McGILL UNIVERSITY
Department of Geography

CLIMATOLOGICAL BULLETIN

NO. 22
OCTOBER 1977

McGILL UNIVERSITY, MONTREAL

ISSN 0541-6256

The CLIMATOLOGICAL BULLETIN is published twice a year in April and October. The subscription price is Five Dollars ($5.00) a year. Please address orders and inquiries to:

Department of Geography (Climatology)
McGill University
805 Sherbrooke Street West
Montreal, Quebec, Canada
H3A 2K6

CLIMATOLOGICAL BULLETIN

CONTENTS

No. 22 October 1977

FOREWORD

Climatological Bulletin No. 5, which appeared nine years ago, was devoted entirely to urban climatology. The present number is also one devoted to urban climatology and in a sense represents an up-date of the earlier publication. Whereas, however, *Bulletin* No. 5 contained some substantive articles on urban climatology as well as reviews of work in progress and a literature survey, the present number is confined only to research reviews and a literature survey.

In the category of research reviews will be found four articles, followed by a group of shorter contributions. Together these provide a survey of the kind of work being carried out at the University level. No claim is, however, made to completeness. It is hoped, perhaps that any notable gaps in the University contributions may be filled by up-date reports in later numbers, and readers from such Universities are invited to submit up-date reports for a future number of the *Bulletin*. There must also be a large amount of research into urban climatology being carried out in industry and by consulting companies. Some contributions from these sectors for future numbers would also be welcome.

The series of articles on research in progress is followed by a review of literature on or closely related to urban climatology. This represents an up-date of the literature review presented in *Bulletin* No. 5.

The material included in this number has been collected by Professor T.R. Oke. I wish to thank him for his help and time spent in putting together a number which I hope will prove valuable to all those interested in the progress of urban climatology in Canada.

Montreal
November, 11, 1977

B.J. Garnier
Editor

RESEARCH IN URBAN CLIMATOLOGY AT THE UNIVERSITY OF BRITISH COLUMBIA

by

T.R. Oke*

Introduction

Urban climatology is one of the main fields of atmospheric research in the Geography Department at the University of British Columbia. The programme is predicated on the need to study the cycling of energy and mass through the urban-atmosphere system if we are to thoroughly understand the workings of urban climates. It is felt that such an approach will provide the physical insights necessary for the development of urban climate models, and help to build the basis of a predictive science. For the purposes of this review this research is classified into two categories, viz: urban heat island and urban energy balance (areal and urban canyon) studies.

Urban Heat Island Studies

Detailed urban heat studies have been completed for both Montreal and Vancouver, and shorter-term observations have been undertaken in Inuvik, N.W.T. and the British Columbian towns of Oliver, Terrace and Penticton. In all cases the two-dimensional air temperature distribution has been mapped with the aid of automobile traverses. The use of potential temperatures eliminated height variations due to vertical pressure differences but the effects of local topography were still evident. The temperature field was always noted to be strongly controlled by local site characteristics. The urban/rural boundary was usually characterized by a sharp temperature "cliff". Within the urban area, parks and other open

*T.R. Oke is Associate Professor of Climatology in the Department of Geography at the University of British Columbia, Vancouver.

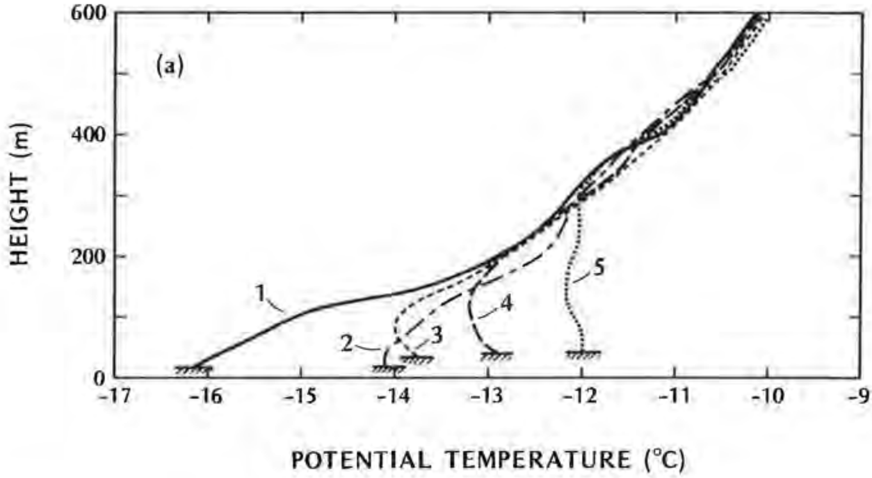


Fig. 1. Potential temperature profiles at five locations on an along-wind traverse of Montreal from the upwind rural area (profile 1), to the city centre (profile 5). Data for 0700 EST on March 7, 1968 with cloudless skies and winds from the N/NE at 0.4 ms^{-1} at 10 m (after Oke and East, 1971).

spaces were cooler, and densely built-up zones warmer, than their surroundings.

