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CLIMATOLOGICAL BULLETIN is published twice a year. It exists primarily to report on the research in climatology in the Department of Geography at McGill University, supported mainly by grants in aid from the National Research Council of Canada and the Department of Transport (Meteorology Branch). The Department also publishes a CLIMATOLOGICAL RESEARCH SERIES, information on which will be found at the end of this Bulletin.

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FOREWORD

CLIMATOLOGICAL BULLETIN No. 5 represents the start of the third year of the BULLETIN's existence. The format remains the same as in previous numbers but the content reflects a growing interest in the purpose behind the BULLETIN in that it contains contributions from persons not in the McGill University climatology group. To attract appropriate contributions from outside has always been an objective behind the BULLETIN, the purpose of which is to provide a medium for reporting rapidly on work in progress, especially within the fields in which the climatology programme at McGill University is interested.

The publication thus provides a forum for early discussion or report of work in progress which nevertheless in no way precludes later publication in a more substantive form in recognized printed journals. Each article is, however, carefully scrutinized and, where thought necessary, is subject to outside advice and critism.

The present number is devoted to urban climatology, which is being developed as a major field of study at McGill University under the guidance of Professor T.R. Oke, who brought together most of the contents of this number of the BULLETIN. The second number planned for 1969 will be devoted mainly to radiation and energy budget studies, representing the other major field of the climatology programme.

A word of explanation as to the date of each number is, perhaps, necessary. The month on the cover, January or July as the case may be, indicates the month up to which material is being reported. It takes six to eight weeks to edit and prepare this material for the BULLETIN, which is then normally distributed, approximately 10-12 weeks after the end of the month named on the cover page.

In order to make the BULLETIN financially self-supporting a subscription list of 300 is needed. So far, one-third of this goal has been achieved. Interested readers are invited to help by either subscribing themselves or ensuring that libraries in their institutions are subscribers.

B. J. Garnier,
Editor.

March, 1969.

TOWARDS A MORE RATIONAL UNDERSTANDING OF THE URBAN HEAT ISLAND

By

T. R. Oke*

This paper seeks to examine the concept of the urban heat island as an example of the way in which the McGill programme is approaching the problem of studying the urban atmosphere. The emphasis is placed upon the need to study process, in an effort to provide a sounder physical basis for the urban heat island and other urban effects.

URBAN HEAT ISLAND CONCEPT

The term 'urban heat island' draws an analogy of the city appearing as a land mass in the sea of the surrounding countryside. The analogy is both climatic and geomorphic. Climatically the comparison is based on the contrasting heat responses of land/water, and city/rural surfaces. Hence Chandler (1961) likens the pulsating winds set up by the city/rural temperature gradient, to land and sea breezes. The geomorphic analogy is drawn upon by reference to the abrupt city/rural temperature gradient as a 'cliff' to the island, and the similarity of the heat island isotherms to topographic contours. However, just as modern geomorphologists are not content merely to map landforms, so climatologists should not be content merely to describe the form of urban heat islands. Both the geomorphologist and the climatologist must involve themselves in the study of process. The study of process begins with an understanding of the controlling factors.

FACTORS CONTROLLING URBAN CLIMATE

There are five classes of factors which, being unique to the city, control the urban climate and hence the urban heat island.

(a) Urban fabric.

The vegetation, crops and soil of the countryside are replaced in the urban environment by bricks, concrete, steel, asphalt and glass. Thus the city is generally a drier, denser, less pervious and more rigid surface. Micro-climatically the surfaces could hardly be more dissimilar.

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TABLE ONE

Rural/urban Albedo Values

Surface	Locality	Month	(%)
Farmland	Indiana	September	14 - 16
City	Bloomington, Ind.	September	14 - 16
Farmland	Wisconsin	September	15
City (downtown)	Madison, Wis.	September	16
City (downtown)	" "	February (snow)	14
City (suburbs)	" "	February (snow)	18 - 42
Farmland	" "	February (snow)	20 - 56
City	Duluth, Minn.	July	12
City (suburbs)	" "	July	16
Woody grassland	Minnesota	July	16 - 17
City	Las Vegas, Nev.	September	19 - 20
Desert	Nevada	September	24 - 27

TABLE TWO

Representative urban and rural roughness lengths

Surface	z_o (cm)	Author
Mud flats, ice	0·001	Sutton (1953)
Lawn grass (1 cm)	0·1	"
Thick grass (10 cm)	2·3	"
" " (50 cm)	9	"
Liverpool, Eng.	123	Jones et al (1968)
Tokyo, Jap	165	Yamamoto and Shimanuki (1964)
Minneapolis/St. Paul	200	Deland and Binkowski (1966)
London, Ont.	230	Davenport (1967)
Fort Wayne, Ind.	300	Csnady et al (1968)

* City values computed without zero-plane displacement (see equation 7)

Attention is usually drawn to the difference in thermal properties between the two surfaces. In particular it is usual to assume the urban fabric to possess a much higher conductive capacity c ($c = \sqrt{\rho \psi}$ where ρ is density, c specific heat and ψ thermal conductivity). The city therefore possesses a greater ability to absorb and store daytime solar radiation. It should be noted, however, that a recent study by Davis (1968) indicated only small rural/urban differences in c between Fort Wayne, Indiana and the surrounding countryside.

The distinctly different rural/urban surfaces might be expected to produce a reduction in albedo (α) values. Aircraft measurements by Kung, Bryson and Lenschow (1964) show some urban/rural differences (Table One), but in general not as large as might have been expected. However, their study does show strong rural/urban differences (up to 40%) when there is a snow cover.

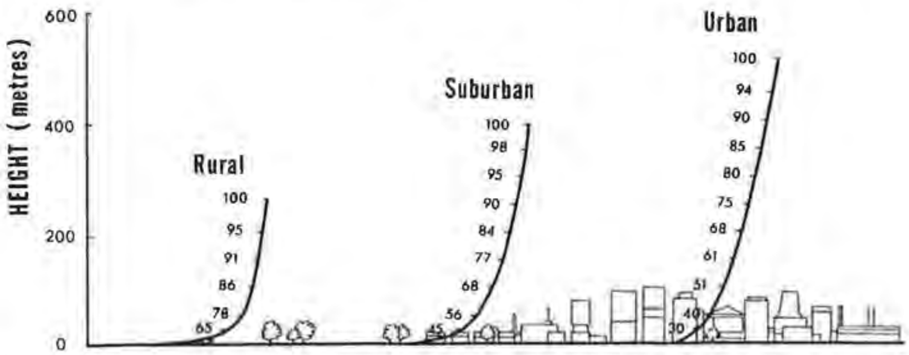


Fig. 1. A typical progression of wind profiles over rural suburban and urban surfaces. Figures are percentages of gradient wind (from Davenport 1965).

(b) City structure.

The effective surface area of a city is much larger than that of a rural countryside of equivalent size. Therefore one might expect the city to possess a greater ability to exchange heat by radiative and turbulent transfer. In reality the configuration of buildings tends to trap radiation within the city and even reduces the turbulent transport at street level, due to stagnation between the roughness elements. The city however, does present a rougher surface to airflow above the buildings, with z_o values (see equation 7) at least an order of magnitude greater than most rural values (Table Two).

The effect of this increased z_o on the wind profile is illustrated in Fig. 1.

As z_o increases the depth affected increases, and the profile becomes less steep. As a result of this increased forced convection, and the increased buoyancy due to the heat island, the urban atmosphere is less stable than the country (Fig. 5 (b)) and the total turbulent energy is increased (Graham 1968).

(c) Artificial heat production (F)

There is no rural counterpart for the heat generated in the city due to the combustion of fuel and the metabolism of it's inhabitants. The fuel-burning activities include the heat produced to provide space heating of homes and offices, to operate industrial plants, and to propel automobiles. Table Three provides a measure of F in a number of cities.

TABLE THREE

Artificially generated heat in cities

City	Averaging period	F ($cal\ cm^{-2}\ min^{-1}$)	Author
Manhattan, N.Y.	Winter	0·285	Bornstein (1968)
"	Summer	0·058	"
*Montreal, P.Q.	Winter	0·218	Summers (1964)
* "	Summer	0·081	"
* "	Year	0·141	"
Berlin, Germ.	Year	0·032	Schmidt (1917)
Sheffield, Eng.	Year	0·028	Garnett and Bach (1965)
Vienna, Aus.	Year	0·023	Schmidt (1917)

*Calculated from Summer's formulae using McGill mean air temperatures for averaging periods indicated.

There would appear to be a considerable difference between the recent North American values, and those from European cities. If this is the case, it may be a function of the greater use of space heating and automobiles in North America. Locally, artificial heat emmissions may be very large. Oke and Hannell (1968) report average sensible heat releases from the steelworks in Hamilton, Ontario of 0·53 - 0·80 $cal\ cm^{-2}\ min^{-1}$.

(d) Urban water balance

It has been suggested that the city is like a desert due to the removal of surface water by sewers, and the mechanical removal of snow from the streets. In addition the general lack of naturally transpiring surfaces should result in decreased evaporation. There are no studies to support or refute such a view. Davis (1968) suggests that it may only be true for the centre of cities, the suburbs remaining close to rural evapotranspiration conditions.

(e) Urban air pollution

The fifth unique property of the urban environment is its envelope of air pollution.. One of the major problems in determining the climatic effects of air pollution is its variability; both in time and space. The temporal variations generally occur in daily, weekly and seasonal cycles (e.g. in Montreal, Summers 1966). The spatial variations are controlled by the location and nature of the effluent sources, and the local meteorological conditions.

Climatically, air pollution plays its most effective role in modifying the component fluxes of the radiation balance.

$$Rn = (Q + q)\ (1 - \alpha) + I\downarrow - I\uparrow\ \ (\text{cal cm}^{-2}\ \text{min}^{-1}) \qquad (1)$$

where, Rn is net allwave radiation, Q,q direct and diffuse beam shortwave radiation respectively, and $I\downarrow$, $I\uparrow$ incoming and outgoing infra-red radiation respectively.

It was previously pointed out that both α and $I\uparrow$ are influenced by the nature of the surface. The remaining terms on the right hand side of (1) are directly affected by the atmosphere transmission characteristics, and therefore by air pollution. The attenuation of (Q + q) by Montreal's pollution haze amounts to 10 - 20% (East 1967), which is a figure in good agreement with results from other North American cities (e.g. Emslie 1964). Mateer (1961) has demonstrated the effect of the weekly pollution cycle on (Q + q) receipts in Toronto, and Sekiguti (1964) has presented the first spatial distributions of (Q + q) in an urban area. Despite the widespread view that the urban haze dome acts as an important 'trap' for infra-red radiation (thus increasing $I\downarrow$ in the city), no observations have been reported to confirm the magnitude of this effect.

AN EXAMPLE OF AN URBAN HEAT ISLAND STUDY

The most pronounced feature produced by the five controls outlined above is the urban heat island. The following section outlines the way in which it has become usual to study this effect in a particular city.

A preliminary study of Montreal's heat island (Oke 1968) pinpointed a number of interesting features. This survey has been extended to encompass most of the island of Montreal, and includes the vertical temperature soundings conducted by Dr. C. East (see p. 21 of this Bulletin). An example of the two-dimensional form of the urban heat island is shown in Fig. 2. This illustrates the conditions at 0700 on March 7th, 1968. The temperatures were gathered by automobile traverses using Assmann Psychrometers and automatic thermistor recorders. The isotherm map was constructed from 364 point values. On this day skies were clear except for the urban smog, and the wind speed at the 61 m level observed at the

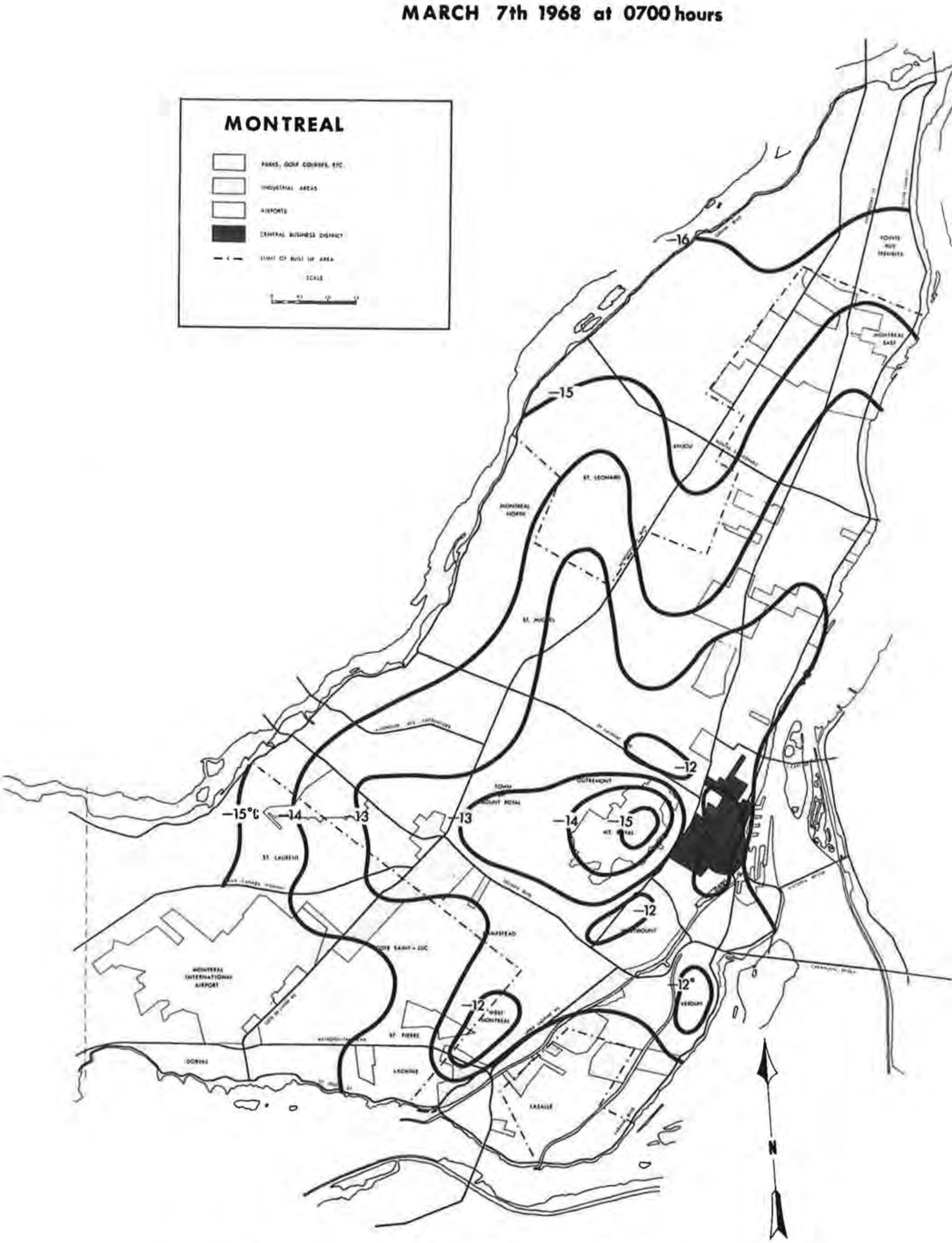


Fig. 2. Two-dimensional distribution of air temperatures at 2m in Montreal.

Botanical Gardens meteorological tower was N - NE at 1·3 - 3·6 m sec^{-1}. Rural areas were characterized by surface-based inversions, but the urban atmosphere exhibited a weak lapse condition (-0·023 to -0·065 $^{o}C\ m^{-1}$) in the lowest 60 m.

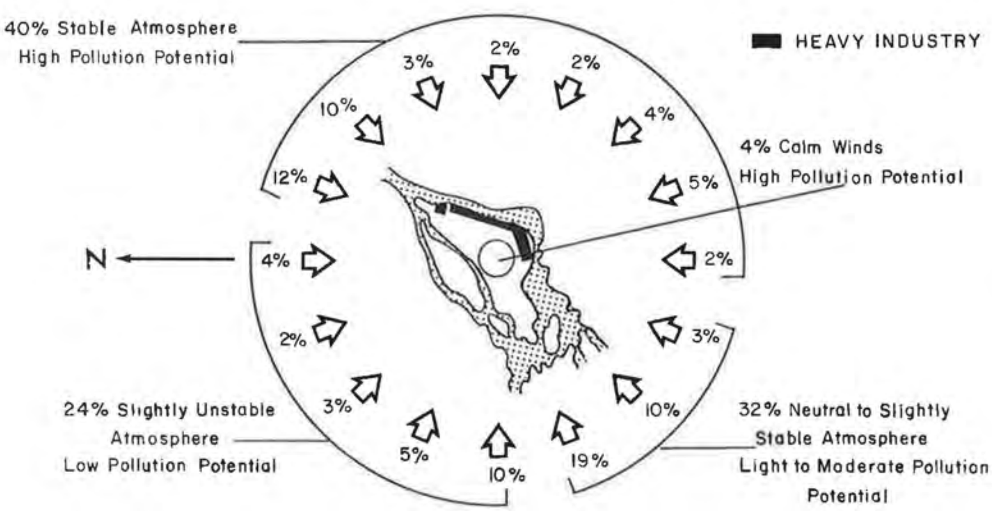
The weather conditions outlined above are exactly those which Summers (1961) classifies as possessing "high pollution potential" for Montreal (Fig. 3(b)). The drift of pollutants from the industrial northeastern end of the island causes a severe fumigation condition across the rest of the city, especially in the early morning hours when the mixing depth is quite shallow (see Fig. 3 (a)).

