\frac{\partial\theta}{\partial t}}+\underset{2}{\mathbf{V}\cdot\nabla\theta}=\underset{3}{-\frac{\partial\overline{w\theta}}{\partial z}}-\underset{4}{\left(\frac{P}{p}\right)^{\kappa}\frac{g}{c_p}\frac{\partial F_N}{\partial z}}, \tag{1}$$

$$\underset{1}{\frac{\partial q}{\partial t}}+\underset{2}{\mathbf{V}\cdot\nabla q}=\underset{3}{-\frac{\partial\overline{wq}}{\partial z}}, \tag{2}$$

where $\overline{w\theta}$ and $\overline{wq}$ represent the covariances between vertical velocity $w$ and temperature or humidity, respectively, $P$ is a standard pressure (1000 mb), $\kappa$ is the ratio of the gas constant to the specific heat of air at constant pressure $c_p$, $F_N$ is the net radiation flux, and the other symbols have conventional meanings. The covariances are subject to the lower boundary conditions

$$\overline{w\theta}=H_0/c_p\rho,\quad \overline{wq}=F_w/\rho,$$

where $H_0$ is the sensible heat flux and $F_w$ is the moisture flux at the earth's surface. Portions of the fluxes $H_0$ and $F_w$ are added to the air not at the surface of the land but in a layer that extends to tree-top level in rural areas and to roof-top level in the city. The time variations of absolute humidity and temperature change at screen level (1.2 m) in Fig. 4 correspond to those for $q$ and $\Delta\theta/\Delta t$ except for the effects of small density differences between the urban and rural sites.

The rural humidity curve in Fig. 4 shows a pronounced double wave characteristic of dry continental sites. The sharp rise prior to sunset has been attributed to vertical flux convergence, i.e., to the effects of term 3 in (2) (Geiger, 1965). After the time of maximum temperature surface cooling by radiation forms a stable layer near the surface and, assuming negligible advection, i.e., term 2 in (2), moisture accumulates because evapotranspiration exceeds turbulent fluxes to higher levels. Eventually a moisture inversion forms and the water content of the air at screen level decreases by slow downward diffusion and removal by dewfall at the surface. Following the onset of surface heating near sunrise the low-level moisture increases sharply due to rapid evaporation of dew and other surface water originally from subsurface soil layers. Time changes of humidity in the city were quite different. In this case advection cannot be neglected, and the combined effects of advection and vertical mixing produced a relatively slow rise in humidity near sunset followed by nearly constant values until well after sunrise. The rural nocturnal wave was absent and positive urban-rural differences were observed at most nighttime hours. Advection alone cannot account for these positive differences and one must conclude that high urban moisture values are maintained during the night either by continued evapotranspiration in the city or by downward mixing of higher specific humidities aloft advected in from rural areas. It should be possible to resolve this question with a few special experiments.

TABLE 2. Times of maximum urban (U) and rural (R) absolute humidities, cooling rates, and heat island intensification at 1.2 m in relation to wind speed on clear nights in June and July at Edmonton.

| | Time of maximum (hours relative to sunset) | | | | | |
|---|---|---|---|---|---|---|
| 10 m wind (m s$^{-1}$) | Absolute humidity | | Cooling rate | | Heat island intensity | Heat island intensification rate |
| | U | R | U | R | | |
| 1–2 | +4 | −1 | +3.5 | −0.5 | +1 | −0.5 |
| 2–5 | +2 | −1 | +1.5 | −0.5 | +3 | −0.5 |
| 5–10 | 0 | −1 | −0.5 | −0.5 | +5 | −0.5 |

Simultaneous cooling rates at screen level at the two airports are shown in the lower part of Fig. 4. Rural cooling reached a maximum at or just prior to sunset and it was at this time that most rapid intensification of the urban heat island occurred as found by Oke *et al.* (1972) for Montreal and Vancouver. This was followed by a cooling rate slightly greater in the city than in the country until sunrise. After sunrise the rural airport warmed much more rapidly than the urban airport thereby greatly reducing heat island intensities.