In Montreal the urban canopy layer temperature field was supplemented by helicopter measurements to provide a fully three-dimensional view of the city's thermal influence. The growth of the thermal boundary layer was studied under conditions when the incident airflow was stable (Fig. 1). The urban layer was found to be composed of a lower unstable layer and an upper slightly stable layer. It seems possible that the former is directly due to the greater surface roughness and heat released from the canopy layer, whereas the latter is the result of heat entrained from the overlying inversion plus heat input from elevated sources.

The temporal variability of the urban heat island has been studied using urban, suburban and rural cooling rates observed during automobile traverses in and near Montreal and Vancouver. In the absence of rapid synoptic changes the heat island intensity was found to reach its maximum value about three to five hours after sunset. This behaviour was largely controlled by the rural cooling rate since the urban one often remained almost constant throughout the night. The nocturnal heat island is therefore a phenomenon due to differential cooling rates and study of its causation is best directed at processes giving rise to urban/rural heat exchange differences in the early evening. Suburban rates were found to be intermediate in value.

Considering the growing number of individual heat island studies it was decided to attempt to seek some general order, albeit under a restricted range of meteorological conditions. The heat island intensities (ΔT_{u-r}) of ten Quebec settlements (with populations, P from 10^3 to $2x10^6$ inhabitants) were measured a few hours after sunset on a number of cloudless nights. It was shown that for this data set ΔT_{u-r} could be related to P and the regional wind speed ($\bar{u}$) as:

$$\Delta T_{u-r} = \frac{P^{0.27}}{4.04\bar{u}^{\,0.56}} \simeq 0.25\ P^{\frac{1}{4}} / \ \bar{u}^{\,\frac{1}{2}} \quad . \tag{1}$$

The relationship was later tested against an independent data set from Vancouver (Fig. 2). The good agreement obtained gives reason to believe the approach can be generalized, at least in the North American context. In the extreme case when winds are calm (i.e. $\bar{u} \rightarrow 0$) it was shown that the maximum observed heat island intensity ($\Delta T_{u-r(max)}$) from many North American and European settlements is strongly correlated with the logarithm of their populations (Fig. 3). Similarly it is also gratifying to note that the values of $\Delta T_{u-r(max)}$ observed at different stages of growth of the new town of Columbia, Maryland almost exactly follow the North Americal relationship (Landsberg, 1975). We have also been able to demonstrate that the critical wind speed required to reduce ΔT_{u-r} to less than 1°C is also related to log P.

Urban Energy Balance Studies

1) Areally-averaged Surface Fluxes

It had always been assumed that the polluted urban atmosphere would absorb much of the outgoing long-wave radiation from the city ($L\uparrow$), and re-emit a large proportion back down as counter radiation ($L\downarrow$), thereby reducing the net long-wave radiation loss at the surface (L^*) in comparison with rural areas. This was tested using a pyrgeometer mounted on a car and traversed across the city of Montreal on cloudless nights. These traverses revealed that $L\downarrow$ was indeed greater in the city and that the distribution was in sympathy with the heat island cross-sectional morphology. The urban anomaly was however small (<40 2 W $^{-2}$) and could

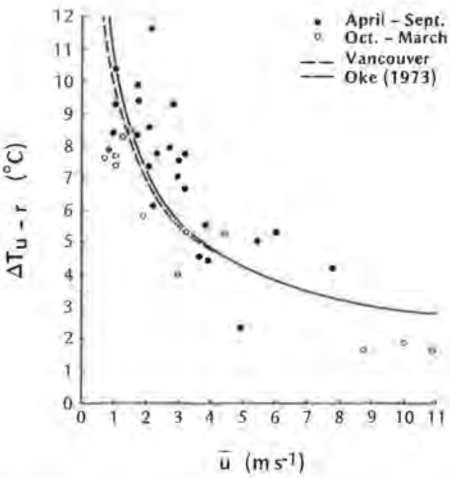


Fig. 2. Relation between measured heat island intensity and the regional wind speed for Vancouver, B.C. Data from 1-3 h after sunset on cloudless nights in all seasons. Dashed - least squares regression fit, solid - equation (1) (after Oke, 1976a).

