A Preliminary Investigation of the Nocturnal Temperature Structure above the City of Edmonton, Alberta

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ABSTRACT.—Information about the nocturnal temperature structure over Edmonton, Alberta. Observations of the temperature fields, including two- and three-dimensional forms of the nocturnal heat island, were obtained from minisonde ascents, an instrumented helicopter, and towers during a 3-week urban air-pollution field study. Results show that urban-induced temperature modification is typically in the lowest 100 m above ground. Along the direction of the prevailing wind, there is a progressive modification of very stable upwind air as it flows toward the city center, the urban air being less stable. Implications of these observed features on urban air pollutants are discussed.

THE NOCTURNAL TEMPERATURE in the lowest few hundred meters above urban areas has received much attention in recent years *(Oke 1974, Garstang et al. 1975)*. Observations have shown that the city's influence on the nocturnal temperature regime commonly can extend up to 300 m and that thermal boundary layers are generated as stable upwind rural air is advected over a warm urban surface. This sometimes results in a well-defined urban thermal and pollution plume extending aloft and downwind of the city. Within the modified urban air, temperature profiles often exhibit near-neutral conditions, thereby supporting the contention of a well-mixed urban layer. Accordingly, there is usually a marked decrease in frequency and intensity of ground-based inversions over urban areas compared to those over adjacent rural surroundings.

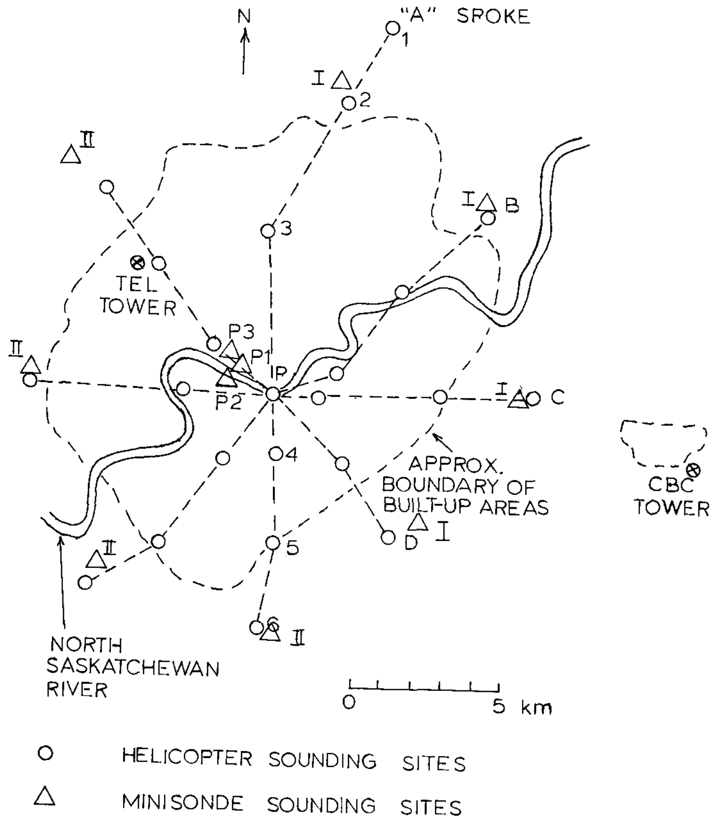
The development of this modified layer above the city is generally attributed to any one or a combination of the following processes: (1) thermal turbulence due to anthropogenic sources or to the release of stored heat in urban structures, (2) mechanical turbulence generated by air flow over urban roughness elements and subsequent redistribution of heat, and (3) radiative processes in the urban atmosphere.

The purpose of this paper is to present some qualitive and quantitative aspects (including spatial characteristics) of the nocturnal temperature regime and associated boundary layer structure over Edmonton, Alberta. The implications for urban air-pollution modelling are also discussed. The study is based primarily on low-level temperature-profile measurements obtained in and near Edmonton during an intensive 3-week urban-air-pollution field study in November and December 1974.

EXPERIMENTAL SITE AND PROCEDURE

Edmonton, a medium-size city with a population of about 0.5 million, was selected as the target for this urban meteorological and pollution study. The city is located on the banks of the North Saskatchewan River in Central Alberta (53°33′N,113°30′W). The topography is generally flat except near the river valley, which runs in an approximately northeast-southwest line through the city (fig. 1). There the valley is steep-sided and narrow, with an average

Figure 1.—Map of the Edmonton area and sampling scheme for probing the urban atmosphere.



depth of about 50 m. From the river banks, the land rises gradually, the most significant change being to the southeast (a slope of 1:200 at 15 km from the city center). The extent of the built-up area is shown in figure 1. The urban core consists primarily of medium-density structures. This is surrounded by mixed low-density commercial and residential areas. Heavy industries are mostly on the eastern fringes of the built-up areas.