From Fig. 2 it can be seen that Montreal is both interesting and complex as a heat island study area. In addition to the purely urban influence, there is the effect of topography due to Mount Royal, and the effects of water since Montreal is an island-city. On March 7th the urban heat island was moderately well developed, with a 4·5^{o}C (8·1^{o}F) urban/rural temperature difference. The 'cold-spot' of Mount Royal is well shown, and there is evidence of a cold tongue of rural air being advected into the city by the N - NE wind. The non-water boundaries of the urban area produce a marked temperature gradient. The core of the heat island is complex; in fact it might be better described as a heat "archipelago". Each of the warm cells are associated with commercial centres in the downtown complex of Montreal itself, and the surrounding municipalities of Westmount, Verdun, and West Montreal. Even more heat cells may be present but the observation density was not sufficiently great to locate them confidently.

If one attempts to suggest which of the controlling factors outlined previously is responsible for the form of the heat island in Fig. 2, it soon becomes obvious that such suggestions can be no more than speculative. Regression analysis of the observed temperatures and such factors as building fabric, density of structures, heat generation, or air pollution does not alleviate the problem, since many of the factors are intricately linked. One exception may be noted in Hamilton, Ontario (Oke and Hannell 1968) where one heat cell is undoubtedly the direct result of heat release in the steelmaking process.

(a)

Photo by
D. McGregor.



(b)

(after Summers
1961)

Fig. 3. Pollution in Montreal
(a) Looking SE at 0830, Jan. 23, 1969. Extreme pollution in light NE winds; height of pollution dome estimated at 185m. Temp. $-3^{\circ}C$; wind NE 0.4m sec^{-1}; COH 3.3ppm; SO_2 0.15 ppm.
(b) Diagram of wind frequencies and pollution potentials, Nov. - Apr.

It may be concluded that beyond a certain point heat island studies of the type illustrated here, are largely descriptive and do not substantially advance our knowledge of the fundamental mechanisms governing the heat island.

HEAT BALANCE APPROACH

Reviewing the literature concerning the urban heat island reveals a surprising lack of knowledge concerning the processes producing or destroying this effect. Thus it is suggested that more attention be focussed upon the ways in which heat is utilized in the urban environment.

For an extensive rural surface we may write it's heat balance:

$$Rn = H + LE + G \qquad (\text{cal cm}^{-2}\ \text{min}^{-1}) \qquad (2)$$

where, H is convective sensible heat transfer, LE latent heat transfer, and G soil heat storage. By day the net available energy (Rn) is used to heat the air, evaporate water and conduct heat into the soil. By night the net radiant loss is compensated for by a reversal of all the fluxes. In the case of the city the radiant energy source is supplemented by the artificial heat generated by combustion processes and therefore (2) becomes:

$$Rn + F = H + LE + G \qquad (\text{cal cm}^{-2}\ \text{min}^{-1}) \qquad (2a)$$

A schematic diagram of the heat balances of rural and urban surfaces is given in Fig. 4. Obviously the suburbs are affected by both balances, and are a transitional zone. As such they will be constantly in receipt of advective effects (ΔA). Hence in Fig. 4 the urban heat balance (2a) is only applicable after some distance (Y) from the windward edge of the city.

All of the terms in (2a) will be directly affected, to some degree by the unique city controls outlined earlier. The urban fabric affects Rn and G; the urban structure affects Rn, H and LE; the urban water balance affects LE; air pollution affects Rn; and heat production controls F. However, only F is understood on even a semi-quantitative basis (see Table Three). The magnitude of the other fluxes remains largely guesswork, and in some cases even their sign is in doubt. It seems

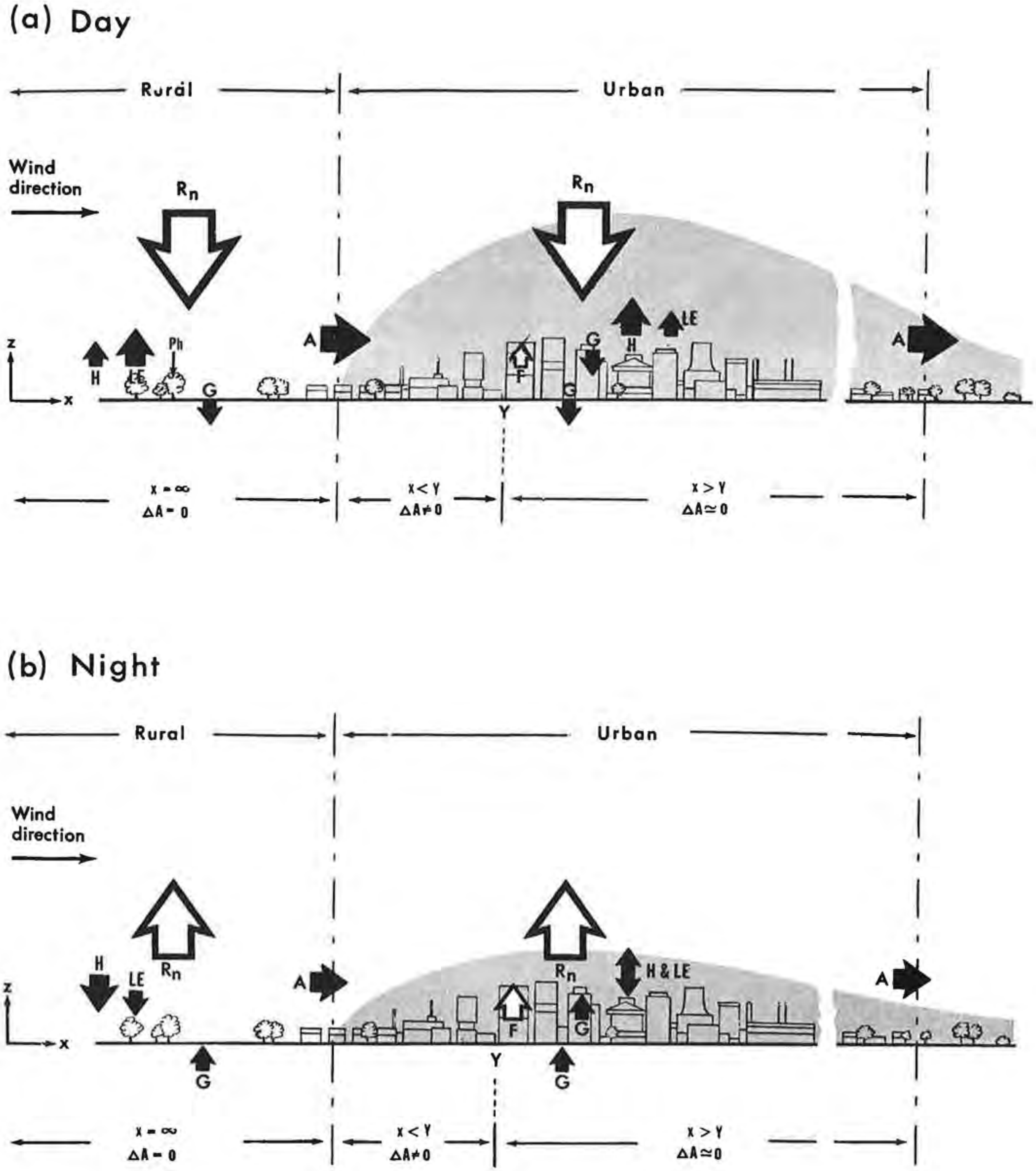


Fig. 4. Two-dimensional schematic of the Heat Balances of Urban and Rural Surfaces.

reasonable therefore to investigate further to see how this approach may be put into effect.

IMPLEMENTATION OF THE HEAT BALANCE APPROACH

There would not appear to be any great obstacles to the direct measurement of Rn in the city, except the problem of choosing a representative surface. This could be overcome by some form of spatial averaging procedure. Alternatively, this term could be estimated using methods similar to those employed by Garnett and Bach (1965) in Sheffield, but the value for net infra-red radiation ($I = I\downarrow - I\uparrow$) in the polluted atmosphere must necessarily be imprecise.

The evaluation of G in a city is much more complex than in the rural case. In the city the heat may be stored in buildings, roads, open ground, etc., all possessing different conductive capacities. If it is possible to provide gross estimates of these properties averaged over an area of the city (e.g. Davis 1968), it should be possible to arrive at reasonable heat storage values. However, it seems unlikely that G will ever exceed 20% of Rn + F.

From the foregoing it becomes obvious that the major portion of the available energy in the city is partitioned between the sensible and latent heat fluxes. In view of the drier city surface one may expect an increase in H compared with the rural value. Unfortunately it is not possible to compute values of H or LE in the absence of observations, therefore one must consider the particular problems involved in implementing the methods derived for rural locations. The three main methods are the eddy correlation, Bowen ratio, and aerodynamic methods.

(a) Eddy correlation technique

At any point in the atmosphere the air possesses density (ρ), vertical velocity (w) and carries with it physical entities such as heat, water vapour and horizontal momentum. The instantaneous vertical flux of any property (s), being composed of a mean value and an instantaneous deviation from the mean, is given by:

$$F_s = \overline{(\rho w)\bar{s}} + \overline{(\rho w)'s'} \qquad (3)$$

where the bar indicates the averaging process, and the prime the instantaneous deviations. But since $\overline{\rho\, w}$ must tend to zero over a uniform site, and since ρ' can be considered so small that ρ may be considered a constant, then (3) reduces to:

$$F_s = \rho\overline{w's'}$$

Thus we may write the fluxes H and LE similarly from the covariances of w and temperature (T), and w and specific humidity (q) respectively:

$$H = \rho C_p \overline{w'T'} \tag{4a}$$

$$\text{and } LE = \rho L \overline{w'q'} \tag{4b}$$

where C_p is specific heat of air at constant pressure, and L the latent heat of vapourization.

By the use of very fast response sensors for w', T' and q' it is possible to measure H and E directly in the field. The Evapotron (Dyer 1961), and Fluxatron (Dyer, Hicks and King 1967) have been designed specifically for this purpose. The great advantages of this method are, firstly, its ability to directly measure the fluxes without need to make assumptions concerning transfer coefficients, or stability such as are necessary in the Bowen ratio and aerodynamic methods, where the fluxes are inferred from gradients, and secondly, the performance of this technique is independent of the nature of the surface, which is an important consideration in urban studies. However, two problems can be foreseen. Firstly, it was assumed that $\overline{\rho w} = 0$. Over most surfaces with reasonable homogeneity this is a safe assumption, but in the case of the city there are non-uniformly distributed sources of heat and water vapour, and sinks for momentum. Secondly, there are the major problems of expense and technical competence necessary to build and operate such a system. Perhaps this may be overcome by a refinement of the method employed by McBean (1968) in a forest.

(b) Bowen's ratio and aerodynamic methods

The urban heat balance in the absence of advection is given by (2a). It may also be written in the form:

$$LE = \frac{Rn + F - G}{1 + H/LE} \tag{5}$$

where $H/LE = \beta$ and is known as Bowen's ratio. By assuming equality of the eddy transfer coefficients for heat and water vapour (i.e. $K_H = K_E$), the fluxes H and LE may be replaced by their respective gradients so that (5) becomes:

$$LE = \frac{Rn + F - G}{1 + \frac{C_p (T_2 - T_1)}{L(q_2 - q_1)}} \tag{6}$$

Thus from estimates or observations of Rn, F and G and measurements of T and q at the same two levels, it is possible to evaluate (6) and ultimately (2a).

The aerodynamic method on the other hand, is based on the classical formulation of the wind profile near the ground. Under neutral stability:

$$u = \frac{u^*}{k} \ln \frac{z - d}{z_o} \tag{7}$$

where u is horizontal wind speed (cm sec^{-1}) at height z (cm), u* friction velocity (cm sec^{-1}) $\equiv \sqrt{\tau/\rho}$ where τ is the shearing stress (dyne cm^{-2}), k von Karman's constant $\simeq 0 \cdot 4$, d zero plane displacement (cm), and z_o roughness parameter (cm) (see table Two). From (7) it can be shown (e.g. Sellers 1965) that the momentum flux under these conditions is given by:

$$\tau = \rho k^2 \left(\frac{u_2 - u_1}{\ln \frac{z_2 - d}{z_1 - d}} \right)^2 \tag{8}$$

and that by extending the similarity principle to include the eddy viscosity (i.e. $K_H = K_E = K_M$), the turbulent fluxes of sensible and latent heat are accordingly:

$$H = -\rho k^2 \frac{(u_2 - u_1)(T_2 - T_1)}{\left(\ln \frac{z_2 - d}{z_1 - d}\right)} \quad \text{(8a)} \qquad \text{and} \qquad LE = -\rho k^2 \frac{(u_2 - u_1)(q_2 - q_1)}{\left(\ln \frac{z_2 - d}{z_1 - d}\right)} \quad \text{(8b)}$$

These aerodynamic equations therefore yield H and LE via measurements of u, and either T or q at the same two levels z_1 and z_2.

The successful implementation of the methods just described depends on certain conditions and assumptions being fulfilled. Firstly it should be pointed out that the methods have been derived and tested for micro-scale surfaces and in applying them to a city their applicability is being analysed under meso-scale constraints for which they were never intended. The Bowen ratio and aerodynamic methods have four assumptions in common. Firstly, steady-state conditions are assumed to hold during the period of observation. This is largely a function of the constancy of radiation and wind conditions. In the city there may be complications due to temporal variations in the generation and emission of artificial heat (F).

Secondly, constancy of fluxes with height are normally assumed in the surface boundary layer. There would appear to be serious doubts that this assumption can be fulfilled in the city's atmosphere. For instance, measurements made beneath the "surface" of the city, between the roughness elements (buildings), will encounter energy and mass sinks and sources at varying elevations. Thus one may expect flux divergence. Thirdly, equality of the eddy transfer coefficients are assumed. At heights <16m Swinbank and Dyer (1967) provide evidence that under lapse conditions $K_H = K_E \neq K_M$ the difference becoming more marked with increasing instability. Thus the Bowen ratio method which assumes $K_H = K_E$, is preferable to the aerodynamic method which requires $K_H = K_E = K_M$. At present the only results concerning the equality of the eddy transfers over a city are those of McCormick and Kurfis (1966) in the lowest 100 m over Cincinnati, Ohio. Their findings show $K_H \simeq K_A$ (eddy transfer coefficient for aerosol materials). Fourthly, one dimensional transport is assumed, i.e. there are no horizontal gradients producing advection. Unfortunately, the great diversity of elements comprising the city preclude the possibility of this ever being perfectly acheived. Micro-scale advective effects are continually being generated and dissipated. Careful choice of site location can only seek to minimize these effects, not eliminate them.

Implementation of the aerodynamic approach in the city is also faced with two additional problems. Firstly, it must be emphasized that (7), (8), (8a) and (8b) are only strictly valid under close to neutral stability, otherwise buoyancy effects must be allowed for. Numerous methods have been suggested to account for stability effects on the curvature of the wind profile, and on the eddy coefficients, but none can be considered wholly satisfactory. However, since the urban atmosphere is characterized by a weak lapse condition due to the heat island, and increased mixing this may not be as severe a problem as in rural locations. Secondly, Munn (1968) points out that the constants in (7) only have their connotations when there is a balance between the production and dissipation of turbulent kinetic energy, a condition unlikely to be fulfilled in the city. Some support for this view is gained from the work of Jones et. al (1968) who consistently found an empirical power law rather than the logarithmic law to best fit wind profile data over Liverpool.

In summary, therefore, it appears that the complexity of the city's "surface" denies the immediate application of the Bowen ratio and aerodynamic approaches.

MODEL BUILDING

One way of overcoming the difficulties just outlined in applying the techniques developed for micro-climatic investigations in the countryside to the city environment, is to build models.

Two types of model have been constructed to provide analogues for the urban heat balance, and/or the urban heat island.

Davis (1968) constructed a 1:1,000 hardware model of Fort Wayne, Indiana. He sought to model all the heat balance components and thus simulate temperature profiles in the urban heat island. This is a new and potentially very valuable advance, but more work is required on the scaling criteria. In the case of Fort Wayne there was no need to account for air pollution or differing rural/urban heat capacities; in models of larger cities these will also have to be simulated.

Summers (1964) was amongst the first to construct a theoretical model of the heat island, based on the concept of an internal boundary layer developing at the leading edge of the city and thickening downstream due to the accumulation of heat in this "urban plume" (Fig. 5 (a & b)). Until recently these models have been hindered by a dearth of knowledge concerning the natural conditions, and hence have remained largely untested. However, the recent work of Clarke (1968) in Cincinnati has provided evidence of the urban plume concept (Fig. 6).

FLUX DIVERGENCE APPROACH

It will have become obvious from the preceeding discussion that the major obstacles to implementing the heat balance approach to a study of urban conditions are, the lack of knowledge of process, and the problems associated with the nature of the city's surface. In an effort to contribute to the former, Fuggle and Oke (1968) have suggested a method of lessening the problems associated with the latter.