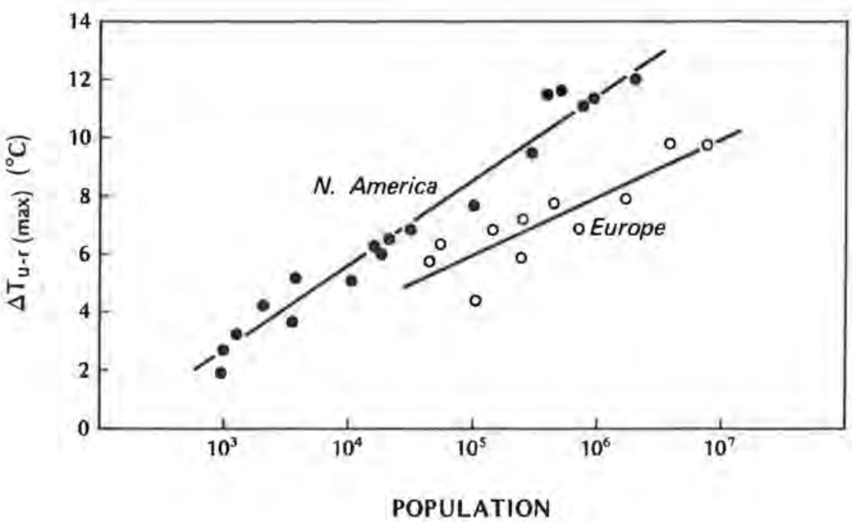


Fig. 3. Relation between maximum observed heat island intensity ($\Delta T_{u-r(max)}$) and population from 18 North American and 11 European settlements (after Oke, 1973).

be attributed to the altered vertical temperature structure of the city atmosphere without need to consider any emissivity changes brought about by pollutants. Urban/ruran L* differences were even smaller due to the compensating effect of a greater L↑ value from the warmer urban "surface".

Carefully conducted long-wave radiative flux divergence experiments above a downtown building at night showed that the urban atmosphere behaved similarly to its rural counterpart. Thus as wind speeds decreased flux divergence became the major means of atmospheric cooling. In fact, in most cases radiative cooling exceeded the actual rate of air temperature change, suggesting sensible heat flux convergence.

Surface energy balance studies have been carried out, mainly using the eddy correlation approach to estimate the sensible heat flux density, and a net pyrradiometer for the net all-wave radiation flux density. Observations have been completed at 4 m above a building roof (Fig. 4), and at 50 m above ground on towers in Vancouver, and Uppsala, Sweden. Temperature, humidity and wind speed profiles were also available from the Swedish site. Preliminary results indicate that although sensible heat fluxes are probably greater over the city, the evaporative flux is still substantial. There appears to be greater variability in urban sensible heat values both from hour to hour, and from day to day. Nocturnal sensible heat fluxes are usually rather small, and may be directed towards or away from the "surface". More detailed observations are in progress using a 30 m suburban tower in Vancouver.

2) Canyon Fluxes

The microclimate of the canopy layer is the result of complex radiative and aerodynamic exchanges below roof-level. Faced with the variety of geometric configurations and the myriad of surfaces comprising the urban "surface" it is impossible to identify a truly typical site. As a compromise we defined the urban canyon (a street, its two flanking walls and the contained air volume) to be a general urban unit whose basic form is repeated throughout an urban area.

A canyon in Vancouver with its axis aligned north-south was instrumented (Fig. 5) with heat flux plates in the walls, a lysimeter in the floor, and a mast suspended from a boom with 8-levels of net radiation and air temperature sensors. The mast could be traversed across the canyon so as to provide measurements at 24 points around the perimeter of the canyon corss-section.