The synoptic-meteorological conditions during the investigation period (19 November to 5 December 1974) were near normal for this time of the year, with one notable exception: a lack of significant snow cover in the region. Otherwise typical winter characteristics prevailed. This period was chosen in part to maximize the chances of observing well-developed heat-island effects and high air-pollution episodes.

For the monitoring of low-level temperature profiles, two mobile minisonde systems, a helicopter, and two instrumented towers were used. The minisonde system is a lightweight version of the radiosonde. It consists of a small inexpensive fast-response temperature sonde (microbead thermistor, time constant 1.5 s, relative accuracy 0.2° C), which is carried aloft by a standard pilot balloon with a rise rate of about 3 m/s. Heights and winds aloft were obtained by tracking the balloon via the double-theodolite method. The helicopter was equipped with a Sign-X temperature unit, along with pollution-measuring equipment. The temperature sensor for this unit consisted of a shielded thermistor with a response time of about 0.5 s and a relative accuracy of 0.2°C. Heights were obtained from a pressure transducer with a similar response time and a relative accuracy of 5 m.

Supplementary temperature information was obtained from two instrumented towers (fig. 1) operated by the Atmospheric Environment Service, Canada. Both the telephone and CBC towers (urban and rural respectively) are equipped with Rosemount platinum resistance thermometers in aspirated radiation shields and with linear matching bridges at heights of 10.0 and 91.5 m above ground. An additional temperature sensor is located at the 45.7-m level on the urban tower. Wind measurements on both towers were recorded at the 91.5-m level.

The adopted sampling scheme for probing the urban atmosphere is also shown in figure 1. Nocturnal measurements, utilizing the minisonde system, consisted of comparative urban and upwind rural temperature profiles during the periods shortly after sunset and before sunrise. Eleven simultaneous comparisons were obtained. One minisonde unit was used at a fixed location near the city center (P1, P2, or P3) depending on the prevailing wind. Simultaneously, the second unit monitored the nearby upwind rural profile at locations A, B, C, or D (I or II), also depending on the prevailing wind.

On two occasions, 12 minisonde ascents were made along two transects across the city, one line perpendicular to the other, to investigate the spatial structure of the boundary layer. At selected points along the spokes A, B, C, or D, helicopter soundings near sunrise provided vertical profiles of temperature upwind, over, and downwind of the urban area. In addition, the instrumented towers gave continuous nocturnal measurements of low-level urban and rural temperature gradients during the entire study period.

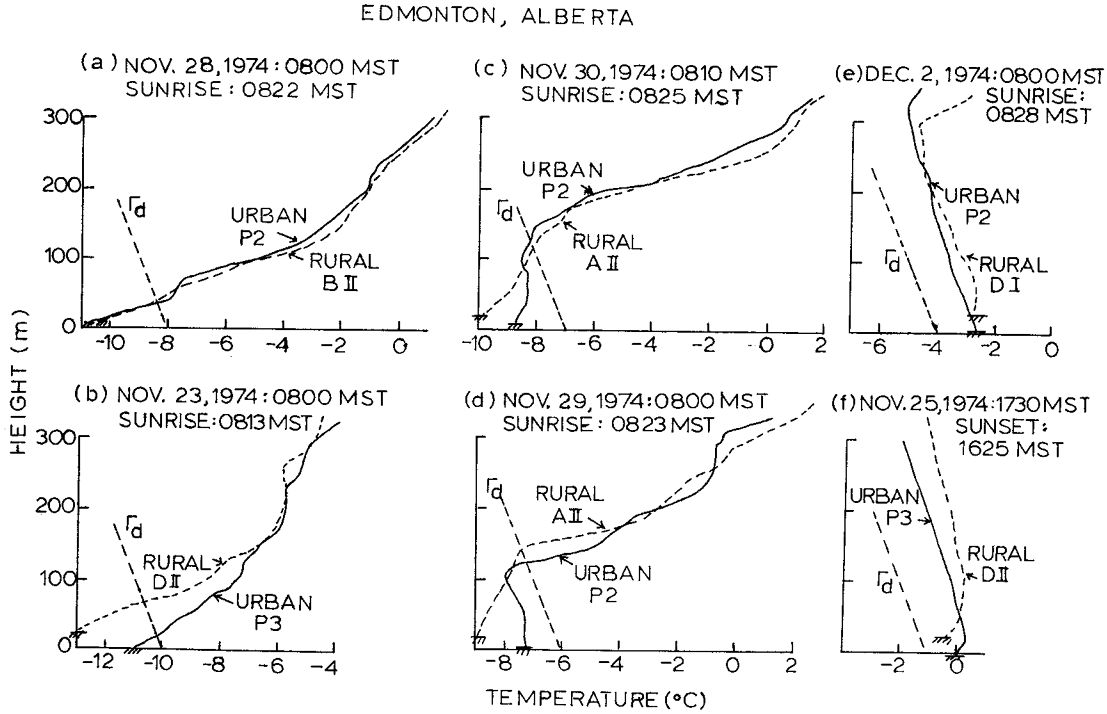
URBAN AND UPWIND RURAL TEMPERATURE PROFILES