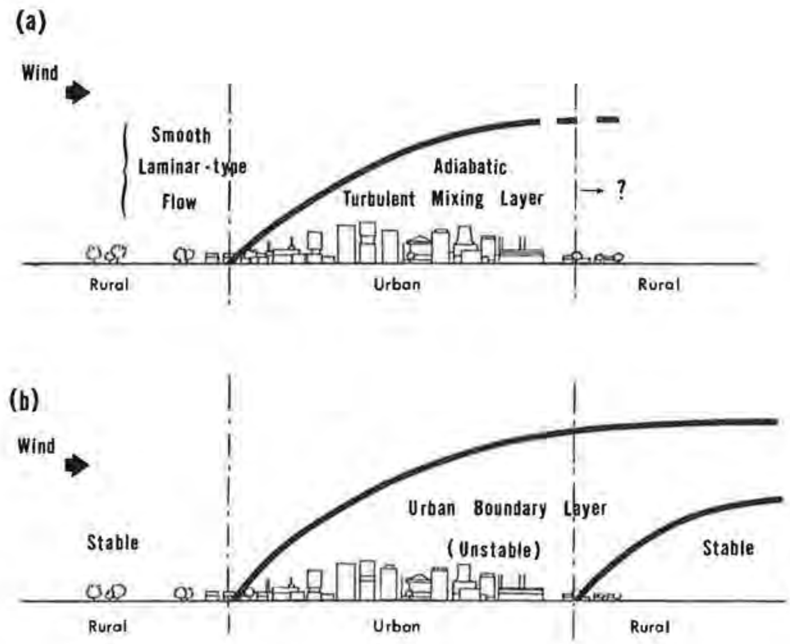


Fig. 5. Urban Boundary Layer Models
(a) After Summers (1964); (b) as modified by Clarke (1968) to include a leeward rural boundary layer.

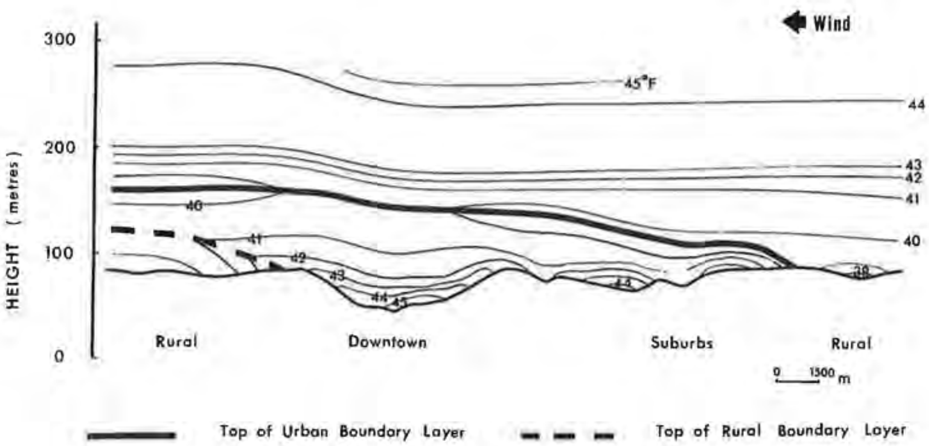


Fig. 6. The Urban Boundary Layer, Cincinnati, Ohio. Observations near sunrise, May 23, 1967. (after Clarke, 1968).

In the absence of advection and latent heat exchange, the temperature change in an air layer Δz in the period Δt is given by:

$$\frac{\Delta \bar{T}}{\Delta t} = \frac{1}{\rho c p}\left[\Delta\left(\bar{K}_H \frac{\Delta T}{\Delta z}\right) + \Delta Rn\right] \qquad (9)$$

This equation shows the well established fact that air temperatures are determined by both turbulent and radiative heat transfer, each of the terms in brackets representing flux divergence in the air layer. Normally it is assumed that turbulent transfer is dominant and that radiative effects are neglible. The results of Funk (1960) over rural surfaces in Australia, however, suggest radiative effects may be the most important under certain conditions.

It was argued earlier that flux divergence may be common in the urban atmosphere. In addition to the height variability of heat, water vapour and momentum sources and sinks, there is flux divergence of radiation throughout the polluted urban atmosphere. Flux divergence of $(Q + q)$ has already been mentioned. It is even more probable that both by day and night there is flux divergence of the infra-red terms, since any aerosols having absorption bands $>5\mu$ must have an influence.

Funk showed that infra-red flux divergence (ΔRn) on calm clear nights could produce temperature changes of $>10\ C^{o}\ hr^{-1}$ over rural surfaces. Calm, clear conditions in the city favour the build-up of aerosols (see Fig. 3a), which may be expected to further enhance ΔRn. It is these same conditions which favour the development of the urban heat island (see Fig. 2). In view of this connection it seems useful to investigate the role assumed by ΔRn in producing the nocturnal urban heat island.

A theoretical treatment of the problem seems impossible in the absence of definitive profiles of temperature, water vapour, and pollution for a city. Consequently, it is proposed to test the ΔRn hypothesis by direct observation. The programme is modelled after that of Funk. A suitable arrangement of temperature sensors and net radiometers will yield values of $\Delta T/\Delta t$, $\Delta T/\Delta z$ and ΔRn for use in (9). It will also be possible to obtain $\Delta I\downarrow$ and $\Delta I\uparrow$ to estimate their contribution to ΔRn.

In this way it is hoped to arrive at conclusions concerning the processes which are responsible for warming the urban atmosphere, without, at the same time, necessarily making specific reference to the surface itself.

Acknowledgements

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References

Bornstein, R.D. 1968: "Observations of the urban heat island effect in New York city", J. Appl. Met., Vol. 7, pp. 575-582.

Chandler, T.J. 1961: "Surface breeze effects of Leicester's heat island", East Midlands Geographer, No. 15, pp. 32-38.

Clarke, J.F. 1968: "Nocturnal urban boundary layer over Cincinnati, Ohio". (in press)

Csnady, G.T., Hilst, G.R. and Bowne, N.E. 1968: "Turbulent diffusion from a cross-line source in shear flow at Fort Wayne, Indiana", Atmos. Environment, Vol. 2, pp. 273-292.

Davenport, A.G. 1965: "The relationship of wind structure to wind loading", Proc. Conf. on "Wind effects on structure", NPL, H.M.S.O.

_____________ 1967: "Instrumentation and measurements of wind speed spectra in a city", Proc. 1st Can. Conf. on Micromet., Part II, pp. 361-369.

Davis, M.L. 1968: "Modeling urban atmospheric temperature profiles", Ph.D. Thesis, Univ. of Illinois, 159 p.

Deland, R.J. and Binkowski, F.S. 1966: "Comparison of wind at 500 feet over Minneapolis and Louisville with geostrophic wind", J. Air Poll. Control Assoc., Vol. 16, pp. 407-411.

Dyer, A.J. 1961: "Measurements of evaporation and heat transfer in the lower atmosphere by an automatic eddy correlation technique", Quart. J. Royal Met. Soc., Vol. 87, pp. 401-412.

_________, Hicks, B.B., and King K.M. 1967: "The Fluxatron - a revised approach to the measurement of eddy fluxes in the lower atmosphere", J. Appl. Met., Vol. 6, pp. 408-413.

East, C.C. 1967: "Comparaison du rayonnement solaire en ville et à la campagne", Paper presented at 35th Congress A.C.F.A.S., Sherbrooke, 8p.

Emslie, J.H. 1964: "The reduction of solar radiation by atmospheric pollution at Toronto, Canada", Can. Dept. Transport, Met. Br. CIR 4094, TEC 535.

Fuggle, R.F. and Oke, T.R. 1968: "Infra-red flux divergence and the urban heat island", paper presented to WMO symposium on "Urban climates and building climatology", Brussels, 10p.

Funk, J.P. 1960: "Measured radiative flux divergence near the ground at night", Quart. J. Royal Met. Soc., Vol. 86, pp. 382-389.

Garnett, A. and Bach, W. 1965: "An estimation of the ratio of artificial heat generation to natural radiation heat in Sheffield", Monthly Weather Review, Vol. 93, pp. 383-385.

Graham, I.R. 1968: "An analysis of turbulence statistics at Fort Wayne, Indiana", J. Appl. Met., Vol. 7, pp. 90-93.

Jones, P.M., de Larrinaga, M.A.B., and Wilson, C.B. 1968: " Some measurements of the urban wind velocity profile in the first 1000 ft", paper presented to WMO symposium on "Urban climates and building climatology", Brussels, 19 p.

Kung, E.C., Bryson, R.A. and Lenschow D.H. 1964: "Study of a continental surface albedo on the basis of flight measurements", Monthly Weather Review, Vol. 92, pp. 543-564.

Mateer, C.L. 1961: "Note on the effect of the weekly cycle of air pollution on solar radiation at Toronto", Int. J. Air Water Poll., Vol. 4, pp. 52-54.

McBean, G.A. 1968: "An investigation of turbulence within the forest", J. Appl. Met., Vol. 7, pp. 410-416.

McCormick, R.A. and Kurfis K.R. 1966: "Vertical diffusion of aerosols over a city", Quart. J. Royal Met. Soc., Vol. 92, pp. 392-397.

Munn, R.E. 1968: "Airflow in urban areas", paper presented to WMO symposium on "Urban climates and building climatology", Brussels, 37 p.

Oke, T.R. 1968: "Some results of a pilot study of the urban climate of Montreal", Climatological Bulletin, McGill University, No.3, pp. 36-41.

________ and Hannell, F.G. 1968: "The form of the urban heat island in Hamilton, Canada", paper presented to WMO symposium on "Urban climates and building climatology", Brussels, 18 p.

Sellers, W.D. 1965: "Physical climatology", Univ. of Chicago Press.

Schmidt, W. 1917: "Zum Einfluss grosser Städte auf das Klima", Die Naturwissenschaften, Vol. 5, pp. 494-495.

Sekiguti, T. 1964: "City climate distribution in and around the small city of Ina in central Japan", Tokyo Geography Papers, Vol. 8, pp. 93-104.

Summers, P.W. 1961: "Smoke concentrations in Montreal related to local meteorological factors", in "Air over cities", SEC Technical Report A 62-5, pp. 89-112.

Summers, P.W. 1964: "An urban ventilation model applied to Montreal", Ph.D. Thesis, McGill University, Montreal.

Sutton, O.G. 1953: "Micrometeorology", McGraw-Hill.

Yamamoto, G. and Shimanuki, A. 1964: "Profiles of wind and temperature in the lowest 250m in Tokyo", Sendia, Tohoku Univ. Science Reports, Series 5, Vol. 15, pp. 111-114.

TWO STUDIES IN THE URBAN CLIMATOLOGY OF MONTREAL

1. Pollution Atmosphérique et Ile de Chaleur par Conrad East, Professor à l'Ecole d'Hygiène, Université de Montréal.

Le programme de recherche "Pollution atmosphérique et île de chaleur" est une étude des relations entre les régulateurs météorologiques et la concentration de l'anhydride suffureux (SO_2) au-dessus d'une vaste agglomération urbaine, en l'occurence Montréal. A cette fin des mesures instantanées de la température et de la concentration du SO_2 sont prises en auto et en hélicoptère. Les autres paramètres météorologiques tels que le vent sont fournis par deux stations de surface et deux tours météorologiques.

L'île de Montréal elle-même (Fig. 1) se situe au centre de la vallée du Saint-Laurent, qui s'étend en terrain plat sur une distance de 25 milles au nord-ouest et au sud-est. Sur l'île même, il n'existe qu'un seul accident topographique d'importance le Mont-Royal, de 200 mètres d'élévation. Cette topographie assez simple devrait permettre une description relativement aisée du flot atmosphérique à partir des quelques stations qui enregistrent le vent à différents niveaux: à Dorval au sol; à Brébeuf à 30 mètres au-dessus du sol; à la tour du Ministère de la Santé de la Province de Québec à deux niveaux à 6 et 60 mètres au-dessus du sol; et à la tour de Radio-Canada, sur le Mont-Royal à 300 mètres par rapport au fleuve.

Le grand Montréal est bâti principalement sur l'île du même nom mais il s'étend aussi sur l'île Laval et le long de la rive sud du Saint-Laurent (Fig. 1). La section fortement peuplée de l'île de Montréal se trouve tout alentour de Mont-Royal, avec la partie commerciale située au sud-est du Mont-Royal et une zône industrielle, le long du canal Lachine et du fleuve Saint-Laurent, et une forte concentration de raffineries de pétrole et de quelques autres industries à l'extrémité nord de l'île, entre les points de sondage 6 et 7 (Fig. 1).

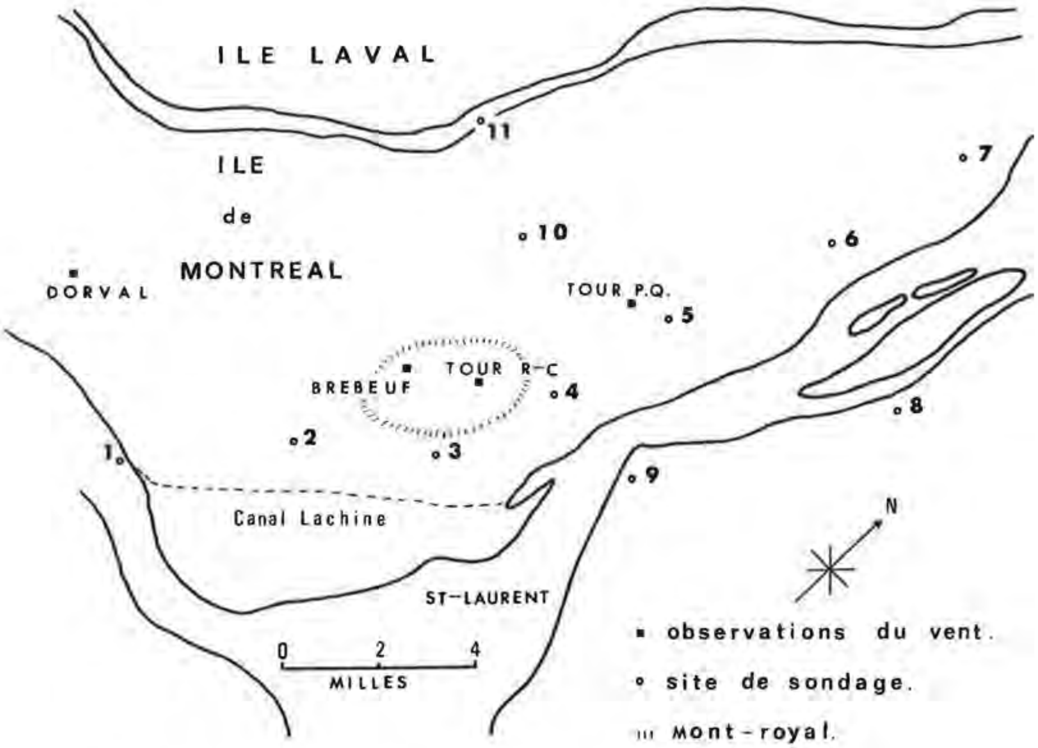

Fig. 1. Carte de Montréal et des sites de sondage.

METHODE

Les mesures en hélicoptère et en auto sont prises selon un trajet prédéterminé dans l'ordre des numéros de sondage. Ce circuit établi au début de 1968, n'a été que légèrement modifié à l'automne. L'hélicoptère et l'auto sont en liaison-radio, ce qui permet des mesures quasi simultanées aux mêmes sites. A chaque site l'hélicoptère exécute le sondage à partir du sol jusqu'à 900 mètres au-dessus du niveau de la mer et passe d'un site à l'autre à un niveau de croisière de 200 mètres environ. Tout ce parcours se fait dans une durée de deux heures à deux heures et demie et s'exécute dans les deux ou trois heures qui suivent le lever du soleil. Par ailleurs, une dizaine d'expériences furent aussi exécutées tôt dans l'après-midi ce qui permettra une étude intéressante de la modification de la couche atmosphérique au cours de la journée.

INSTRUMENTATION

L'hélicoptère, un Hughes-300, transporte un analyseur de SO_2 basé sur la conductivité de l'eau (type Davis), de sensibilité de un centième de partie par million (0.01 p.p.m.) et d'une constante de temps de 2 secondes, une sonde thermistor d'une précision de 0.2 degré C et d'une constante de temps de 0.7 seconde, et un convertisseur de pression-hauteur d'une précision de 5 mètres. Ces trois paramètres sont enregistrés sur un seul enregistreur Hewlett-Packard.

L'auto utilise le même genre de thermistor et d'analyseur de SO_2 combinés à des enregistreurs Rustrak.

RESUME DES MESURES EFFECTUEES

A date, deux séries d'expériences ont été accomplies, dont un résumé apparaît dans le tableau I.

Expériences et mesures effectuées. Tableau I.

PERIODE	16 février-12 avril 1968	17 septembre-19 décembre 1968
EXPERIENCES		
Nombre total	37	26
le matin	27	26
l'apres-midi	10	0
DUREE MOYENNE (heures)	2	2.5
SONDAGES		
nombre à chaque expérience	11	12
hauteur à chaque sondage (mètres)	900	900

QUELQUES RESULTATS

La figure 2 présente les profils de température obtenus tôt le matin et l'après-midi du 12 mars 1968, alors que le vent soufflait du nord-est dans la même direction que la ligne des sites 1 à 7 (Fig. 1). Les hauteurs y sont données par rapport au niveau de la mer. L'influence thermique de la ville y est évidente dans les basses couches de l'atmosphère qui se réchauffe en passant du site rural 7 aux sites urbains 5 à2. Même le site I, situé à l'extrémité nord-est du vaste lac Saint-Louis (pas indiqué sur la Fig. 1) se ressent de l'influence urbaine grâce au vent qui souffle de la ville. Le second point d'intérêt concerne la modification thermique de l'atmosphère dans le temps entre le matin et l'après-midi: on

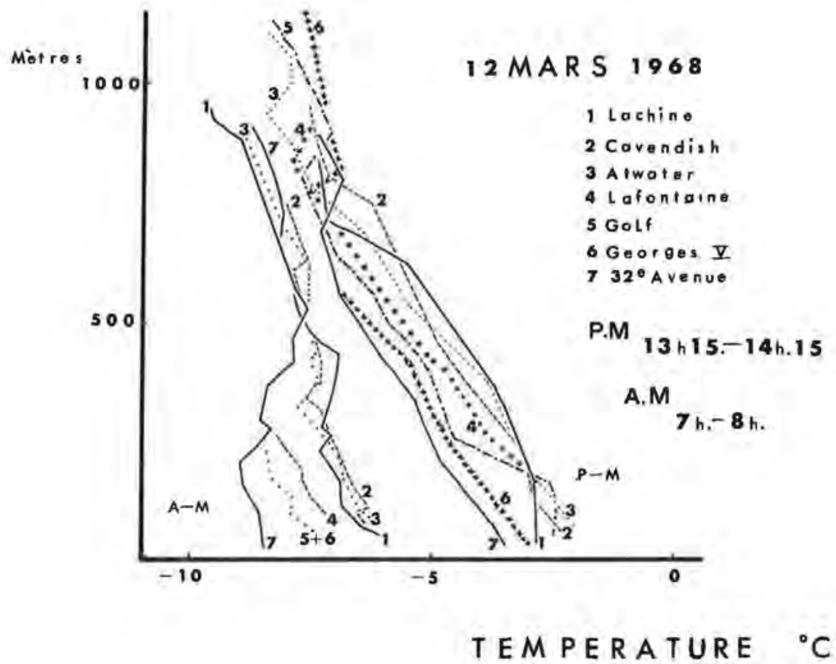

Fig. 2. Profils de température aux sites de sondage 1 à 7. Altitude en mètres au-dessus du niveau de la mer.