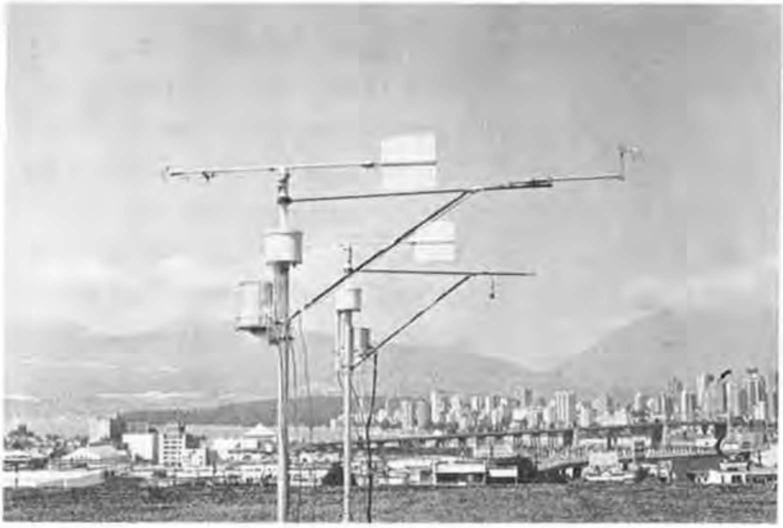


Fig. 4. Two yaw sphere-thermometer eddy correlation systems mounted to measure sensible heat flux densities over Vancouver.

Fig. 5. The experimental urban canyon in Vancouver.

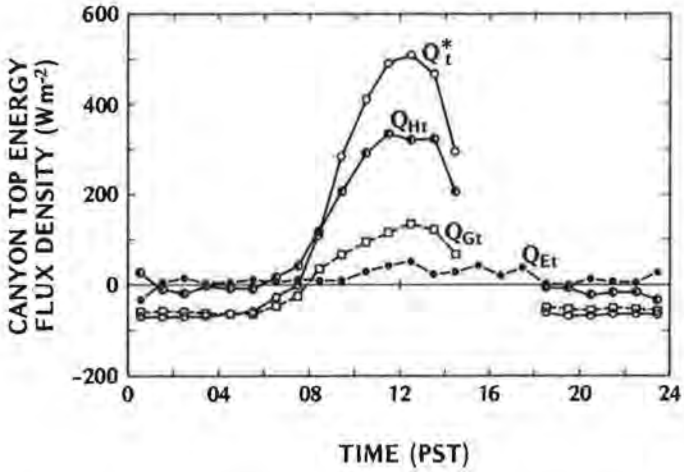


Fig. 6. The diurnal energy balance of the canyon system expressed as equivalent fluxes through the canyon top. Data are mean hourly values averaged over the period 9-11 September, 1973, with cloudless skies and weak air flow (after Nunez and Oke, 1977).

Observations during summer weather showed that the timing and magnitude of the energy regime of the individual canyon surfaces (walls and floor) were very different, each being strongly affected by the influence of the canyon geometry on radiation receipt and loss. Despite this the diurnal course of the energy balance for the entire canyon system (i.e. the fluxes calculated to pass through the canyon top) was relatively smooth and symmetric (Fig. 6). By day the canyon's radiative surplus was mainly dissipated as turbulent sensible heat transfer to the air, with about 25-30% being stored in the canyon fabric. At night the radiative deficit was almost completely balanced by the release of this heat storage. Advective contributions to the canyon balance were shown to depend on wind direction and speed and the state of the external thermal environment.

Nocturnal measurements of the three-dimensional radiative flux divergence within the canyon-air volume showed that radiative cooling of the air was very much less than had been previously found above roof-level and in rural areas. With calm, cloudless conditions the radiative rate was almost exactly the same as the actual rate of air temperature decrease.

These results help in the formulation of a process-response model of the urban heat island. Since the heat island is the result of urban/rural cooling rate differences it is appealing to attribute its development in the evening to urban/rural differences in radiative flux divergence. In this framework the effects of wind speed and cloud can be viewed as an expression of the relative strengths of turbulence and radiation in effecting air temperature change.

Acknowledgements

Research in urban climatology at the University of British Columbia has been supported by funds from the National Research Council and the Department of Fisheries and the Environment (Atmospheric Environment Service). The World Meteorological Organization has also made it possible for Dr. Oke to attend a number of conferences in his capacity as Rapporteur on Urban Climatology.

List of Publications and Theses

1) Publications

Fuggle, R.F. and T.R. Oke, 1970: "Infra-red flux divergence and the urban heat island", World Meteorological Organization Technical Note No. 108, WMO No. 254, TP 141, pp. 70-78.

Fuggle, R.F. and T.R. Oke, 1976: "Long-wave radiative flux divergence and nocturnal cooling of the urban atmosphere. I - Above roof-level", Boundary-Layer Meteorology, Vol. 10, pp. 113-120.

Hay, J.E. and T.R. Oke, 1976: The Climate of Vancouver, B.C. Geographical Series No. 23, Tantalus Press, Vancouver, 49 pp.