Typical examples of comparative urban and upwind rural nocturnal temperature profiles, based on minisonde ascents, are shown in figure 2. These were selected primarily to illustrate the wide range in urban atmospheric temperature profiles than can occur under inversion conditions in the nearby upwind rural areas.

In figure 2(a), the prevailing wind was from the southwest with speeds below 4.0 m/s in the lowest 100 m. Despite the lack of significant snow cover in the area, intense and deep surface-based inversions (6.9°C/100 m in the low-levels, inversion top at 430 m) occurred at both urban and rural sounding sites. As no urban-induced temperature effects are discernable, it is not possible to define a mixed or modified layer. This suggests that radiative cooling over the southwestern areas of the city was at least as intense as that over the nearby rural surroundings. In this sector of the city, larger segments of green areas than urbanized land occur. It was noted, however, that similar urban and rural inversion profiles occurred on occasions with westerly winds.

The situation, illustrated in figure 2(b), is for a northwest wind. Typical wind speeds were less than 2.5 m/s below 100 m, and less than 5.0 m/s in the layer between 100 and 200 m. The upwind rural inversion was both intense and deep. The air trajectory was mainly over built-up areas as it approached the urban site. A significant heat island, decreasing with height, was evident. Noteworthy, however, was the fact that the modified urban layer, about 140 m deep, remained strongly stable (3.2°C/100 m inversion), although slightly weakened

Figure 2.—Examples of simultaneous urban and upwind rural temperature profiles from the minisonde systems for the period between sunset and sunrise.



in comparison to that in the rural environment. This type of effect was observed on several nights. The dominance of radiative processes over the relatively low-density urban structures would perhaps explain this type of urban profile.

Another situation that occurred commonly is shown in figure 2(c). Here, the upwind rural site was characterized by a ground-based inversion, more intense aloft than near the ground. Winds were from the south, and speeds were less than 0.5 m/s below 20 m, increasing to about 4.5 m/s in the layer 20 to 100 m. At the urban site, the profile is near isothermal below 100 m. This type of modification may also be ascribed to radiation processes as suggested by Hage and Longley *(1970)*, in which the city experiences less radiative heat loss than the surrounding countryside. Radiation equilibrium (isothermal) conditions would thus be expected with increasing urban heat-island intensities.

As in the previous example, figure 2(d) shows similar upwind rural conditions with a southerly flow. Wind speeds, however, were much stronger, 4 to 5 m/s below 50 m, and about 10.0 m/s between 50 and 100 m. A well-defined mixing layer (about 100 m deep) with near adiabatic conditions, developed over the urban site. This type of urban profile has been observed often in mid-latitude cities *(Clarke and McElroy 1974)* and supports Summers *(1967)* concept of the city acting as a heat source to create its own mixed layer characterized by an adiabatic lapse rate. In this particular example, mechanical turbulence, thermal turbulence, and radiative factors probably all contributed to the modification process.

Figure 2(e), a situation for southeast winds, indicates considerable modification below 300 m at both urban and rural sites. Wind speeds ranged from 3 to 6 m/s in the lowest 50 m. Between

50 and 100 m, speeds increased to about 10 m/s and for the subsequent 200 m aloft, averaged about 13 m/s. Lapse rates below the inversion were near adiabatic. As the modification occurred both inside and outside the city, the dominant influence is considered to be of meso-scale extent. The presence of extensive cloud cover on this morning would appear to support this. The slight increase in mixing depth over the city may have been caused by additional mechanical turbulence over urban roughness elements.

Last, figure 2(f) illustrates an example of conditions after sunset for a northwest wind. Shallow ground-based inversions at both urban and rural sites were evident, despite the fact that wind speeds averaged about 7.0 m/s in the lowest 50 m depth. There was, in addition, a small heat-island effect. The urban inversion was slightly weaker in intensity than that over the rural site.

These examples offer some insight into the problems of defining or predicting the nocturnal urban boundary layer. In the past, this layer, expressed in the form of an urban mixing layer, has often incorporated in air-quality dispersion models. The recent works of Clarke and McElroy *(1974)* and DeMarrais *(1975)* suggest that the depth of the nocturnal boundary layer over the center of the city can be estimated from the temperature structure of the upwind rural environs or by the dry adiabatic extension of the maximum heat-island temperature to an upwind rural temperature profile.