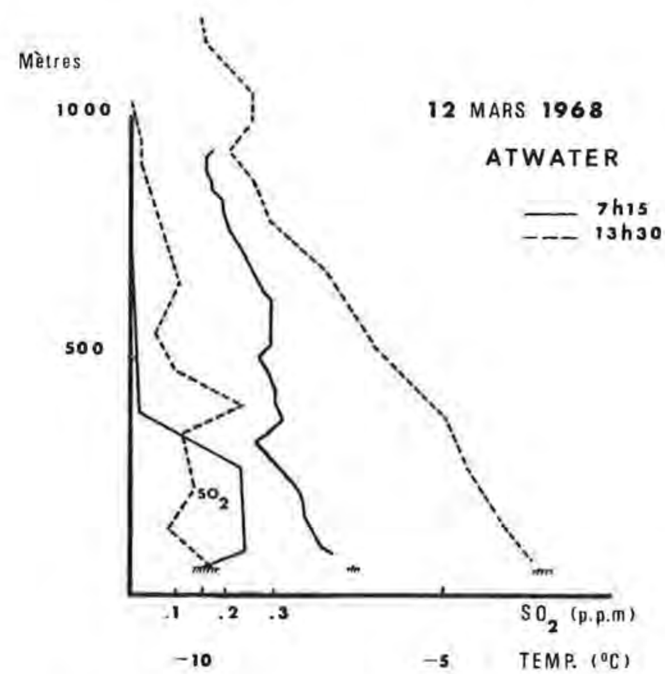

Fig. 3. Profils de température et de SO_2 au site de sondage 3.

voit que l'inversion du matin, située à 200 mètres, a été détruite et que la température décroît à un taux de 0.75 degré C par 100 mètres à travers toute la couche atmosphérique. Ce changement dans la structure thermique de l'atmosphère a sa répercussion dans la distribution du SO_2, tel qu'illustré au site Atwater (Fig. 3). Le sondage du matin indique une forte concentration du polluant dans les 300 premiers mètres; à ce niveau, où commence une couche stable, le SO_2 décroit rapidement pour atteindre un niveau négligeable vers 400 mètres. Par ailleurs, le sondage d'après-midi illustre bien comment s'est réparti le SO_2 sur une couche plus épaisse, grâce à une atmosphère relativement moins stable: on retrouve, en effet, le polluant jusqu'à 1,000 mètres.

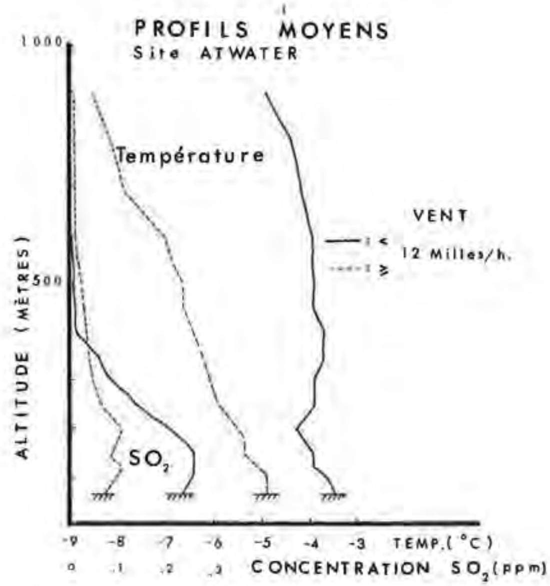

Fig. 4. Profils moyens de température et de SO_2 pour 9 matins avec vent inférieur à 12 milles à l'heure et 7 matins avec vent supérieur ou égal à 12 milles à l'heure (période du 19 février au 11 avril 1968).

La figure 4 présente pour le même site urbain les profils moyens de température et de SO_2 pour deux groupes de sondages pris le matin, selon que le vent de surface à Dorval était inférieur (9 cas) our supérieur (7 cas) à 12 milles à l'heure. Cette borne de 12 milles à l'heure a été choisie de façon quasi arbitraire après inspection rapide des profils de température: il semble, en effet, que pour des vents supérieurs à ce chiffre, il n'y ait pas d'inversion dans la couche atmosphérique, soit que les vents élévés appartenaient à une circulation atmosphérique (sur les 7 cas de vent élevés 6 cas appartenaient à des vents soufflant de l'ouest) caractérisée par de l'air plus instable. Quelle que soit l'explication, on voit de toute façon l'effet que l'une et l'autre distribution thermique peut apporter sur la dispersion des polluants.

CONCLUSION

Les nombreux profils de température et de SO_2 obtenus jusqu'ici constituent probablement une série unique de mesures au-dessus d'une ville. Elle nous permettra de mieux définir le microclimat urbain de Montréal, d'étudier la modification dans le temps et l'espace de l'atmosphère par la chaleur et les polluants, sans parler des applications pratiques au problème de la diffusion et du transport du SO_2.

2. A Preliminary Analysis of Gusts over Montreal by O.J. Diduch and C.E. Klaponski, students of climatology in the Universities of McGill and Winnipeg respectively.

INTRODUCTION

A well-known fact among engineers and architects is that with the large increase in the number of high-rise buildings in the cities, wind loading on structures is of major importance if buildings are to be economical and satisfactory from a performance standpoint. As Davenport (1963) suggests, the traditional approach to the problem of wind load has been one of convenience. The wind has been erroneously assumed to be relatively steady resulting in steady pressures on the structures. This assumption leads to a false impression as to the real behaviour of a tall building - or any other structure for that matter. The fact is that every structure has a natural frequency of vibration, and should dynamic loading occur at or near it, structural damage out of all proportion to the size of the load may result (Dalgliesh et al, 1962). Present use of flexible light-weight steel has made it even more imperative to explore the problems of resonance in gusty winds. Every tall building is designed to sway a little; if it were totally rigid, the structure might crack. For example, the Toronto-Dominion Centre building in Toronto is designed to sway 12 to 14 inches, but the most it has swayed has been 6 to 7 inches in a 60-70 mph. gust.

Due to the climatological inavailability of high speed turbulence data, it was decided in this paper to study the one-minute peak gust and its relation to the mean wind speed and diurnal stability pattern. Although not an entirely acceptable alternative, the behaviour of peak gusts is of qualitative value and has been used in some engineering studies.

THE SITE

Montreal is situated on an island just east of the junction of the Ottawa and the Upper St. Lawrence Rivers and occupies an area of about 360 sq. mi. It is in the St. Lawrence Lowlands which are low and flat, especially around Montreal. The uniformity of the plain is broken by the group of widely spaced Montegerian Hills of which Mount Royal is one. Mount Royal is situated in the centre of the city. Tall structures are confined to the city-centre primarily, with an occasional tall building in the suburbs.

INSTRUMENTATION AND DATA

The aerovanes and temperature sensors used in this study are mounted on the self-supporting CBC television tower on top of the 700 foot Mount Royal. The instrumented tower height is 294 feet above the mountain, (940 feet above the city floor and 1040 feet above sea-level). The highest buildings in the downtown area are approximately equal to the height of the mountain.

Wind data were obtained from the analog charts of a Bendix-Friez aerovane; the charts ran at a speed of 3 inches per hour. Further information regarding the recording of the data has been given in a publication of the Canadian Meteorological Branch (1964) dealing with wind data for climatological purposes.

The temperature sensor is a Honeywell resistance bulb, aspirated by a Beckman-Whitley Model N327 radiation shield. It is connected to a Honeywell 4-pt differential temperature recorder.

The data is this preliminary report consisted of selected 10 min. mean wind speeds, directions of wind and 1 min. peak gusts. Only those values of wind speeds 25 mph. and over, and concurrent 1 min. peak gusts 30 mph. and greater were used. There were 620 such observations from the charts obtained from the McGill Observatory for the 3 spring months of March, April and May 1966.

The temperature data were obtained from the monthly tabulations prepared by the Climatological Division of the Meteorological Branch for March, April and May 1966.

ANALYSIS OF DATA

The choice of a suitable time or distance interval for averaging mean velocities is dictated by consideration of the dynamic characteristics of the wind, the structure and the anemometer (Davenport, 1966). Davenport (1962) states that mean wind speeds averaged over a 10 min. period are reasonably stable quantities and are unaffected by slight shifts in the time origin. This is not true for shorter averaging periods and therefore 10 min. values were used to define the mean velocity. A gust analysis time of 1 min. was governed by the incapability of reading the charts over a shorter interval, due to the slow chart speed.

The 'gust factor', defined as the ratio of the peak wind speed, u', for a given duration, t, to the mean wind speed, $\bar{u}$, for a given averaging period, T, is necessary in the computation of pressure (lb. ft. $^{-2}$) or load in building design (Davis et al, 1968). In the present case, t=1 min. and T=10 min. Mitsuta (1962) has noted that for constant T, the gust factor decreases with increasing t.

The prevalence of the winds greater than 25 mph., in Montreal, from the southwest-west sector (Fig. 1) makes this site very suitable for a study of gustiness. The persistence of one direction allows a study of winds arriving at the tower after blowing over a certain type of terrain. The wind-rose shows that about 75% of the wind occurrence over 25 mph. are from this sector. This compares well with 60% as reported by Powe (1968) for all the winds for the period 1957 to 1966 at Montreal International Airport. Powe shows that the steadiness of wind is due to the channeling effects of the broad St. Lawrence River valley.

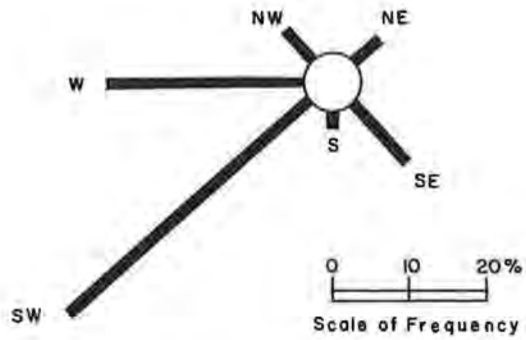

Fig. 1. Wind Rose for Montreal CBC TV tower site, March to May, 1966 for speeds greater than 25 mph.

RESULTS

Fig. 2 is a contingency table of peak gusts versus mean speeds. Isolines are drawn for 3, 10, 30, 50, 70 and 90 occurrences per 3 months. A high frequency of 25-26 mph. mean winds with 30-34 mph. peak gusts is evident. An interesting finding was the isolated maximum of the 33-34 mph. mean wind with 42-43 mph. peak gusts.

Fig. 3 shows the average gust factor for each half hour of the day, for the 3 month period; a diurnal trend is evident. Within an hour and a half, 0430 to 0600 hrs. the mean gust factor increases from 1.21 to 1.38 then steadies off for several hours. The gust factor reaches its maximum value about 1530 hours with a slow decrease, falling to a midnight low of 1.15. This behaviour can be explained physically; (see discussion later in connection with Fig. 5). From Fig. 3, day can be defined as between the hours of 0430 and 1730 (actual sunrise occurs from 4.09 a.m. to 6.34 a.m., EST) and night as between 1730 and 0430 hrs. (sunset occurring between the hours 5.41 p.m. and 7.35 p.m. during the 3 month period). On this basis, separate frequency distributions were prepared for the day-time and night-time (Fig. 4). A

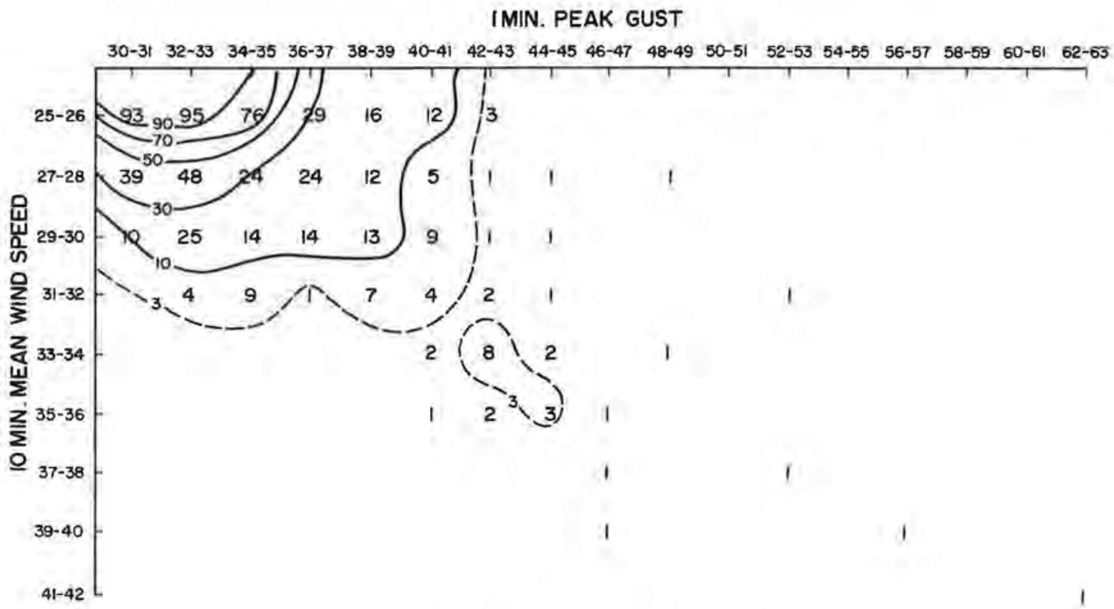

Fig. 2. Frequency Distribution of Wind Occurrences, 1 min. peak gusts vs 10 min. mean wind speeds