Nunez, M. and T.R. Oke, 1976: "Long-wave radiative flux divergence and nocturnal cooling of the urban atmosphere. II - Within an urban canyon", Boundary-Layer Meteorology, Vol. 10, pp. 121-135.

Nunez, M. and T.R. Oke, 1977: "The energy balance of an urban canyon", Journal of Applied Meteorology, Vol. 16, pp. 11-19.

Oke, T.R. and F.G. Hannell, 1970: "The form of the urban heat island in Hamilton, Ontario", World Meteorological Organization Technical Note No. 108, WMO No. 254, TP 141, pp. 113-126.

Oke, T.R. and C. East, 1971: "The urban boundary layer in Montreal", Boundary-Layer Meteorology, Vol. 1, pp. 411-437.

Oke, T.R., 1972a: "City size and the urban heat island", AMS Conference on the Urban Environment, American Meteorological Society, Boston, pp. 144-146.

Oke, T.R., 1972b: "Evapotranspiration in urban areas and its implications for urban climate planning", in Teaching the Teachers, Swedish National Institute for Building Research, Vol. 3, pp. 57.1-57.9.

Oke, T.R. and R.F. Fuggle, 1972: "Comparison of urban/rural counter and net radiation at night", Boundary-Layer Meteorology, Vol. 2, pp. 290-308.

Oke, T.R., G.B. Maxwell and D. Yap, 1972: "Comparison of urban/rural cooling rates at night", AMS Conference on the Urban Environment, American Meteorological Society, Boston, pp. 17-21.

Oke, T.R., D. Yap and R.F. Fuggle, 1972: "Determination of urban sensible heat fluxes" in International Geography 1972, Adams, W.P. and F.M. Helleiner (eds.), University of Toronto Press, pp. 176-178.

Oke, T.R., 1973: "City size and the urban heat island", Atmpspheric Environment, Vol. 7, pp. 769-779.

Oke, T.R., 1974: "Review of urban climatology, 1968-73", World Meteorological Organization Technical Note No. 134, WMO No. 383, Geneva, 132 pp.

Oke, T.R., 1975: "The urban heat island in Vancouver, B.C. - form, controls and models", in C.A.G. '75, Department of Geography, Simon Fraser University, B.C., pp. 58-61.

Oke, T.R. and G.B. Maxwell, 1975: "Urban heat island dynamics in Montreal and Vancouver", Atmospheric Environment, Vol. 9, pp. 191-200.

Oke, T.R., 1976a: "The distinction between canopy and urban boundary layer heat islands", Atmosphere, Vol. 14, pp. 268-277.

Oke, T.R., 1976b: "Inadvertent modification of the city atmosphere and the prospects for planned urban climates", Proc. WMO Symposium on Meteorology as Related to Urban and Regional Land-Use Planning, WMO No. 444, World Meteorological Organization, pp. 150-175.

Oke, T.R. and J.E. Hay, 1976: "Climate of Vancouver", in The Vancouver Book, C.Davis (ed.), Vancouver, pp. 118-122.

Oke, T.R., 1977a: "The significance of the atmosphere in planning human settlements", Proc. DFE/CMHC Conference on Biophysical Land Classification for Human Settlements, Dept. Environment, Ottawa (in press).

Oke, T.R., 1977b: "Review of urban climatology, 1973-1977", Report to CoSAMC of the World Meteorological Organization, Dept. Geog., University of B.C., 119 pp.

Oke, T.R., 1977c: "The urban atmosphere as an environment for air pollution dispersion", Special Environmental Report, World Meteorological Organization, Geneva (in press).

Oke, T.R., 1977d: "The climate of urban areas", in Yearbook of Science and the Future, Encyclopedia Britannica, Chicago, pp. 116-131.

Yap, D. and T.R. Oke, 1974: "Sensible heat fluxes over an urban area - Vancouver, B.C.", Journal of Applied Meteorology, Vol. 13, pp. 880-890.

2) Theses

Nicol, K.S., 1977: "Anthropogenic heat and its relation to building and urban climate in Inuvik, N.W.T.", unpubl. M.Sc. Thesis, Dept. of Geog., University of B.C., Vancouver.

Nunez, M., 1975: "The energy balance of an urban canyon", unpubl. Ph.D. Thesis, Dept. of Geog., University of B.C., Vancouver.

Yap, D. 1973: "Sensible heat fluxes in and near Vancouver, B.C.", unpubl. Ph.D. Thesis, Dept. of Geog., University of B.C., Vancouver.