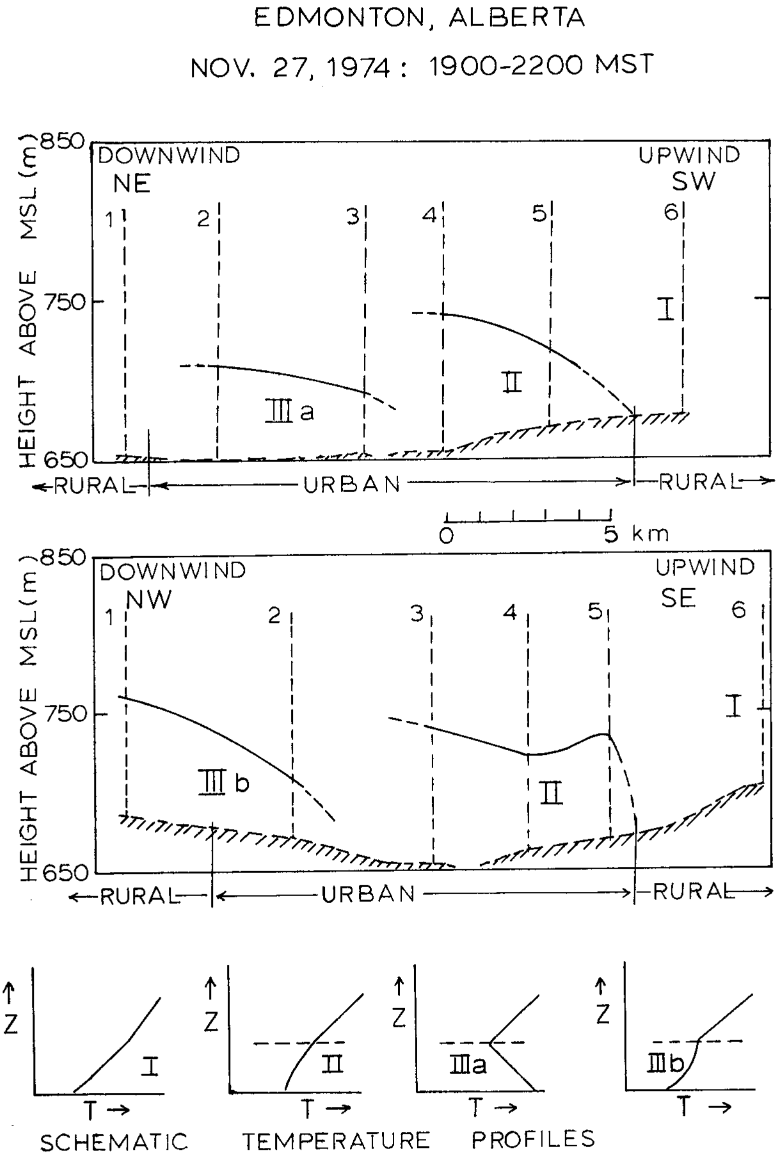
Such techniques unfortunately do not seem suitable for the situation observed in Edmonton, where a near-adiabatic assumption may often be inapplicable. Indeed, the concept of a nocturnal urban mixing depth, with the important implication of a more or less uniform vertical distribution of pollution, would perhaps be more aptly replaced by the term 'modified depth', in which the urban lapse rate can range from inversion to adiabatic and in which pollution can be stratified. Land-use patterns and associated radiative processes, as well as mechanical and thermal turbulence effects, could then be combined with information on the upwind rural temperature profile to formulate a scheme to predict this modified depth (including its nonoccurrence). The use of a modified depth to define the nocturnal urban boundary layer thickness over Edmonton yields values typically of about 100 m or less near the city center. This corresponds to a boundary layer slope of 1:50 or shallower.

NOCTURNAL URBAN BOUNDARY LAYER STRUCTURE

Spatial aspects of the boundary layer structure over Edmonton were investigated on two nights, 27 November (1900-2200 MST) and 30 November (0500-0810 MST). On both occasions, minisonde ascents were made along two transects, perpendicular to each other, across the city. These low-level profiles were then used to estimate the thickness of the modified depth and the shape and structure of the urban boundary layer. The height of the modified depth was identified as that point on the temperature profile (a continuous temperature trace output) above which the gradient approximately coincided with that of the upwind rural profile or, in some instances, the point where a distinct change in gradient on the urban profile could be readily identified.