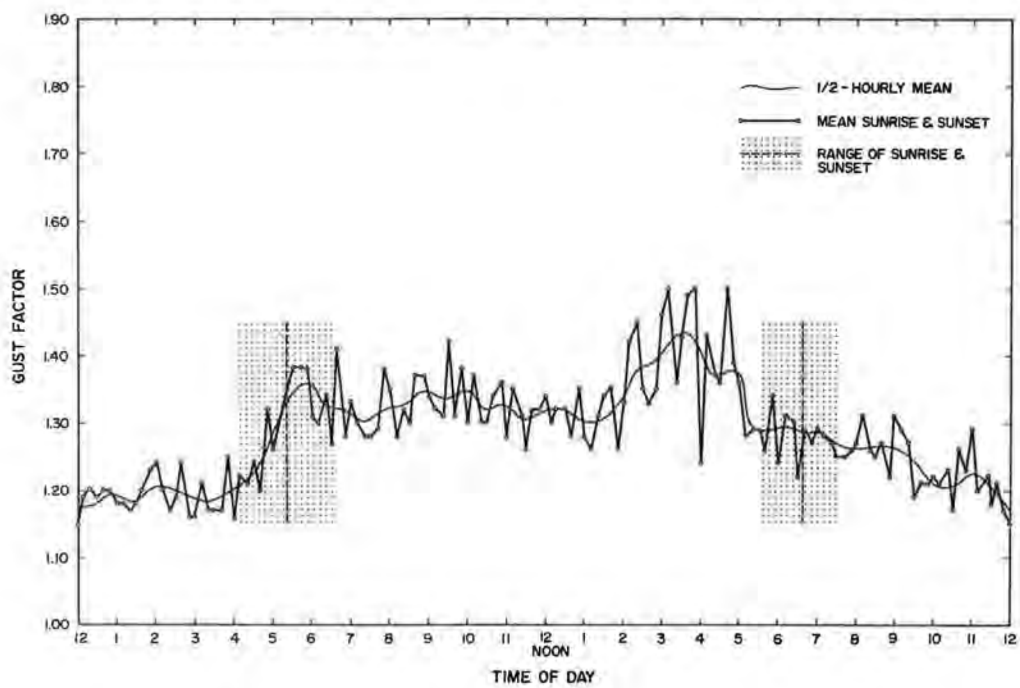

Fig. 3. Gust Factor vs Time of Day

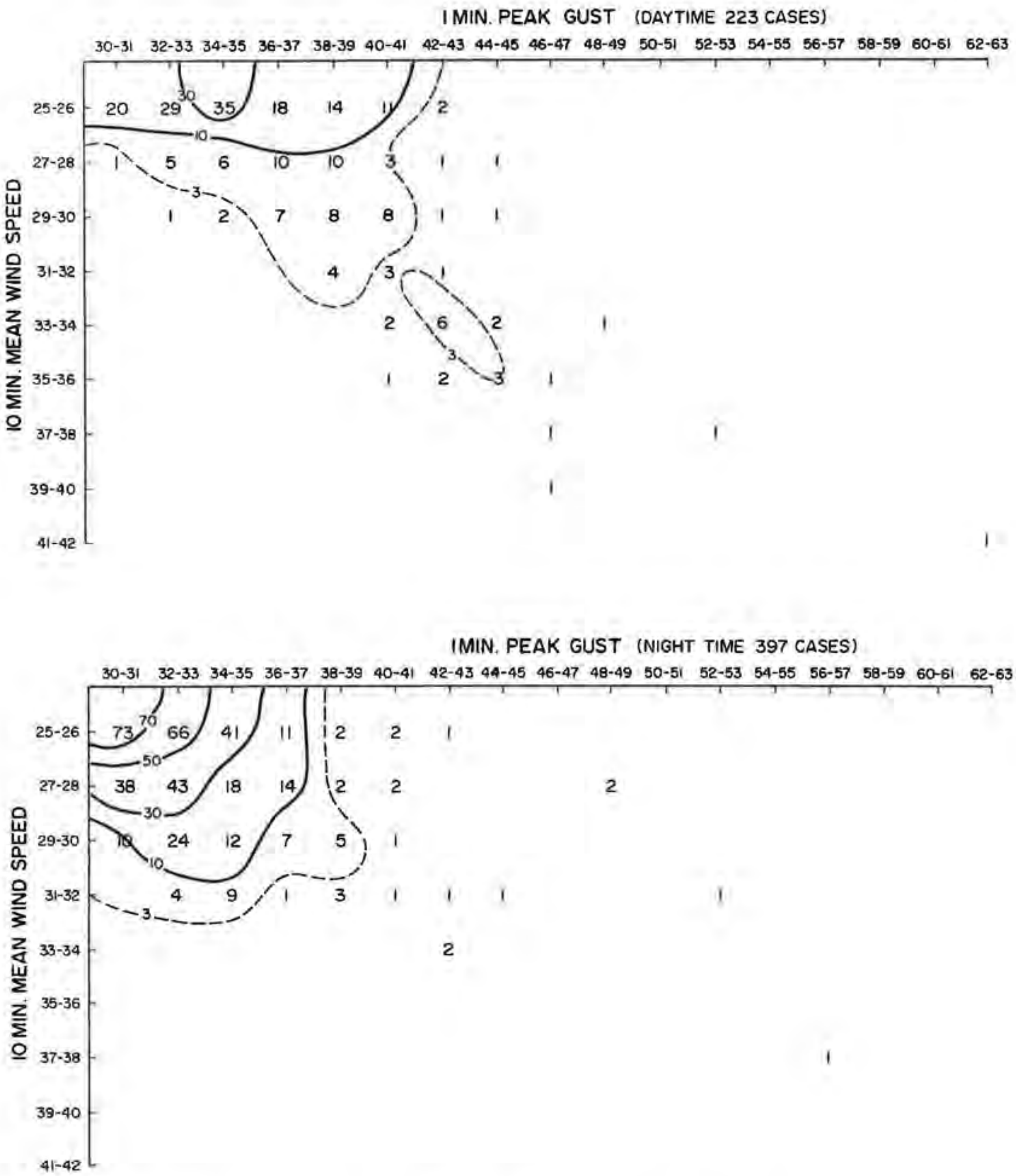

Fig. 4. Contingency table of 1 min. peak gusts vs 10 min. mean wind speeds

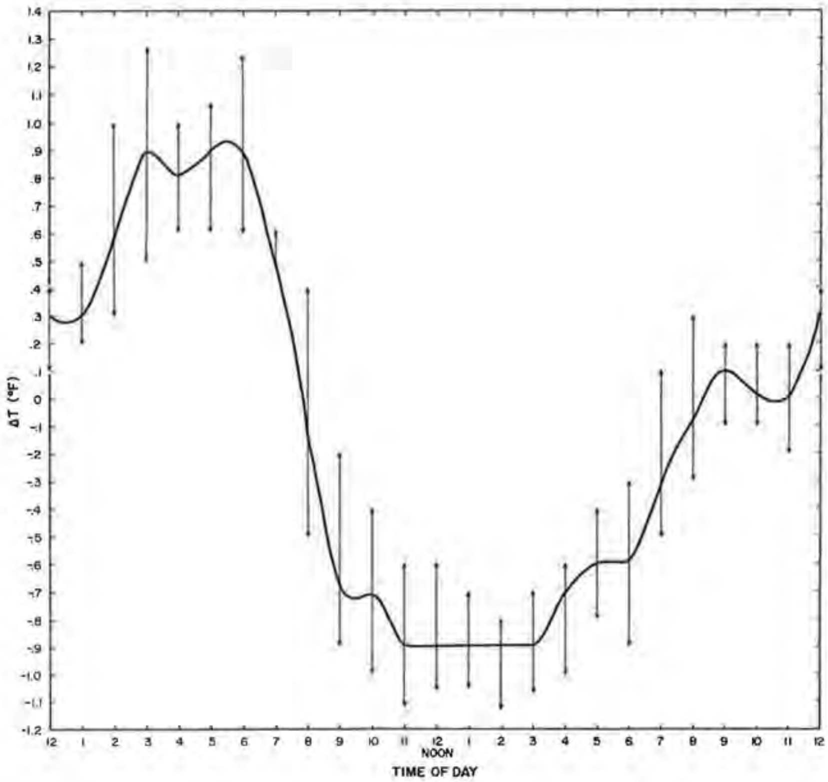

Fig. 5. Vertical Temperature Differences vs Time of Day

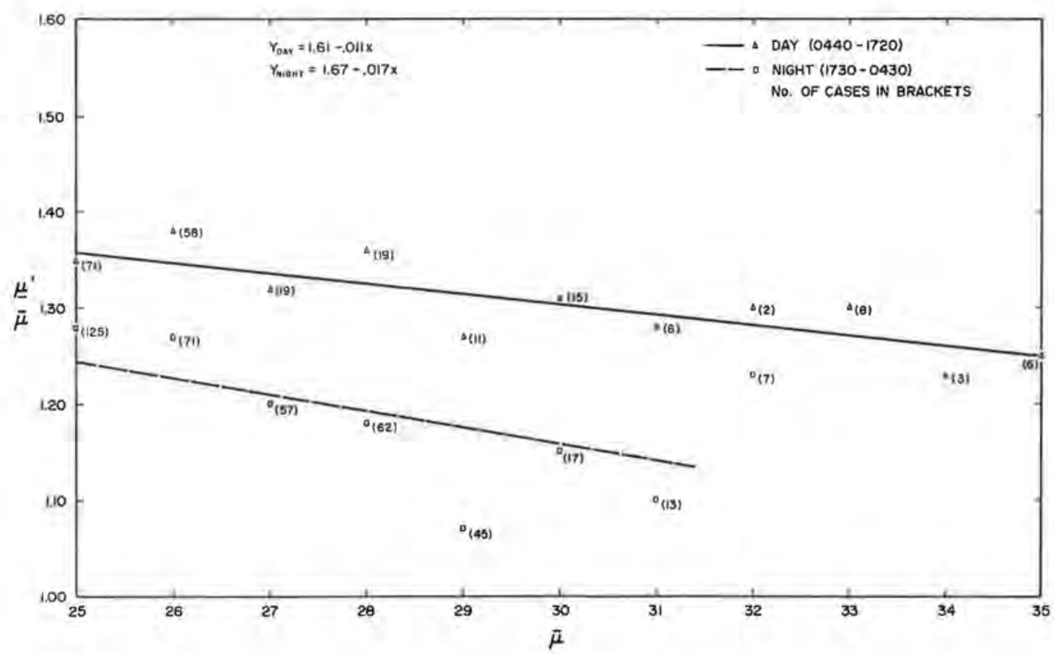

Fig. 6. Mean Gust Factors vs 10 min. Mean Wind Speeds by day and by night

comparison of night and day, with isolines drawn, shows that the modal frequencies along each horizontal line shift towards the right in the day-time. For mean speeds of 27-28 mph. for example, the modalgust is about 32 mph. at night and 37 mph. in the daytime.

Gustiness is caused by both the roughness of the underlying surface and the stability of the air mass. It seems reasonable, therefore, to assume that the diurnal cycle of the gust factor in Fig. 3, was due to a stability cycle. Fig. 5 shows vertical temperature differences, T, between 290 and 100 foot tower heights averaged over the same period of observation. There are inversions at night and lapse conditions during daylight hours. This supports the assumption that increased instability during the day due to solar heating causes an increase in peak gusts and thus in gust factors.

Fig. 6 shows the mean gust factor, $\frac{u'}{\bar{u}}$, versus the mean wind speed, $\bar{u}$, after grouping the observations into various wind speed classes. Best fitting straight lines have been drawn separately for the time divisions, 'day' and 'night'. In both cases the gust factor decreases slightly with increasing wind speed. In addition and as indicated earlier in the discussion of Figs. 3 and 4, gust factors are less at night than in the daytime.

CONCLUSION

Winds from the SW-W sector are prevalent at the CBC TV tower for speeds of over 25 mph. during the period of study. In this preliminary study, the 1 min. gusts have been studied over a 3 month period for cases when the 10 min. mean wind was over 25 mph.

A diurnal trend is found in the gust factor. This trend can be explained in part, by the diurnal cycle of the mean hourly vertical temperature differences. Winds are shown to be less gusty during the 'night' than during 'day'. Finally, the gust factor decreased slightly with increasing wind speed.

Acknowledgement

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References

Canadian Meteorological Branch, 1967: Climatology Division; Wind Data for Climatological Purposes, DS No. 14-64, p. 2-3.

Davis, F.K., and H. Newstein, 1968: The Variation of Gust Factor with Mean Wind Speed and with Height, Journal of Applied Meteorology, Vol. 7, p. 372-3.

Davenport, A.G. 1962: The Response of Slender, Line-Like Structures to a Gust Wind, Excerpt Proc. Instn Civ. Engrs, Westminster, London Vol. 23, p. 390.

Davenport, A.G. 1963: The Relationship of Wind Structure to Wind Loading, Paper 2, National Physical Laboratory, Teddington, Middlesex, England. p. 18.

Davenport, A.G. 1966: The Treatment of Wind Loading on Tall Buildings, uncorrected pre-print, Pergamon Press, p. 444-446.

Mitsuta, Y. 1962: Gust Factor and Analysis of Time of Gust, Meteorological Research Institute, Shorter Contribution, Kyoto University, 551. 551.2.

Powe, N.N. 1968: The Influence of a Broad Valley on the Surface Winds Within the Valley. Canada, Dept. of Transport, Meteorological Branch, Technical Memoranda Series, TEC-668.

RESEARCH IN URBAN CLIMATOLOGY IN CANADA

The Reports which follow are intended to provide an indication of the scope of research in urban climatology currently underway in Canada. They essentially sample the field and make no claim to constituting an exhaustive study, or to including reference to all the work that is going on. It is hoped, however, that their presentation in this BULLETIN will provide readers with some indication of the widespread activity and interest in this field, which is a matter of direct importance to the health and well-being of some seventy per cent of the Canadian population.

- Editorial Note.

Research in Urban Climatology in the Atmospheric Research Section, Meteorological Service of Canada, by R.E. Munn, Meteorological Service of Canada, Toronto.

1. Introduction

The Meteorological Service of Canada has been interested in urban climate for many years. One of the earliest investigations was by Middleton and Millar (1936), who undertook automobile temperature traverses along Yonge Street in Toronto.

Within the Atmospheric Research Section there are two Units with current programs related to urban climate:

(a) the Micrometeorological Research Unit, which initiates studies and provides advice on the meteorological aspects of air pollution; and

(b) the Mesometeorological Research Unit, which has begun an experimental program designed to develop short-range (an hour or less) aviation terminal forecasts, and which has some other projects in hand.

2. Studies in the Micrometeorological Research Unit

Beginning with the Trail smelter investigation for the International Joint Commission (Hewson, 1954), the Meteorological Service has had an expanding program of air pollution investigations. In recent years, more and more attention has been given to the question of urban pollution from multiple sources. The first efforts were empirical or descriptive, and studies of this type are continuing. Two papers "in press" concern the development of an air quality index, using data from Hamilton (Weisman et al 1969) and an analysis of the spatial distribution in Windsor of suspended particulate and iron concentrations (Munn et al 1969). Over the years, too, there has been a search for a satisfactory pollution wind-rose, one that is not only meaningful but also easy to interpret by pollution control officers; a recent analysis, not yet submitted for publication, appears promising.

With the co-operation of the Occupational Health Division, Provincial Health Departments, the Ontario Research Foundation, McGill Department of Meteorology, and Atomic Energy of Canada Ltd., a network of meteorological towers has been established across Canada. The Meteorological Service

(Climatological Division) has been transferring the hourly data to punched cards, and there are vertical temperature differences and/or tower winds on file from Glace Bay, Upsalquitch (near Moncton), Montreal Botanical Gardens, Montreal CBC TV tower, Toronto Meteorological Research Station, Toronto Mimico, Hamilton, Sarnia, Detroit TV tower, Whiteshell, Edmonton and Calgary. In addition, a TV tower has just been instrumented near Winnipeg while other installations are planned for Quebec City and Suffield. Quite recently, the program has been expanded to include publication of a Quarterly Meteorological Tower Bulletin.

In order to predict the diffusion and transport of pollution in a large metropolitan area, it is necessary to have a better understanding of urban meteorology than is presently available in most cities, particularly at locations where there are interactions with other mesoscale influences such as lakes and valleys. A problem of some concern in the Hamilton-Toronto-Oshawa area occurs in the daytime in spring and summer; heavy industry is concentrated along the shore-line, and lake breezes (with associated temperature inversions) carry the pollution inland to residential areas.

An analysis of the daytime Toronto urban heat island has been completed (Munn et al 1969) using the climatological network of maximum-temperature observing stations. Two of the winter results are given in Fig. 1; these indicate a displacement of the heat island from the central business district, northward when winds are off the water and southward when winds are off the land. In the summer of 1968, automobile traverses were undertaken across the city (as yet unpublished). In addition, Findlay and Hirt (1969) have described a case of convergent wind flow towards the heat-island centre on a day when regional winds were light and the lake-air temperature difference was small.

3. Studies of the Mesometeorological Research Unit

The Mesometeorological Research Unit is studying short-range aviation terminal forecast techniques (Clodman and Overs 1967). A network of automatic weather stations is being installed around Toronto International Airport, and because some of the observing sites impinge on the built-up area, there is an opportunity to investigate urban meteorology. Indeed,

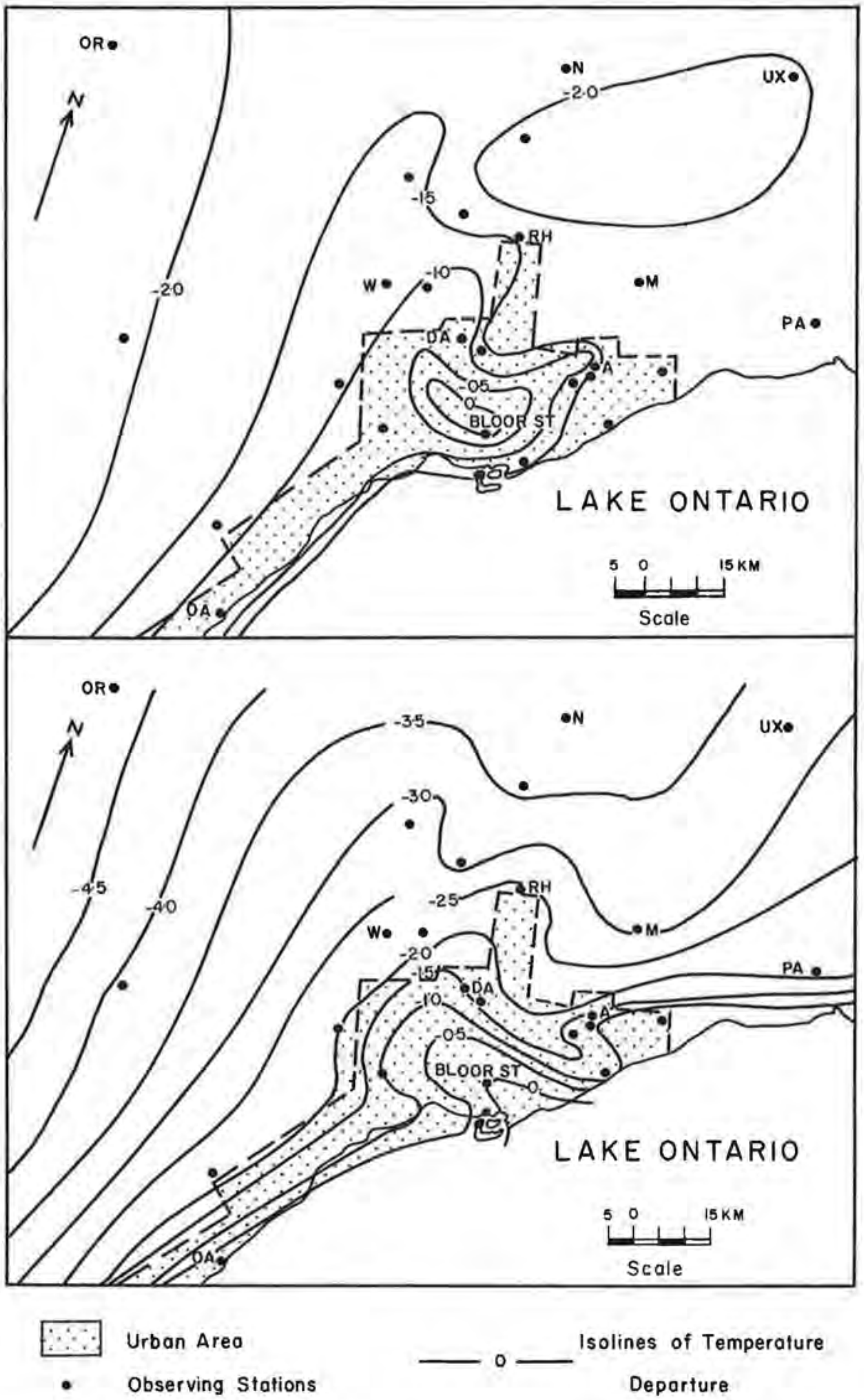

Fig. 1. Mean Departure of Maximum Temperature from the Bloor St. Maximum for Two Cold Periods.
Upper: Mean of 8 days, Bloor St. Max. 2°C, geostrophic wind from water at a speed greater than 5m sec^{-1}.
Lower: Mean of 35 days, Bloor St. Max. -8°C, geostrophic wind from land at a speed greater than 5m sec^{-1}.

the presence of the adjacent city may be very important in some synoptic situations.