REFERENCE

Landsberg, H.E., 1975: "Atmospheric changes in a growing community (the Columbia, Maryland experience)", Technical Note BN 823, Instit. Fluid Dynamics Appl. Math., University of Maryland, College Park, Maryland.

RESEARCH IN URBAN CLIMATE AT McGILL UNIVERSITY

Surface Energy Exchange as a Function of Urban Terrain Characteristics

by

John E. Lewis*

As man alters the terrestrial surfaces, he changes the complex processes of energy exchange and in this way alters his climatic environment sometimes beneficially but often detrimental to his existence.

It is the purpose of the present research to develop and examine ways to understand better the terrestrial surface and its interaction with the air above it. Techniques have been developed for rapid measurement by electro-optical scanners in satellite platforms of phenomena related to energy exchange across the surface-to-air interface. Techniques have also been developed to replicate the same phenomena by means of numerical computer simulation using the mathematical models of the processes involved. The spatial distributions of the energy exchange phenomena observed by remote sensing show the effects of different types of land use. The numerical simulation gives insight into the causes of the diversity of the distributions. Alteration of the values employed in the many mathematical submodels of the larger simulation model indicate the types of changes that can be expected in surface energy balance and which potentially can affect the characteristics of the overlying air and thereby affect the climate. An appropriate name for this avenue of the study is "land use climatology" (Pease et. al., 1978).

Lewis and colleagues have employed this particular methodology for assessing surface energy exchange in an urban area. Accomplishment of the effort results from the coupling of simulation modelling with remote sensing. The ongoing research is an enlargement and additional

* John E. Lewis is Assistant Professor of Climatology in the Department of Geography at McGill University.

TABLE ONE

Necessary Simulation Data

Meteorological Variables	Geographical Terrain Parameters
Station Pressure	Substrate Thermal Diffusivity
Incoming Solar Radiation	
Incoming Thermal Radiation	Surface Albedo (Effective)
Mean Air Temperature	Surface Aerodynamic Roughness
Mean Relative Humidity	Surface Wetness
Mean Wind Velocity	

TABLE TWO

Computation of Geographical Parameters

Parameter	Definition	A Function of
Substrate Thermal Diffusivity	traditional definition	wetness fraction
Surface Albedo (Effective)	includes radiation absorption from vertical surfaces	silhouette ratio obstruction ht.
Surface Aerodynamic Roughness	used in computation of turbulent fluxes	silhouette ratio obstruction ht.
Surface Wetness	direct	surface wetness

TABLE THREE

Urban Terrain Factors

Wet Fraction	That fraction of a terrain tract in lawn cover and tree cover.
Silhouette Ratio	The ratio of the vertical silhouette area in a tract to the horizontal area of that tract.
Obstruction Ht.	The mean height of building and vegetation which forms an obstruction to air flow and creats a vertical silhouette which collects radiation in addition to the radiation absorbed on horizontal surfaces.

verification of this recent work using the city of Montreal as a test site (see short list of references).

The work by Lewis and others has concentrated on only warm season synoptic conditions and none of the effort has been devoted to radiation exchange for urban areas during the winter period for snow/or no snow surface conditions. To rectify this situation, multi-spectral scanning imagery will be collected for Montreal during these two winter-time periods. The cold season boundary layer dynamics have important implications, because many times during this period of the year pollution concentrations are the highest. Therefore, the surface energy exchange, which is the forcing function for the urban meso-scale wind circulation, becomes an essential ingredient in the assessment of potential pollution concentrations and distribution.

1. Research Philosophy: The nature of the urban surface controls both the magnitude and partitioning of energy at the earth's interface. The site properties which affect the local climate are the thermal properties of the surface (thermal diffusivity and conductivity), surface aerodynamic roughness, surface reflectivity (albedo) and the distribution of moisture (evaporation and transpiration) at the interface. The combination of these surface properties will then establish a mosaic of microclimates in the city, each having its particular radiation-energy budget. Therefore, when the surface properties are modified the phase and amplitude relationships between the components of the surface energy are perturbed.

2. Research Sequence: The research is following a four step process: a) parameterization of the urban fabric by developing spatial numerical quantities for aerodynamic surface roughness, area of transpiring surface, and types of surface materials are obtained in that this information constitutes a set of boundary conditions which activates an energy budget simulation model; b) actual simulation of urban temperature fields for different diurnal and seasonal conditions; c) verification of the simulated surface radiant temperature field with observed surface temperatures using the technique of 2-dimensional surface correlation; and d) construction of net radiation maps which provides the spatial distribution of non-radiative energy sources and sinks within the urban area.