Figure 3 shows the boundary layer structure for 27 November along with schematics of the observed temperature profiles. Southerly winds prevailed during this experiment, with mean speeds of about 2.5 m/s below 50 m and 5.5 m/s between 50 and 100 m. The two transects, northeast-to-southwest and northwest-to-southeast, closely followed spokes B and D, respectively (fig. 1). The upwind rural area was denoted region I. Here similar ground-based inversions occurred, both southeast and southwest

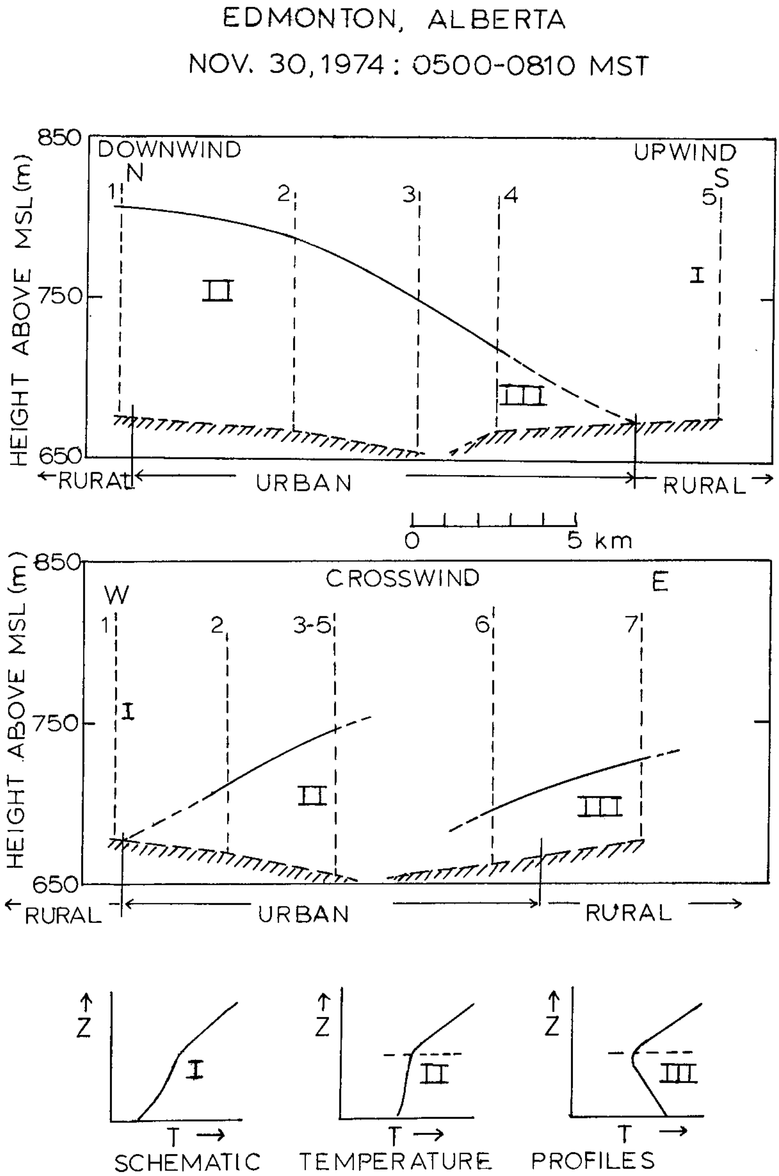
Figure 3.—The nocturnal boundary layer structure over Edmonton on the late evening of 27 November 1974.



of the city center. The characteristic temperature profile of this region was assumed to extend to the edge of the upwind built-up areas. As the air flowed across urbanized land, region II developed, consisting of a modified layer of less intense inversions and a general progressive increase in boundary layer thickness towards the urban center. Further downwind, a second boundary layer could be identified (designated regions, IIIa and IIIb). Here, lapse rate in the modified layer was extremely unstable (superadiabatic) to the northeast, whereas it was relatively stable and of distinct shape to the northwest. Boundary-layer depth on this night over the city was confined to the lowest 100 m.

The second experiment (fig. 4) showed

Figure 4.—Along-wind and cross-wind structures of the nocturnal boundary layer over Edmonton on the early morning of 30 November 1974.



the structure on the early morning of 30 November. The two transects, north-south and east-west, closely followed spokes A and C respectively (fig. 1). The air flow was again from the south. Wind speeds below 20 m were light, about 1.0 m/s, increasing to about 4.5 m/s in the layer 20 to 100 m. Along the direction of the wind, an increasing boundary layer could be identified from the upwind south side across to the downwind side of the city. In this layer of modified air, temperature profiles decreased in stability from near adiabatic upwind to slightly stable downwind of the city center. Crosswind, the boundary layer structure closely resembled that which was observed on 27

November (fig. 3). These examples of the spatial nature of the nocturnal urban boundary layer over Edmonton are believed to reflect the heteorogenous nature of the urban surfaces.