Meso-scale weather variability is caused by travelling meso-systems and by stationary surface features such as hills, cities and lakes. The special network of weather stations around Toronto International Airport will provide some physical insight into the nature of the interactions.

Another study (Muller and Clodman 1968) concerns the distribution of snowfall in and around Metropolitan Toronto. The fundamental empirical orthogonal patterns have been established for a fairly large sample of storms. The four most important patterns explain approximately 70% of the variance of the snowfall, normalized on a storm-by-storm basis. A Monte Carlo approach is being used to establish the statistical and practical significance of the patterns, and methods of prediction from storm to storm are being examined.

A report in press (Muller 1969) contains an analysis of lake-breeze occurrences in the Toronto area for fifteen years, using hourly weather reports. Potential lake-breeze days (when a wind reversal could have been observed) have been identified and related to readily available predictors. Timing, maximum temperature contrast and the use of a Biggs-Graves-type lake-breeze index have also been examined.

Finally a study is nearing completion on the control of surface wind at Toronto airport by subsynoptic pressure patterns and local terrain, together with low-level thermal gradients. The subsynoptic pressure pattern is important only for time scales of about twelve hours or longer, fluctuations of shorter period all being the result of local influences. Even on the scale of 12 hours and longer, the control of the pressure pattern is influenced by terrain features, the relevant scale increasing with the strength of the pressure gradient.

Acknowledgements

I am indebted to Dr. C.D. Holtz and F.B. Muller for helpful suggestions.

References

Clodman, J., and Overs, J.E. 1967: The Malton meso-meteorological project. Proc. First Can. Conf. on Micrometeorol. Vol. 2, 353-359. Meteorol. Branch, Toronto.

Findlay, B.F. and Hirt, M.S. 1969: An urban-induced meso-circulation. Atm. Envir. 3 (in press)

Hewson, E.W. 1945: The meteorological control of atmospheric pollution. Quart. J.R. Meteorol. Soc. 71, 266-282.

Middleton, W.E.K., and Millar, F.G. 1936: Temperature profiles in Toronto. J. Roy. Astronom. Soc. Canada 7, 265-272.

Muller, F.B. 1969: Interactive influences on lake-breeze at Toronto, Canada. Met. Branch Res. Report (in press).

Muller, F.B., and Clodman, J. 1968: The application of empirical orthogonal functions to the analysis of mesoscale variations of precipitation in storms. Proc. First Nat. Conf. on Statistical Meteorol., Am. Meteorol. Soc., Boston, 116-123.

Munn, R.E., Hirt, M.S., and Findlay, B.F. 1969: A climatological study of the interaction between the daytime lake and urban meso-scale circulations at Toronto (Submitted to J. App. Meteorol.)

Munn, R.E., Thomas, D.A. and Cole, A.F.W. 1969: A study of suspended particulate and iron concentrations in Windsor, Canada. Atm. Envir. 3 (in press).

Weisman, B., Matheson, D., and Hirt, M.S. 1969: Air pollution survey for Hamilton, Canada. Atm. Envir. 3 (in press).

Research on Urban Pollution at the University of Alberta by Richmond W. Longley, Professor of Geography, in the University of Alberta.

Two members of the Department of Geography, University of Alberta, Professors K.D. Hage and Richmond W. Longley, are co-operating with the Alberta Department of Public Health on pollution in Calgary and Edmonton. In this work, they are closely linked with the operations of Geoscience Research Associates, J.J. Kinisky, President, as the latter collects and analyses meteorological data in and around the two cities.

The meteorological situations of the two cities, when considering the pollution potential, are quite different. Calgary is located in the foothill area of the Rocky Mountains, at the junction of the Bow and Elbow Rivers. On the north and west sides of the city area hills rise to 800 ft above the relatively broad valleys in which most of the city lies. An industrial park is located in the valley of the united rivers southeast of the city center. This area in which the park lies has been discovered to be the coldest area of the city so that inversions are common. The chinook winds of southern Alberta contribute to the pollution. On one winter day in three, Calgary temperatures rise to 40°F or over because of these winds. On other occasions, the warm air stays aloft, and cold air remains near the surface. Pollution occurs under the warm air when southeast winds carry the gases from the industrial park toward the city center where they add to the gases from cars and other sources. Pollution can, under these circumstances, rise to high values before the strong chinook winds descend to the surface or a fresh outbreak of polar air arrives with northwest winds, sweeping away the offending gases.

Edmonton is situated on a broad plain intersected by the narrow valley of the North Saskatchewan River. Here the winter inversion found in polar continental or Arctic air is common and although the urban heat does reduce the intensity of the inversion near the center of the city, it fails to remove it. Winds can remain light for long periods, so that pollutants are not removed from the city area. The inversion plus the light winds reduce turbulence and diffusion, with the result that a plume

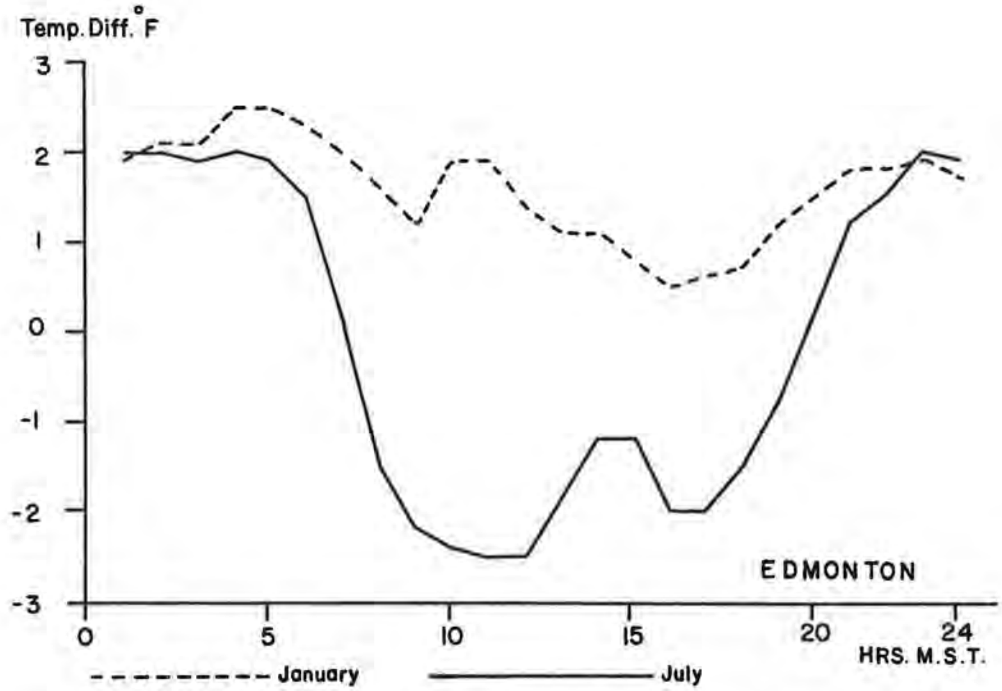

Fig. 1. Mean lapse rates per 100 m between 17 m and 112 m at Edmonton, Alberta, January and July, 1968.

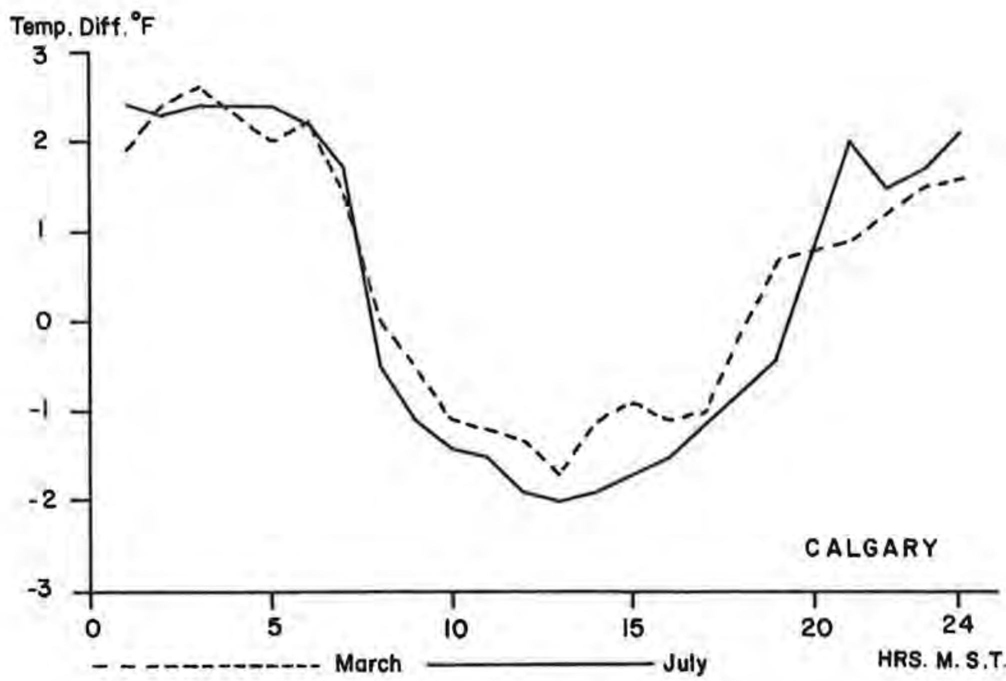

Fig. 2. Mean lapse rates per 100 m between 3 m and 92 m at the tower in Calgary, Alberta, March and July, 1968.

meanders downwind with only slowly decreasing concentration. Smoke is not a major problem because most heating is done by the burning of natural gas. On the other hand, the water vapor condenses readily to form cloud and fog which can persist over the city when the air is clear on the upwind side of the city. The pollution danger lies with other gases from automobiles and industrial plants around the city, particularly those in the industrial area east of the city. With vertical mixing limited at times to 500 ft or even less, the concentration of noxious gases can and does increase to offensive values.

The observing program of Geoscience Research Associates has been to observe the spatial variation of surface temperatures within the two cities, and also the vertical variation to 300 ft using in Calgary a tower situated in the lower Bow Valley and in Edmonton the C N Tower, the highest building in Edmonton. Some traverses of the city have been made using a kytoon to obtain data to 500 ft. It is hoped that a number of trials can be done to determine the dispersion of particulates released into the atmosphere and from this a measure of the diffusion.

Some results are given in the accompanying figures. Fig. 1 gives the mean temperature difference per 100 m between 17 m and 112 m at Edmonton for January and July, 1968. The January figure shows that the inversion tends to persist throughout the day, decreasing somewhat in intensity during the afternoon. During the mid-day hours of July, the surface layer tends to have a superadiabatic lapse rate. Fig. 2 gives similar data for the Calgary tower, for the layer from 3 m to 92 m for March and July, 1968. No winter data are available to compare with the January data at Edmonton.

Figs. 3, 4, 5, 6 present the same data in another form, giving the frequency distributions of lapse rates by hours. The intensities of the nocturnal inversions can at times be extreme, suppressing vertical currents and thus keeping noxious gases close to the city streets.

As yet only one report has been prepared for publication. A number of memoranda have been sent to the Department of Public Health to make them acquainted with some of the results of the investigations.

References

Hage, K.D. and Richmond W. Longley, 1968. "Ventilation and Mixing in Alberta Cities." University of Calgary, Proc. Banff Conf. on Pollution, May, 1968, 16 p.

TEMP. GRAD. °C $(100\ m)^{-1}$	HOUR (MST) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	TOTALS
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99								1															1	1	3
-1.99	1	3	1		1		2	1	4	2	1	2	4	5	2	4	3	4	3	3	2	1			49
-0.99							2	1	1	2	1	2	3	4	1	3	1	2	1	1	1				26
0.01	10	9	10	11	9	12	9	9	10	7	9	10	7	6	12	7	11	6	8	5	8	9	10	12	216
1.01	8	7	7	8	10	7	4	8	8	8	7	6	10	7	7	10	9	12	12	11	9	10	9	7	201
2.01	2	4	5	3	1	4	4	5	3	4	6	6	2	3	4	4	5	4	1	5	4	4	2	3	88
3.01	5	2	3	3	3	1	5	1		3	3	1	1	2	3	2	1	2	1	3	2	1	3	4	55
4.01	3	1	1	3	3	3	1	2	2	2	1	2	2	3	2				4	1	2	4	3		45
5.01	1	3	1			2	2	1	1					1		1			1	2	1		2	2	21
6.01		1			1	1	1	2	1	2	3	2	1				1	1			1	1		2	21
7.01	1	1	3	1	1		1		1	1			1								1	1	1		14
8.01				1	2																				3
9.01						1																			1
10.00				1																					1
																						TOTAL			744

Fig. 3. Frequency distribution of lapse rates, by hours, January, 1968, at Edmonton, Alberta, C N Tower, 17 m to 112 m.

TEMP. GRAD. °C $(100\ m)^{-1}$	HOUR (MST) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	TOTALS
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99								2	4	3	5	2					1	1							18
-2.99							1	5	4	6	5	8	3		1	3	3	3	1						43
-1.99						3	11	12	13	13	14	16	20	10	13	18	22	17	13	9					204
-0.99										3	4	3	6	5	7	6	5	10	1	5					55
0.01	5	4	3	4	7	13	14	11	9	5	3	2	1	13	8	3			16	13	11	8	6	5	164
1.01	15	10	12	8	7	9	4	1		1			1	2	1	1				4	19	13	14	17	139
2.01	5	11	8	15	9	5	1		1					1	1						1	7	10	5	80
3.01	4	4	5	2	7																	3	3	3	29
4.01	2	2	3	2	1	1																		1	12
5.01																									
6.01																									
7.01																									
8.01																									
9.01																									
10.00																									
																						TOTAL			744

Fig. 4. Frequency distribution of lapse rates, by hours, July, 1968, at Edmonton, Alberta, C N Tower, 17m to 112m.

TEMP. GRAD. °C $(100\ m)^{-1}$	HOUR (MST)																								TOTALS
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
-9.99																									
-8.99																									
-7.99													1											1	2
-6.99																									
-5.99																									
-4.99																									
-3.99										1	1														2
-2.99								1	1	1	1		2			1									7
-1.99		1		1	1	1		3	3	4	7	12	8	10	7	9	6	1	2		1			2	79
-0.99		1		1				1	1		3	1	2	1	1	2	4		1		1			1	21
0.01	8	6	8	7	8	8	9	10	12	10	7	8	7	9	12	7	12	14	9	13	11	10	11	5	221
1.01	5	3	2	1	2	4	5	4	3	6	4	2	3	3	2	3	1	5	5	5	3	6	3	3	83
2.01	3	5	6	5	5	3	5	2	3	1						1		3	2	1	3	2	3	5	58
3.01	3	2	1	3	3	1	1	1											2	1	1	1	1	1	22
4.01	2		1	2	2	3	1	1							1				1	2	3	3	4	1	27
5.01	1	3	2	1		1	1												1	1		1	1	4	17
6.01	1	1	2	1	1	1																			7
7.01					1																				1
8.01			1	1			1																		3
9.01		1				1																			2
10.00																									
																								TOTAL	552

Fig. 5. Frequency distribution of lapse rates, by hours, March, 1968, at the meteorological tower, Calgary, Alberta, 3 m to 92 m.

TEMP. GRAD. °C $(100\ m)^{-1}$	HOUR (MST)																								TOTALS
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
-9.99																									
-8.99																									
-7.99																									
-6.99																									
-5.99																									
-4.99																									
-3.99																									
-2.99											1	1	2	2		2									8
-1.99	1					1	1	7	9	10	9	10	18	14	9	10	7	6	4			1	1		118
-0.99							1	2	2		1		4	2	1	2		1							16
0.01	8	7	6	8	7	12	21	17	11	8	12	10	5	9	18	14	21	16	14	11	6	6	6	6	259
1.01	7	6	7	5	9	7	5	5	7	6	7	6	1	4	2	2	3	8	11	9	8	3	5	4	137
2.01	7	6	7	8	6	5	3		2	6	1	2							2	8	8	6	6	7	90
3.01	2	4	7	6	5	5				1		1	1							3	3	6	5	5	54
4.01	2	5	3	4	3	1									1	1					1	1	1	3	26
5.01	2	3	1		1																4	4	2	3	20
6.01	2																					3	2	3	10
7.01																					1		2		3
8.01																						1			1
9.01																							1		1
10.00																									
																						TOTAL			743

Fig. 6. Frequency distribution of lapse rates, by hours, July 1968, at the meteorological tower, Calgary, Alberta, 3 m to 92 m.

Research in Urban Climate in the University of Calgary, by I.Y. Ashwell, Professor of Geography in the University of Calgary.