3. Simulation Model: Present modelling technology permits the numerical simulation of the surface thermal and energy balance regime as a function of local meteorological observations and the radiative, aerodynamic and thermal properties of the near surface environment. The specific data in these categories necessary for simulation is listed in Table One.

The complete structure of the simulation model will not be discussed here in detail. Briefly, the method hinges on the specification of all the variables needed to calculate the components of surface energy transfer based on the meteorological (M) and geographical (G) data listed in Table One. Then, the four components of surface energy transfer (net radiation (R), soil (S), sensible (H) and latent (L) heat flux) can be specified as transcendental in surface temperature (T) in the familiar energy conservation equation:

$$R\ (G,M,T) + S(G,T) + H(G,M,T) + L(G,M,T) = 0.0 \quad .$$

A suitable numerical algorithm is selected to carry out a search for that surface temperature which will drive the above equation to a zero sum condition. Then, an explicit or implicit finite difference algorithm is employed to generate an update soil temperature/depth profile. Thus, at each iteration, the surface temperature and all the components of surface energy transfer are output in addition to the substrate (soil) thermal profile.

4. Model Input: The activation of the simulation model requires the assessment of the geographical terrain parameters from easily measurable characteristics of urban terrain in sample tracts several blocks in area. Initially, it was discovered that the geographical parameters were related to three easily measured features of urban terrain which could be abstracted from stereo air photography, multispectral imagery and zoning maps. The relationships are summarized in Table Two and are derived from considerations based on the earlier work of Lettau and Myrup. In turn, the three underlying terrain parameters are defined in Table Three.

After these values of obstacle height, silhouette ratio, building density, total surface area, spacing and type of surface materials and vegetation conditions are acquired, the geographical terrain parameters are calculated and then mapped employing a digital mapping routine.

Based on these maps, attempts are made to asses the efficiency of different land-use schemes as surrogate measures of the surface parameters.

5. Remote Sensing: Electro-optical scanners on board an aircraft or spacecraft have successfully monitored radiant energy both reflected solar energy and thermally emitted energy from the earth's surface for use in climatological research (see list of references). Canada Center for Remote Sensing has an aircraft equipped with a Daedalus (dual-channel) scanner with spectral bandwidth of 8-14 μm and 3.5-5.5 μm or a multispectral scanner which also measures radiation in ten wave bands within the solar spectrum. This aircraft mission is employed in the collection of reflected solar energy and emitted thermal energy and thus provides the means to produce both surface radiant temperature and net radiation maps of Montreal. Two separate flights are planned: a) an early November flight which eliminates the effect of vegetation and b) a flight sometime during the winter with snow cover. The timing of these two flights provide interesting temporal thermal contrasts in addition to indicating the winter time effects of urban waste heat rejection.

6. Montreal Test Case: A substantial effort has already been made on the compilation of the urban terrain boundary conditions for block size units. The surface cover that is being mapped is defined as a subset under one of the four major types of land-use within Montreal - high density residential, parks, industrial-commercial, and central business district (CBD). For each of these land-use types, the following information has been extracted from large-scale aerial photography and zoning maps of Montreal: a) street area vs. developed area; b) area in rooftop, impervious (surface) area, and vegetative area; c) obstacle height, silhouette area, and number of elements per total area of the terrain block. These data are utilized in the calculation of the parameters listed in Table Two.

Since the land-use of Montreal city proper is dominated by high density (multifamily) residential type (≈40%), it was felt that a small section of this land-use type as represented by a section of Rosemount could be intensively studied and these results generalized to similar land-use types in the city. To test this proposition, two distinct noncontiguous areas of the same land-use were chosen elsewhere in Montreal. These latter areas are designated as test area 1 and 2. The various surface properties were extracted and then compared to ascertain if the surface cover values drawn from the test areas were from the same population as the values developed for Rosemount. Surprisingly, the statistical test showed that the samples of terrain characteristics for test area 1 and 2 were drawn from different populations when compared to the Rosemount distribution. In fact, each section appeared to have different sampling distribution. Therefore, each terrain block within the sampled area had to be assessed for its surface cover character within that "unique" land-use type. Fortunately the same situation did not exist for the industrial and parkland types. The CBD is essentially considered as a small enclave of very unique surface cover type.