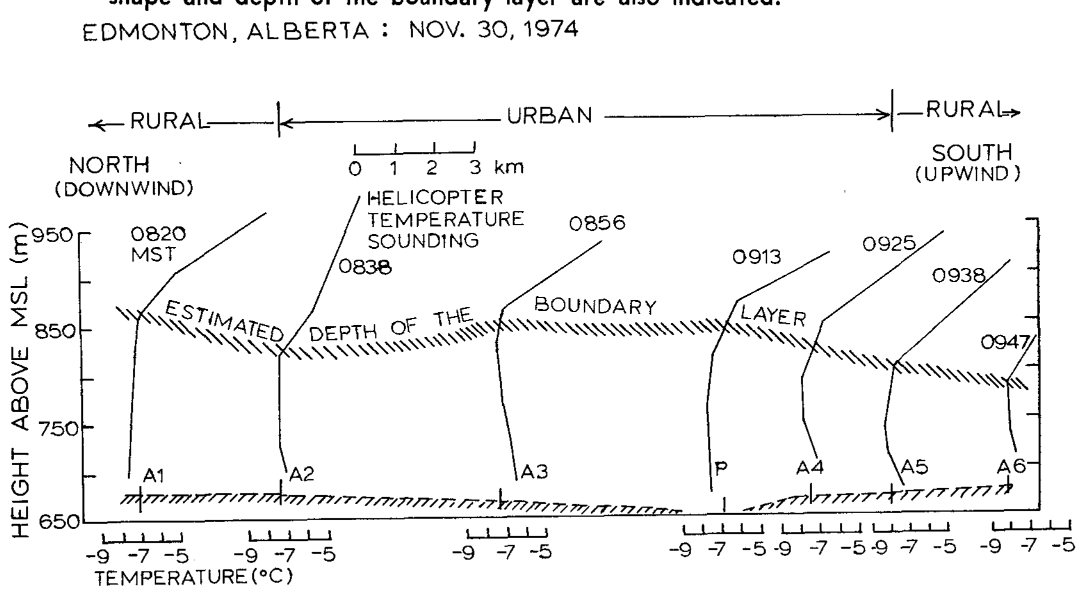
URBAN BOUNDARY LAYER STRUCTURE NEAR SUNRISE

Observations of the boundary-layer structure over Edmonton from detailed helicopter temperature profiles were made only during daylight hours because of restriction on night-time flying. Hence, for this study, only the measurements near sunrise were considered relevant. These provided information on the temporal evolution of the nocturnal boundary layer through the sunrise transition period.

The example (fig. 5) was obtained on the morning of 30 November (0800-1000 MST) along spoke A (fig. 1). It depicts the temperature structure upwind of, over, and downwind of the urban area, along with the associated boundary layer, and, in addition, it represents the evolution of the nocturnal boundary layer (fig. 4) through the sunrise transition period. Wind direction and speeds remained almost the same as previously given for the period 0500-0810 MST.

The most significant change in boundary-layer shape and depth occurred over the upwind rural areas. Here the nocturnal ground-based inversions were destroyed up to a depth of about 120 m through natural convection processes within an hour and a half after sunrise. This effect was observed on most late-morning temperature soundings from both the minisonde and helicopter measurements. In general, the effect of solar radiation and subsequent warming from below created significant daytime rural mixing depths of almost similar magnitude to that over the urban areas by mid-day. The structure below the boundary layer closely followed that observed before sunrise (fig. 5). Profiles generally decreased in stability along the direction of the prevailing wind, from near adiabatic upwind to slightly stable on the downwind side of the city.

Figure 5.—Helicopter temperature profiles across Edmonton in the direction of the prevailing wind at and after sunrise on 30 November 1974. The inferred shape and depth of the boundary layer are also indicated.