Most nocturnal temperature prediction models show maximum cooling at or near sunset followed by a fairly regular decline in agreement with rural observations (Brunt, 1932; Frost, 1948; Atwater, 1972; Zdunkowski *et al.*, 1967). According to the most sophisticated numerical models the rate of cooling at sunset is very sensitive to the specification of surface physical properties (Atwater, 1972; Zdunkowski and Trask, 1971). However, even with large variations in surface properties and vertical moisture profiles (Zdunkowski and Barr, 1972) no significant lag of maximum cooling beyond sunset is predicted. This strongly suggests that the occurrence of maximum urban cooling rates 1–3 h after sunset and the occurrence of maximum heat island intensity 3–5 h after sunset instead of near sunrise are due to the interaction of advection and vertical flux divergences (radiative plus turbulent,) i.e., none of the terms 2, 3 and 4 in (1) can be neglected. Some evidence in support of this is given in Tables 2 and 3 which separate the data of Fig. 4 according to wind speed.

It will be seen that, while magnitudes changed, the times of maximum cooling and of maximum absolute humidities at the rural airport were not functions of wind speed in the range 1–10 m s$^{-1}$. However, the times of these events in the city varied considerably with wind speed. In particular, nights with light winds

TABLE 3. Maximum values of urban (U) and rural (R) absolute humidities, absolute humidity differences, and cooling rates at 1.2 m in relation to wind speed on clear nights in June and July at Edmonton.

| | Maximum values | | | | |
|---|---|---|---|---|---|
| 10 m wind (m s$^{-1}$) | Absolute humidity (g m$^{-3}$) | | Humidity difference R−U (g m$^{-3}$) | Cooling rate (°C h$^{-1}$) | |
| | U | R | | U | R |
| 1–2 | 9.0 | 10.2 | 2.8 | 1.6 | 3.3 |
| 2–5 | 8.9 | 8.9 | 0.9 | 1.4 | 2.8 |
| 5–10 | 7.9 | 8.4 | 0.7 | 1.4 | 2.6 |

(1–2 m $s^{-1}$) were characterized by large cooling rates, maximum heat island intensities, and large absolute humidity differences (2.8 g $m^{-3}$ or 25% less moisture in the city) just after sunset. By midnight urban moisture exceeded rural values and the temperature differences declined.

The coincidence in timing of maximum cooling rates and maximum humidities at the rural airport may suggest that moisture was a significant factor in heat island development. This is not supported by observations in dry months such as May and September. Cooling rates and heat island intensities on clear nights in these months were almost as large as those in midsummer but urban-rural moisture differences were marginal.

## 4. Summary

A comparative study of 13 years of humidity data from rural and urban weather stations in the Edmonton area showed that on the average in all but winter months the city experienced lower relative humidities at all hours with mean monthly differences of more than 10% at night in summer. Urban absolute humidities were lower by day but higher at night than those in the country in the warm season. In winter both relative and absolute humidities were higher in the city because of vertical mixing and combustion sources of water vapor. Rough calculations indicated that both processes were important at average winter temperatures but that combustion sources dominated at low temperatures.

Annual maxima in absolute humidity differences were found at night in March and August (city moist) and by day in July (city dry). The March peak was attributed to urban snowmelt acting as a water vapor source on nights when rural temperatures were below freezing. The largest mean monthly differences in absolute humidity exceeded 0.5 g $m^{-3}$. The August peak difference at night was attributed mainly to rural dewfall as suggested by Ackerman (1971) in an earlier study of humidity data from Chicago. The double diurnal wave which is characteristic of rural absolute humidity changes in dry climates was absent in the urban data. It is difficult to imagine how the observed time changes in urban temperatures and humidities at night in summer can be explained without including all of the physical processes of horizontal advection, radiative flux divergence, and vertical turbulent flux divergence.

The results obtained in this study provide valuable guidance for the design of experiments that will be undertaken in an attempt to obtain quantitative estimates of the relative importance of water vapor sources and sinks and transfer processes. Specifically it is clear that there is a need for much better resolution of both rural and urban temperature and moisture profiles in the lowest 50 m at night in winter and summer, preferably supplemented by net radiation, vertical turbulent flux and dewfall measurements.

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