The first observations on the urban climate of the city of Calgary were made as part of a project by B.E. Sullivan (1965). This involved the setting-up of thermometers at Fire Halls throughout Calgary, and the arrangement by which duty Firemen made observations at certain times of the day, starting in 1965. This system of temperature recording was amplified in 1966, and tested statistically by N. Yudcovitch (1967 a). In all, seventeen stations measuring horizontal temperature are presently in operation in Calgary. The horizontal temperature distribution in the city has been discussed by Yudcovitch (1967 a & b). The most interesting results of these observations have been the discussion of the effect of chinooks on the city of Calgary. Under normal winter conditions, with arctic air well established, the city itself sets up a marked heat island of from 5 - 10°F. However, with the arrival of warm air from the west, this air may or may not reach the surface, depending upon the amplitude of the wave caused by the Rocky Mountain system. If the chinook air does not reach the ground surface, it remains as a warm current above the cold arctic air trapped in the valley in which Calgary lies, with consequently large inversions, and a marked haze of water vapour and pollutant over the city area. Normally these inversion periods are not very well marked, because at some stage the chinook current reaches the surface and breaks up the inversion with strong winds. Under these conditions the heat island is dispersed and temperature differences of from 10 - 20°F may be noted in different parts of the city, depending on elevation, and the locations where the chinook air is preponderant over the arctic air. The project now forms part of a major investigation being carried out under the auspices of the Province of Alberta, in which a number of agencies are co-operating. The investigation covers both pollution, research into causes of pollution, and the investigation of meteorological factors, by a large number of agencies. This project, however, does not examine the pollution *per se*, but only the meteorological conditions connected with it.

Within the last two years the mast of television station C.F.C.N., on a hill just outside and above the city has been instrumented with temperature sensors. During the first year (1966-67) when thermocouple sensors were used at 25, 100, 200 300 ft on the tower, inversions of about 30° were measured on the 300 feet of the tower during chinook conditions. During the winter 1967-68 a thermistor set-up was substituted, but this has so far not registered satisfactorily, and it is hoped that the problem with the system can be resolved before the winter of 1969-70. Vertical temperature measurements, and probably vertical wind measurements, on this mast promise to be a fruitful field of investigation into the effect of chinooks on inversions and consequent air pollution and if these can be combined with upper air ascents for part, at least, of the winter, this may lead to a more meaningful picture of this particular phenomenon.

Traverses have been made across the city during the winter months and on occasions during the summer. At first these were made by operators using an Assmann psychrometer, but the problem of stopping in traffic long enough to carry out the observation has not yet been overcome. Recent observations have been carried out with an aircraft thermometer attached to the outside of the car and read either by the driver or by an assistant. Although these readings cannot be considered exceptionally accurate, they confirmed the picture given by the horizontal and vertical temperature measurements, and indicate that the topography of the Calgary area is a very important factor in the temperature distribution. On cold nights, for instance, the Bow Valley is several degrees cooler than the heights surrounding the city area.

References

Sullivan, B.E. 1965: "An Areal Survey of Winter Temperature Conditions in the Calgary Area" Unpublished Geography 305 paper, Geography Department, University of Alberta at Calgary.

Yudcovitch, N.T. 1967 a "Temperature Conditions in Calgary" M.Sc. thesis, Geography Department, University of Calgary.

Yudcovitch, N.T. 1967 b "Factors Affecting the Temperature Variation in Calgary", The Albertan Geographer, 3, pp. 11-19.

Research in Urban Climatology at the University of Winnipeg, by William C. Bell, Lecturer in Geography at the University of Winnipeg.

The Department of Geography, University of Winnipeg, is currently engaged on a large and comprehensive investigation of urban climatology and air pollution in Winnipeg.

The situation of Winnipeg makes it ideal for this type of study. It is the case of the city interrupting the flat prairies with no complicating topographic effects or mesoscale circulations due to lake or sea influences. Any differences in the climate between the surrounding prairie and the urban area can be ascribed almost entirely to the urban climate of Winnipeg.

In the Fall of 1968, the 1,057 foot C.B.C. tower at Starbuck, 15 miles west-south-west of the city, was instrumented. It is now the tallest meteorologically instrumented tower in Canada, and the only tall meteorological tower on the prairies.

The present site measures wind speed and direction, and air temperature. Equipment consists of two Bendix-Friez aerovanes mounted at 35ft. and 810ft. A third unit will be added in the Spring of 1969 at a level still to be determined. Temperature equipment, in the form of Beckman and Whitley radiation shields with thermistors, is mounted at 35ft., 200ft., 400ft. and 810 ft. Only the lower level is working at present but the others will be in operation by late March. Wind recording is done on strip chart recorders whilst temperature is recorded on punched tape with automatic programmable scanning.

In the spring of 1969 data will also be gathered on radiation (Eppley pyranometer), net radiation (CSIRO net radiometer), ultra-violet radiation (Eppley precision spectral pyranometer), Stevenson screen temperature and humidity, and smoke.

The above data will operate as control data for work being done in the city of Winnipeg proper. This work at present uses two vehicles equipped with digital thermometers for horizontal temperature traverse work. Data is gathered on selected days only. Results to date have shown a maximum heat island effect of $18^{\circ}F$. with north-east winds of two miles per hour under clear skies and snow cover. Results of these traverses will be published in the near future.

Urban climatological investigations will be stepped up considerably during 1969. Radiation, net radiation, and ultra-violet radiation will be measured close to the downtown area. Eight hand anemometers are on order. These will be used to examine the wind field in the city, and the effect of local features such as parks upon it. Temperature and humidity data, using digital thermometers, will also be gathered in the park investigations.

The vertical temperature structure over the city will also be examined using parafoils. This work will commence in July. The possibility of instrumenting a light aircraft is also being investigated and looks optimistic. These data will be compared to the Starbuck control data and radiosonde ascents.

Air pollution will also be investigated in much greater detail. Eight R.A.C. F2 smoke samplers are on order and these will supplement the present three operated by the Department of Health. Three high volume samplers, an SO_2 sampler, and an H_2S sampler will also be in operation by Fall 1969.

The above data will yield results on the modification of air and of the mixing layer as air progresses over the city. From this an urban heat island model will be developed. Regression equations will be developed for the urban heat island showing the effect of various meteorological factors and urban morphology upon its intensity. Air pollution data will also be examined in relation to meteorological conditions, hour of day, day of week, heating versus nonheating season, and season.

The above project will be carried on over at least a two year period.

Acknowledgement

Financial and technical assistance in the above project is being provided through the University of Winnipeg and the Canada Department of Transport.

Programme de Recherches sur la Climatologie Urbaine de la Région de Québec, sous la direction de A. Hufty, Professeur à l'Université Laval, Institut de Géographie.

Les projets en cours ou à venir se fond à plusieurs niveaux:

1. des recherches personnelles:

   a) depuis 1967, comparaison du rayonnement solaire direct, par beau temps, dans la ville et à l'extérieur de celle-ci;

   b) à partir d'avril 1969, étude du gradient de température et de vent le long de la tour de télévision du canal 4, en vue d'une application à la pollution de l'air.

2. une recherche de maîtrise: cartographie des facteurs géographiques qui ont une importance dans une étude du rayonnement.

3. des recherches appliquées diverses, qui vont faire partie d'un futur atlas d'aménagement du territoire de la région urbaine de Québec. Elles se feront en collaboration avec les ministères intéressés. Les matières suivantes, mais cette liste n'est pas exhaustive, seront les premières traitées; températures, vents, enneigement.

Research in Urban Climate at McMaster University, by F.G. Hannell, Professor of Geography in McMaster University.

Pilot Studies

Pilot studies of Hamilton's urban heat island have been reported on by Oke and Hannell (1968). Automobile surveys indicated that the urban heat island was a well developed phenomenon whose magnitude was very closely dependent upon cloud amount and wind speed. Under good radiation conditions at night, with wind speeds < 2 m sec^{-1}, its magnitude was at least $6^{o}C$ ($11^{o}F$), and it sometimes approached $9^{o}C$ ($16^{o}F$).

The heat island often displays two separated cores, each of which can be directly attributed to urban causes. The larger, in terms of area, is located in the zone of heavy industrial development along the southern shore of Hamilton Harbour, whilst the smaller is centred upon the central business district. The former is the result of the production of heat in the steel making process. It was calculated that averaged over the total plant of the Steel Company of Canada this heat results in a sensible heat flux of 281-422 kg cal cm^{-2} yr^{-1}, and a latent heat flux of 35 kg cal cm^{-2} yr^{-1}. The sensible heat value is very high but is not inconsistent with the results of Bornstein (1968) in Manhattan.

Maps of mean particulate loading (mg cm^{-3}) in Hamilton over the period January 1963 - December 1966 (Stewart and Matheson 1968) clearly indicate that the area of greatest air pollution has two cores, and these coincide almost exactly with the two cores of the urban heat island.

Analysis of the 20 surveys indicate that Hamilton's urban heat island becomes insignificant (i.e. rural/urban temperature difference $<1^{o}C$) when the wind speed is greater than 6-8 cm sec^{-1} (13-18 mph). Comparison with other cities and towns showed this value to fit into a more general relationship between city size and the wind speed necessary to obliterate the heat island effect.

Future Studies

More frequent and much more detailed surveys of the urban climatology of Hamilton are to be commenced in September 1969. During each two-hour survey period, temperature traverses in each of the city's six sectors are to be conducted simultaneously with automobiles, each of which is to be equipped with a battery-operated recorder and a single sensor system made of nine thermocouples mounted in series. Temperatures in the vertical are to be obtained through the use of a number of tethered balloons inflated with helium. Each of these will carry aloft a sensor system precisely similar to that with which each of the automobiles is to be equipped, and temperatures in the vertical will be measured at intervals of about 15 m (50 ft.). It will thus be possible to construct observed three-dimensional models of Hamilton's heat island under different meteorological conditions. The literature is remarkably deficient of such three-dimensional observations, and even when temperatures in the vertical have been measured (Duckworth and Sandberg, 1954) they have not been taken simultaneously at a sufficient density per km^2.

Air pollution surveys at ground level are also to be conducted under different conditions of wind and atmospheric stability (Forde and Matheson, 1965; Steward and Matheson, 1968). In addition, evacuated aluminum cylinders, each of which has a volume of precisely $1m^3$, will be attached to the tethered balloons at intervals of 30m (100 ft.). A mechanical device is being designed by means of which the seals on the cylinders can be broken at will. Air rushing into each cylinder will then pass through a fine filter-pad, thus permitting quantitative data of mean particulate loadings in the third dimension to be obtained. So far as is known, no such data is currently available.

By means of vertical and horizontal thermocouple "ladders", each carrying sensors spaced at intervals of 1m, detailed surveys are to be udertaken of the three-dimensional temperature field which surrounds a single building. Other thermocouples will be drilled into each of the four walls to depths varying by 1 cm. Each of the 192 sensors will be coupled to one of two 96-point recorders, and an automatic switch will call for all temperatures to be recorded every hour both by day and by night throughout selected periods in each of the four seasons. Three-dimensional temperature models will then be constructed by McMaster University's computer (CDC 6400) to accord with specific values of the sun's altitude and azimuth.

After this study of the temperature field around a single building has been completed, simultaneous studies around buildings of different size and constructed of different materials will be undertaken in an attempt to establish seasonal correlations between the exposed surface areas of buildings, types of building material and the intensities of those air temperature gradients which surround them.

References

Bornstein, R.D., (1968). Observations of the urban heat island effect in New York City. J. Appl. Met., Vol. 7, p. 575-582.

Duckworth, F.S. and Sandberg, J.S. (1954). The effect of cities upon horizontal and vertical temperature gradients. Bull. Amer. Met. Soc. Vol. 35. p. 198-207.

Forde, A.V. and Matheson, D.H., (1965). The design and operation of a municipal air pollution survey, a paper presented at the 58th Annual Meeting APCA. Toronto.

Oke, T.R., and Hannell, F.G., (1968). The form of the urban heat island in Hamilton, Canada. (A paper read at the World Meteorological Organization's Symposium on Urban Climates and Building Climatology in Brussels on 16 October, 1968. This paper is to be published in the Proceedings of that Symposium).

Stewart, I.M., and Matheson, D.H., (1968). Methods of relating high volume sampler particulate loadings to wind direction. Atmospheric Environment. Vol. 2, p. 181-185.

CANADIAN URBAN CLIMATES - A BRIEF LITERATURE SURVEY

by

M.K. Thomas*

The first significant Canadian paper on urban climate, written and published after field research, was Middleton and Millar's "Temperature Profiles in Toronto" (1936). The authors had investigated the distribution of temperature across the City of Toronto under various meteorological conditions, and one particular figure in their paper, representing conditions on a cold winter night with clear skies and a slight breeze, showed a startling difference in temperature, some 27 degrees, along Yonge Street between the Don River valley and a nearby crest. This figure became classic, was reproduced in many papers and text books, and has given Toronto a perhaps undeserved reputation of being a city where large temperature contrasts may be expected.

In general Canadian meteorologists have been more interested in the dynamics of the atmosphere and in the meteorological contrasts from one representative station to another than in the differences which might be found across urban areas. As a result there have been few research papers published on urban climatology or on the city or urban effect. Operational meteorologists responsible for urban area forecasting have shown a greater interest in the problem than have research meteorologists, and as a result, several reports have been published on the distribution of temperatures across such cities as Vancouver, Winnipeg, Toronto and Halifax. Over the past decade or so, however, an increasing awareness of the dangers of atmospheric pollution has led to increased attention by research meteorologists to this field. Within the Meteorological Branch Dr. R.E. Munn has been the leader of a small group engaged in this work; much interest has been generated and numerous papers and articles have been published. A list of selected references to papers concerning Canadian urban climates is attached to this brief report.

Following World War II, concern over atmospheric pollution at Edmonton and Windsor led to papers by Robertson (1951 and 1955), Baynton (1953 and 1956), and Munn and Katz (1959 and 1960). Forecasters at

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Halifax and Winnipeg, using automobiles equipped with recording thermometers, drove across urban areas to ascertain the extent of the urban effect and published the results (Dexter 1954, Einarsson and Lowe 1955). Other meteorologists undertook to analyze and publish statistical climatological reports on the climates of their cities - Montreal (Longley 1954), Vancouver (Harry and Wright 1957), Toronto (Shenfeld and Slater 1960), and Winnipeg (Labelle, Brown and Hasinoff 1966), and other articles pertaining to the urban climates of Toronto were published by Thomas (1953, 1954), Mateer (1961), and Potter (1961), of Halifax by Dexter (1958), and of Montreal by Mahaffy (1961).

Increased attention to atmospheric pollution and urban climates has led to the employment by the Meteorological Branch of graduate students and summer assistants on research projects during the 1960's. The result has been a series of papers by Munn, Emslie, Wilson and others on temperature, radiation, wind, rainfall and pollution in Vancouver, Edmonton, Winnipeg, Windsor, Toronto, Ottawa, Montreal and Saint John. The contribution of the increasing urban effect to climatic change has been the subject of much speculation, but only Gargett (1965) has used modern statistical methods in this field. During the past two years several papers have been prepared and presented on different aspects of the Toronto urban climate by Munn, Hirt and Findlay, and it is expected that those will be published in 1969. Also a new Climatological Handbook for Montreal is being prepared by Powe.

Meteorologists and geographers at Canadian universities are becoming very active in pollution and urban meteorological research. Dr. P.W. Summers, formerly of McGill University, was a pioneer early in the 1960's publishing on the Montreal pollution problems (1962, 1963, 1966). Csanady at Waterloo has been active in this field, and recent papers by Yudcovitch (1967), and Longley (1968) show interest at Calgary and Alberta. Finally the work of Oke, formerly of McMaster and now at McGill, on different aspects of the urban climates of Hamilton and Montreal must be noted.

Seventy years ago only one third of all Canadians lived in urban areas, but today there are more than 70 per cent of us living in the city.

The proportion is increasing every day, and by the turn of the century it is forecast that 80 to 90 per cent of all Canadians will be living in large urban areas. Meteorologists and climatologists, regardless of whether they have physics or geography backgrounds, are going to be forced to pay increasing attention to urban meteorology - forecasts for weather and atmospheric pollution control, design data for urban planning, zoning and building, etc. It is hoped that when a selected bibliography on the urban climates of Canada is prepared some ten years hence, there will be many more times as many references as have been included here.

SELECTED REFERENCES TO PAPERS CONCERNING CANADIAN URBAN CLIMATES

1936 MIDDLETON, W.E.K. and F.G. MILLAR

Temperature profiles in Toronto. J.R. Astr. Soc. Can., 30:7:265-272. Sept. 1936.

THOMAS, M.K.

Winter temperatures at Toronto. Roy. Meteor. Soc., Canadian Branch, 4:3. 1953. 10p.

1954 DEXTER, R.V.

Some local temperature variations at Halifax, May to September 1953. Dept. of Transport, Met. Div., CIR-2473, TEC-184. April 23, 1954. 11p.

THOMAS, M.K.

Toronto's winter of minimum snowfall. Weather, 9:4:110-111. Apr. 1954.

1955 COLLINS-WILLIAMS, C. and A.C. BEST

Atmospheric pollen counts in Toronto, Canada. Journal of Allergy, St. Louis, 26:5:461-467. Sept. 1955.

EINARSSON, E. and A.B. LOWE

A study of horizontal temperature variations in the Winnipeg area on nights favouring radiational cooling. Dept. of Transport, Met. Div., CIR-2647, TEC-214. April 22, 1955. 19p.

ROBERTSON, G.W.

Low temperature fog at the Edmonton Airport as influenced by moisture from the combustion of natural gas. Roy. Meteor. Soc., Quart. J., 81:348:190-197. April 1955.

1956 BAYNTON, H.W.

Multiple correlation of particulate air pollution with weather factors at Detroit and Windsor. Bull. Amer. Met. Soc., 37:7:333-337. Sept. 1956.