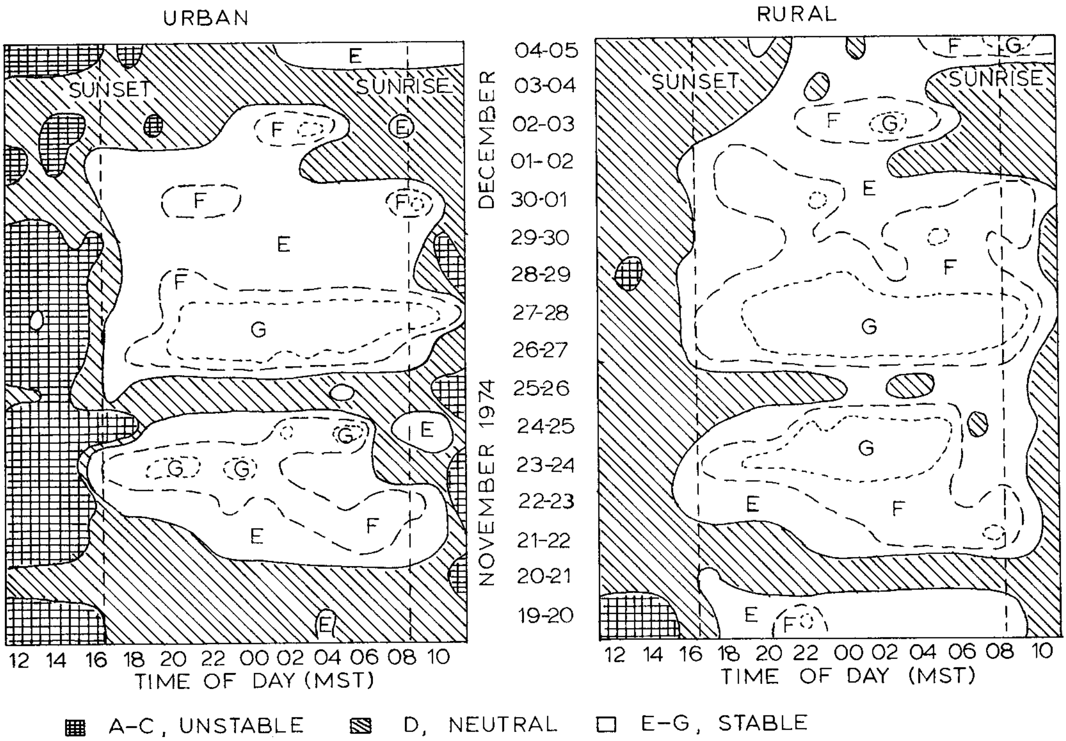
URBAN AND RURAL TOWER STABILITIES

The hourly vertical temperature gradiants, monitored between 10.0 and 91.5 m on the urban and rural towers during the period 19 November to 5 December 1974, were used to approximate low-level stabilities in and near Edmonton. Initially, the gradients were examined in terms of Pasquill stability categories as defined by USAEC (1972) (table 1). The stability patterns are illustrated in figure 6. Between sunset and sunrise, both urban and rural towers showed a prevalence of stable conditions (63 and 78 percent respectively). An examination of these nocturnal stability patterns indicates that, relative to the rural environs, the urban site is characterized by no change in stability 56 percent of the time, decreased stability 42 percent, and increased stability 2 percent. Of the cases with decreased stabilities, a change by one stability category (D to C, E to

Table 1.—Classification of atmospheric stability

Stability classification	Pasquill categories	Temperature change with height (°C/100 m)
Extremely unstable	A	< —1.9
Moderately unstable	B	—1.9 to —1.7
Slightly unstable	C	—1.7 to —1.5
Neutral	D	—1.5 to —0.5
Slightly stable	E	—0.5 to 1.5
Moderately stable	F	1.5 to 4.0
Extremely stable	G	> 4.0

Figure 6.—Urban and rural tower stabilities (temperature gradients) in Edmonton during the period 19 November to 5 December 1974.



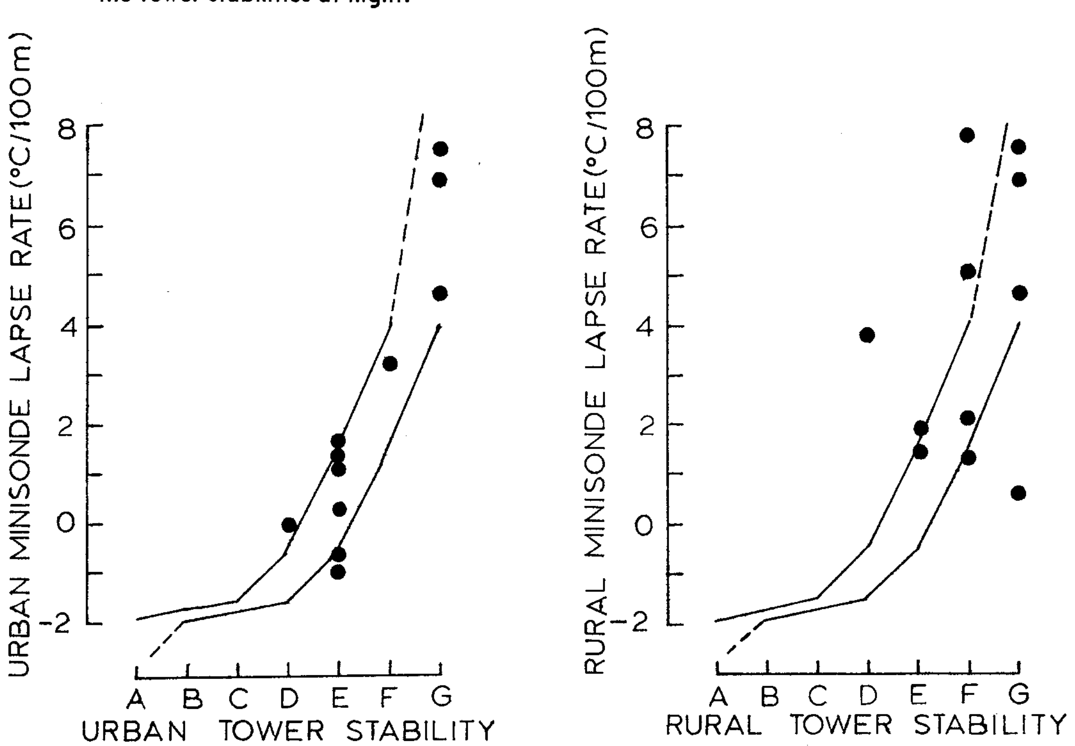
D, etc.) occurred on 83 percent of the occasions. If the cases of coinciding neutral stability (D) on both towers are excluded (such conditions being likely to occur under overcast conditions, regardless of urban or rural terrain), the following urban stability changes are obtained: no change 45 percent, decreased stability 53 percent, and increased stability 2 percent.

A comparative study of the nocturnal stability variations between 10.0 and 45.7 m with that between 10.0 and 91.5 m on the urban tower gave no difference in stability 69 percent of the time. For the other occasions, stability variations with height were almost equally shared between an increase and a decrease. Hence, it was inferred that vertical stability changes on the urban tower were relatively insignificant.

The tower data suggested that two dominant patterns are likely to occur in the lower urban atmosphere with stable nocturnal rural conditions: in one case, no change between urban and rural stabilities; in the other, a decrease of one stability category over the urban area. The latter situation is commonly assumed for estimating the vertical diffusion length over a city *(Gifford 1972)*. These nocturnal features are in general agreement with the detailed observations of temperature profiles previously discussed. In addition, the persistence of inversion conditions on the urban tower for a few hours after sunrise on several mornings (fig. 6) agrees with the minisonde results, which showed urban ground-based inversions around 0930 MST on 22, 23, and 28 November 1974.

A comparison of the 11 simultaneous upwind rural and urban minisonde soundings at night with the rural and urban tower stabilities for the same time periods is given in figure 7. From the urban profiles, lapse rates within the

Figure 7.—Comparison of the low-level lapse rates from minisonde ascents with the tower stabilities at night.



modified layers, or in some instances, the lowest 100 to 150 m above ground (cases of no modification) were estimated. The lowest 100 to 150 m were used to obtain the rural lapse rates also. In figure 7 the solid-dashed lines represent the envelope relationship between temperature gradients and stability *(USAEC 1972)*. In general, the urban tower stabilities showed good agreement with the minisonde derived urban lapse rates. There was slightly less agreement between the rural tower stabilities and the rural minisonde lapse rates. This was not surprising because the rural tower stabilities may not always be representative of conditions upwind of the city. This limited comparison suggested that the urban tower stabilities may yield reasonable approximations of diffusion characteristics within the modified urban layer over Edmonton and may be potentially useful in the development of an urban dispersion climatology of the area.

CONCLUSION

This preliminary investigation of the nocturnal temperature structure over Edmonton provided some experimental evidence of the manner in which a medium-size city can alter the lower atmospheric thermal regime and the associated boundary layer structure. In contrast to similar investigations for other mid-latitude cities, the results here showed a wide range in urban-induced temperature modification (from inversion to adiabatic and in some instances, no change) when stable upwind rural air is advected over the city.

On the average, nocturnal boundary layer depth seldom exceeded 100 m. Within this modified layer, lapse rates were often stable (inversion). Hence, it is suggested that the term "urban nocturnal mixing depth" would be more aptly replaced by the term "urban nocturnal modified layer" and that suitable techniques should be developed to predict this depth in which the lapse rate can vary over a wide range.

Case studies of the variation in the nocturnal boundary layer structure exhibited complex patterns that seem to reflect the heteorogeneous nature of the urban surface. Urban tower gradients, expressed in terms of Pasquill Stability categories, indicated two dominant regimes: no change in stability, and a decrease by one stability category (less stable) as compared to simultaneous rural values. The determination of these urban stabilities from tower measurements could be applied usefully in developing an urban dispersion climatology for the area.

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