1958 DEXTER, R.V.

The sea-breeze hodograph at Halifax. Bull. Amer. Met. Soc., 39:5:241-247. May 1958.

1959 MUNN, R.E. and M. KATZ

Daily and seasonal pollution cycles in the Detroit-Windsor area. Int. J. Air Poll., 2:51-76. 1959.

1960 MUNN, R.E. and M. KATZ

Air pollution levels associated with a 49-hr. inversion at Detroit-Windsor. Bull. Amer. Met. Soc., 41:5:245-249. May 1960.

1961 MAHAFFY, F.J.

The ice storm of 25-26 February 1961 at Montreal. Weatherwise, 14:6:241-244. Dec. 1961.

MATEER, C.L.

Note on the effect of the weekly cycle of air pollution on solar radiation at Toronto. Int. J. Air and Water Poll., 4:1/2:52-54. 1961.

1961 MUNN, R.E.

Analysis of smoke observations at Ottawa, Canada. J. Air Poll. Contr. Ass., 11:410-416. 1961.

POTTER, J.G.

Changes in seasonal snowfall in cities. The Canadian Geographer, 5:1:37-42. Spring 1961.

POTTER, J.G.

Areal variation of snowfall in Metropolitan Toronto. Dept. of Transport, Met. Br., CIR-3431, TEC-342. Jan. 6, 1961. 9p.

1962 CHAMP, H.

A comparison of the diurnal relationships between the mean smokiness and the mean inversion intensity at Detroit-Windsor during June and December. Dept. of Transport, Met. Br., CIR-3612, TEC-399. Feb. 23, 1962. 34p.

CROWE, B.W., C.L. KUCHINKA, and W.A. ROSS

Modifications of extreme winter temperatures at Winnipeg International Airport due to urban development. Dept. of Transport, Met. Br., CIR-3754, TEC-432. Nov. 8, 1962. 4p.

1962 LEAHEY, D.M.

An analysis of smoke observations in Winnipeg. Dept. of Transport, Met. Br., CIR-3769, TEC-439. Dec. 11, 1962. 6p. and 8 figs.

SUMMERS, P.W.

Smoke concentration in Montreal related to local meteorological factors. Symposium, Air Over Cities, U.S. Public Health Service. SEC Technical Report, Cincinnati, A.62-5:89-113. 1962.

1963 IMBEAU, Jacques A.

Distributions des différences de température à la tour de micro-météorologie d'Ottawa. Dept. of Transport, Met. Br., CIR-3919, TEC-488. Oct. 28, 1963. 30p., 19 figs. and 3 tables.

SUMMERS, P.W.

Urban ventilation in Montreal. Smokeless Air, 34:128:118-123.

1964 EMSLIE, J.H.

The reduction of solar radiation by atmospheric pollution at Toronto, Canada. Dept. of Transport, Met. Br., CIR-4094, TEC-535. Aug. 1964. 8p., 2 figs. and 4 tables.

1964 FERLAND, M.

Pollution de l'air à Ottawa, en rapport avec les facteurs météorologiques locaux. Dept. of Transport, Met. Br., CIR-3970, TEC-502. Jan. 15, 1964. 6p. 13 figs. and 10 tables.

MUNN, R.E. and J.H. EMSLIE

The frequency and intensity of early morning ground inversions at Edmonton, 1950-1960. Dept. of Transport, Met. Br., CIR-4009, TEC-511. April 3, 1964. 4p. and 14 figs.

MUNN, R.E., R.L. TITUS, and H.J. WILSON

A preliminary estimate of the inversion climatology along the Toronto lakeshore. Dept of Transport, Met. Br., CIR-4123, TEC-549. Oct. 6, 1964. 12p., 7 figs. and 8 tables.

WILSON, H.J.

Atmospheric pollution at Saint John, N.B. Dept. of Transport, Met. Br., CIR-3962, TEC-497. Jan. 13. 1964. 7p. 15 figs. and 2 refs.

1965 GARGETT, A.

Long term fluctuations in the Toronto temperature and precipitation record. Dept. of Transport, Met. Br., CIR-4199, TEC-599. March 9, 1965. 10p. and 13 figs.

1966 EMSLIE, J.H., and J. SATTERWAITE

Air pollution - meteorological relationships at Vancouver, British Columbia. Dept. of Transport, Met. Br., CIR-4396, TEC-605, March 7, 1966. 9p., 4 figs. and 10 refs.

GILLESPIE, T.J.

Frequency of large daily rainfall amounts in the Montreal area. Dept. of Transport, Met. Br., CIR-4387, TEC-604. Feb. 22, 1966. 8p., 5 figs., 7 refs. and 4 tables.

LABELLE, J.J., R.J. BROWN, and M.D. HASINOFF

Climate of Winnipeg. Dept. of Transport, Met. Br., CIR-4437, CLI-35. June 7, 1966. 57p. and 25 figs.

SUMMERS, P.W.

The seasonal, weekly and daily cycles of atmospheric smoke content in central Montreal. J. Air Poll. Contr. Ass., 16:8:432-438.

WRIGHT, J.B.

Precipitation patterns over Vancouver city and the lower Fraser valley. Dept. of Transport, Met. Br., CIR-4474, TEC-623. Aug. 30, 1966. 4p., 9 figs. and 9 refs.

1966 WRIGHT, J.B.

Long term trends in Vancouver's weather. Dept. of Transport, Met. Br., CIR-4375, TEC-596. Feb. 4, 1966. 6p., 4 figs., 1 table and 6 refs.

1967 YUDCOVITCH, N.

Factors influencing the temperature variation in Calgary. The Albertan Geographer, 3:11-19. 1967.

SUMMERS, P.W.

An urban heat island model: its role in air pollution problems, with applications to Montreal. Proc. First Can. Conf. on Micromet. Pt. II, 1967. p.435.

1968 EMSLIE, J.H.

Wind flow in Burrard Inlet, Vancouver, B.C. - A summary of six years of data. Dept. of Transport, Met. Br., TEC-686. 1968. 6p., 5 figs., 4 tables and 4 refs.

LONGLEY, R.W.

The diurnal variation of wind direction at Calgary. Atmosphere, 6:2:23-38. 1968.

OKE, T.R.

Some results of a pilot study of the urban climate of Montreal. Climatological Bulletin, 3:36-41. 1968.

Awaiting Publication

EAST, C.C.

Total solar radiation recorded in Montreal and in the countryside. Presented at ACFS, Sherbrooke, 1967.

FINDLAY, B.F. and M.S. HIRT

An urban-induced meso-circulation. Atm. Envir. 3. (in press).

FUGGLE, R.F. and T.R. OKE

Infra-red flux divergence and the urban heat island. Presented at WMO Symposium on Urban Climates and Building Climatology. Brussels, Oct. 1968.

MUNN, R.E., M.S. HIRT and B.F. FINDLAY

A climatological study of the interaction between the daytime lake and urban meso-scale circulations at Toronto. (Manuscript).

OKE, T.R. and F.G. HANNELL

The form of the urban heat island in Hamilton, Canada. Presented at WMO Symposium on Urban Climates and Building Climatology. Brussels, Oct. 1968.

WEISMAN, B., D. MATHESON and M.S. HIRT

Air pollution survey for Hamilton, Canada. Atm. Envir. 3. (in press).

RESEARCH REPORT

Readers of previous numbers of CLIMATOLOGICAL BULLETIN will be aware that the principal climatological research activities of the Department of Geography lie within the fields of energy budget investigations and studies in urban climatology.

Since the publication of BULLETIN NO. 4 (July, 1968), the only field work in respect of energy budget investigations undertaken at Mont St. Hilaire consisted of a short experiment to check the accuracy of the method to compute global radiation (Ohmura, 1968; Garnier and Ohmura, 1968). This experiment took place from August 28th to September 2nd. It consisted of measuring global and sky-diffuse radiation by means of five Kipp and Zonen pyranometers and one Eppley radiometer. Three Kipp and Zonen pyranometers measuring global radiation were inclined continuously at 20° in a north, south, and east direction respectively, and the Eppley was used to sample sky-diffuse radiation each hour for twenty minutes in each direction for each slope. The remaining two instruments continuously recorded global and sky-diffuse on a horizontal surface. The data from the latter instruments were used to compute the radiation for the slopes being measured by the other instruments, and computed and measured values were then compared. From a total of over 200 observations, the correlation coefficients and linear regression lines obtained for the three slopes are as follows:

North 20°	$r = 0{\cdot}995$	$Y = -0{\cdot}16+1{\cdot}06X$
East 20°	$r = 0{\cdot}996$	$Y = -0{\cdot}07+1{\cdot}00X$
South 20°	$r = 0{\cdot}996$	$Y = -0{\cdot}09+0\ 96X$

Field work on energy budget investigations in Barbados since the publication of the last BULLETIN in July 1968 and the end of December can be considered in two phases.

The first phase is from the middle of July to the end of August. During this time the observational programme was planned in close co-operation with the Barbados Experiment of Florida State University (Garstang and La Seur, 1968). The Florida State Group maintained temperature, humidity and wind profile measurements at 2,4,8 and 16 meters during both July and August, at three stations in Barbados: the Caribbean Meteorological Institute near the west of the island, at Cottage Plantation in the centre, and at East Point Lighthouse on the east coast. Net radiation, albedo, and surface soil temperatures were also measured at Cottage Plantation. From the middle of July the McGill programme was able to contribute temperature and humidity profile measurements at 2 and 0.2 meters at the Caribbean Meteorological Institute and Cottage Plantation, thus continuing the profile measurements there towards the ground. At both stations net radiation was added by McGill and recorded continuously, and soil heat flux was also recorded at Cottage Plantation.

In addition to contributing the continuous recording indicated above, the McGill group undertook additional periods of special and more detailed observations at the two sites: for the period August 10-12 at the Meteorological Institute and the period August 16-18 at Cottage. Delays in the arrival of equipment did not permit simultaneous special observations at the two sites. By using what equipment was available, however, it was possible during these short periods to extend the data at each of the two sites to include global and sky-diffuse radiation, soil temperature profiles at three depths (4,8 and 12 inches), and spot checks of the temperature/humidity profiles being automatically recorded by using Assmann psychrometers at the same levels. Rainfall data are collected routinely at both sites by standard rain gauges and some automatic rainfall records were also taken during the period of the experiment. Since the middle of August, global radiation has been recorded continuously by a Kipp and Zonen pyranometer and sky-diffuse radiation by a bi-metallic actinograph at the Meteorological Institute site.

The third major Florida State station maintained during July and August was at the lighthouse at East Point. Here, from August 9-31, the McGill unit made observations four times a day of temperature and humidity at 2 and 0.2 metres by means of Assmann psychrometers, and of net radiation by means of a portable (non-recording) net radiometer. In addition, a 50-hour observation period, similar to those at Cottage and the Meteorological Institute, was undertaken during the period August 24-26.

The second phase of the experimental work extends from the beginning of September to the end of November. During this time two special experiments were undertaken: from September 18-23, and from November 19-26.

The first experiment took place at Waterford, the main McGill climatology station on the island. Wet and dry recording thermistors were set up at 4,2,0,4, and 0.2 meters and Assmann psychrometers were observed regularly at the same levels. Net radiation and soil heat flux was also recorded. The object of the experiment was two fold: (a) to provide data from which to study the effect on Bowen ratio calculation of the choice of level for wet and dry bulb thermistor probes, and (b) to give guidance on the frequency of manual observations required in order to obtain reasonably accurate daily totals of latent and sensible heat flux.

The second experiment, that of November 19-26, was also based on Waterford. It constituted, firstly a repetition of the September experiment to cover a different climatic season, and secondly an extension of the observations to include surface and soil temperature measurements. Within the period of the experiment a series of manual hourly observations covering a continuous period of 100 hours enabled the addition of surface temperatures read from thermocouples and temperature/humidity data read by Assmann psychrometers to be added to the recorded data. Soil temperatures at 1cm. depth were continuously recorded by means of mercury in steel remote sensing thermometers. In addition to the work at Waterford two net radiometers were set up at Cottage Plantation. One was set horizontally on top of a ridge and the other set parallel to a 15° slope of the ridge and facing south. It is hoped the results of these observations will provide a guide to topographic variations in net radiation which can be incorporated in the general programme of radiation evaluation over the island. Unfortunately it was not possible to record global radiation at the same slope of the angled net radiometer owing to the fact that the recorder to be used for this purpose was broken in transit from Montreal to Barbados.

In general terms, one can say that the experimental work in Barbados from mid-July to the end of November has provided some energy budget data for different parts of the island of which the most detailed is for one site - Waterford. It has also provided valuable experience in equipment handling and experimental organization under local conditions. At the time of writing, all charts up to and including those for the experiment at Waterford in November have been analysed. Only minor difficulties arose in this analysis. However, the results have yet to be fully evaluated. During October the necessary computer programming for this was prepared and the accumulated data is now being put on punch cards.

The urban climate and micro-advection studies are continuing under the direction of Dr. T.R. Oke. The Montreal heat island studies (see CLIMATOLOGICAL BULLETIN NO. 3 p.36-41, and this issue p. 1-20) are preparing for the spring and summer observation periods. The study of the spatial and temporal variations in the heat island in Montreal is now equipped with automatic temperature recorders for use in moving automobiles. This will greatly assist in aleviating the sampling problems associated with such research. The infra-red flux divergence study is ready to take its first observations now that the sensing equipment has been purchased and calibrated, the mast constructed, and the site finalized.

The analysis of the data from the 1968 joint McMaster-McGill advection experiment continues. Plans for the 1969 experiment include a study of the adjustment of the eddy fluxes following a change in the surface moisture concentration, similar to that of Dyer and Crawford (1965) at Davis, California.

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References

Dyer, A.J. and T.V. Crawford. 1965: "Observations of the modification of the microclimate at a leading edge", Q.J. Royal Met. Soc., Vol.91, p.345-348.

Garnier, B.J. and Atsumu Ohmura. 1968: "A Method of Calculating the Short-Wave Radiation Income of Slopes", Journ. Appl. Meteor., Vol.7 pp.796-800.

Garstang, Michael and N.E. LaSeur. 1968: "The 1968 Barbados Experiment", Bulln.Amer. Meteor. Soc., Vol. 49, No.6, June, pp.627-635.

Ohmura, Atsumu. 1968: "The Computation of Direct Insolation of a Slope", Climat. Bulln., (McGill Univ.), No.3, Jan., pp.42-53.

NEWS AND COMMENTS

Dr. T.R. Oke was a Canadian delegate to the joint World Meteorological Organization, and World Health Organization Symposium on 'Urban Climates and Building Climatology' in Brussels, Belgium on October 15-25, 1968. Dr. Oke read two papers to the symposium: (a) Fuggle R.F. and T.R. Oke: "Infra-red flux divergence and the urban heat island"; and (b) Oke T.R. and F.G. Hannell: "The form of the urban heat island in Hamilton, Canada."

Professor B.J. Garnier attended the Fourth Annual Meeting of the Solar Energy Society at Palo Alto, California, from October 21-23, 1968, where he read a paper on "The Evaluation of Surface Variation in Solar Radiation Income."

Richard G. Wilson has been awarded his M.Sc. in Geography (climatology). He presented a thesis "Topographic Influences on a Forest Microclimate" resulting from field work over two summers at Mont St. Hilaire.

Richard F. Fuggle has been admitted to candidacy for doctoral work in climatology. His field of research is urban climatology and his dissertation will deal with Infra-Red Flux Divergence and the Urban Heat Island.

B.K. Basnayake, who was admitted to doctoral candidacy last spring, is in Barbados undertaking field work for a dissertation on Radiation Intensities and their contribution to daily convective patterns. He is also working as field supervisor for an investigation of topographic variations in the energy budget directed by B.J. Garnier with financial support from the Office of Naval Research (Geography Branch)

During November, B.J. Garnier visited Colombia at the request of the Colombian Government and the Montreal Engineering Company to advise on a programme of water resource development in the Ariguana Basin in northern Colombia. During his visit he gave a seminar to government research scientists on using a knowledge of topographic variations in the radiation balance to evaluate water resource potential in a river basin.

ERRATA

It is regretted that the references for the article by D.S.M. Munro, "Evaporation Measurements for Lac Hertel, Mont St. Hilaire" (Climat. Bulln. No.4, July 1968, pp.40-48) were inadvertently omitted. These references are:

Kohler, M.A., Nordenson, T.G., and Fore, W.E., 1958: Pan and lake evaporation, pp. 38-60. In Water Loss Investigations: Lake Mead Studies. U.S. Geological Survey, Professional paper 298, Washington.

McKay, G.A., and Stickling, W., 1961: Evaporation computations for prairie reservoirs. Proc. Hydrol. Symp. No.2, Evaporation. Queen's Printer, Ottawa, 135-163.

Penman, H.L., 1948: Natural evaporation from open water, bare soil, and grass. Proc. Roy. Soc. London, A 193, pp. 205-208.

Sellers, W.D., 1965: Physical Climatology. University of Toronto Press, Toronto, pp. 272.

Wang, J.Y., and Wong, S.C. 1962: A simple graphical approach to Penman's method for evaporation estimates. Journ. Appl. Meteor. 1, pp. 582-588.

Equations (5) and (6) on p.5 of Climat. Bulln. No.4, July 1968, should be amended to read:

$$LE = - L\rho k^2 \frac{(q_1 - q_2)(u_2 - u_1)}{(\ln z_2/z_1)^2} \qquad (5)$$

and $$H = - C_p\rho k^2 \frac{(T_1 - T_2)(u_2 - u_1)}{(\ln z_2/z_1)^2} \qquad (6)$$

The errors were typographical and do not affect the results published.

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