At the present time, the major research effort is concerned with collecting observed surface radiant temperatures and other elements of the radiation budget in Montreal. The work is accomplished through intensive ground survey and with the collection of multi-spectral imagery by aircraft. The former will serve as ground truth which must accompany any remote sensing experiment, and will also aid in assessing the applicability of generalizing point data to serial measurements in an urban context. Surface radiant temperature, global radiation, surface reflectivity, sky radiation and net radiation will be measured for two winter time surface conditions of snow/no snow. These parameters will be monitored for each of the land-use types three times for the two respective synoptic situations. For two of the days the ground survey will coincide with aircraft flights flown for Montreal by Canadian Center for Remote Sensing. On the two appointed days, there will be two flights each day, one around the time of maximum temperature, the other near the time of minimum temperature. Further, each flight will consist of a west to east and north to south traverse - 8 miles in length. With calibration of the energy received in the 8-14 μm spectral band of the sensor, a map of surface radiant temperature can be produced which possesses very fine resolution, approximately 30 x 30 meters on a side. The thermal imagery and temperature map serve as an observed data set for verification of the energy budget simulation model.

The reflected energy collected in the spectral bands of solar radiation is used to generate maps of surface albedo. Two bands can be employed, one serving at wavelengths shorter and the other at wavelengths longer than the critical wave band around .725 μm. However, care must be taken in choosing the proper waveband when snow is the predominate surface cover. Test panels with known reflectivity will be placed on the ground at the time of the overflight to assess which wavebands are optimum for calculating albedo.

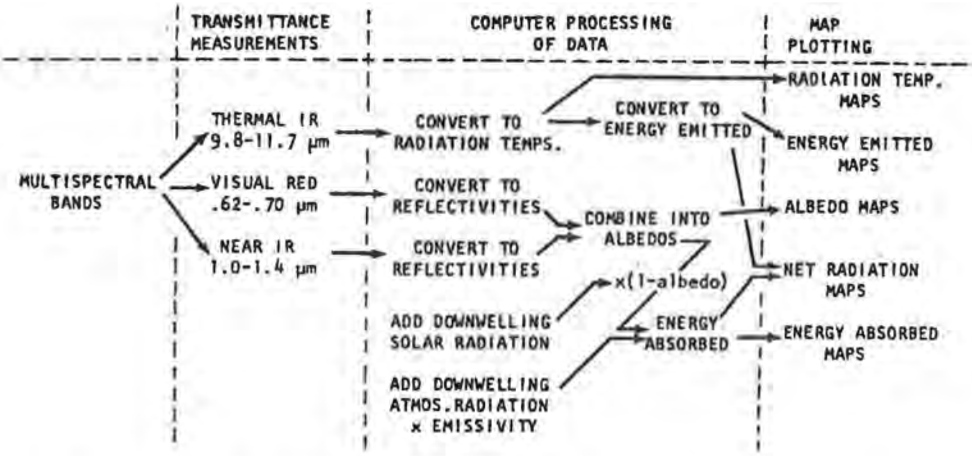


Fig. 1. A simplified diagram of the flow of data followed in making the maps (Pease and Nichols, 1976).

Assuming that the downwelling radiation, global solar and sky radiation, is conserved in space for a "small" specified region, the albedo distribution and emitted surface energy collected by multispectral scanning techniques can be included to produce a net radiation map. The procedure is outlined in Figure 1.

In addition, a spectral band ratioing technique will be used, following the work of LeShack, Del Grande and Lewis (1975), to produce surface emissivity maps. Very little information exists concerning emissivity and its spatial variation in an urban area. With the ratioing of 5 μm to 10 μm signals, the effect of surface radiant temperature is removed leaving emissivity as the quotient. The emissivity values will aid in reducing the degree of parameterization of the simulation model.

REFERENCES

LeShack, L., N. DelGrande and J. Lewis, 1975: "Correlation of Dual-channel Airborne IR Data with soil moisture measurements", Final Report, Contract 4-35308, National Environmental Satellite Service, NOAA, Washington, D.C., 55 pp.

Lettau, H.H., 1969: "Note on aerodynamic roughness parameter estimation on the basis of roughness element description", Journal of Applied Meteorology, Vol. 8, pp. 828-832.

Lewis, J. and C. Jenner, 1976: "A review of applications in urban land-use climatology", paper presented at the Annual Meeting of the Association of American Geographers, New York City, New York.

Lewis, J., S.I. Outcalt and R. Pease, 1976: "Urban surface thermal response associated with land use", McGill University, Montreal, Climatological Bulletin, No. 19, pp. 23-29.

Myrup, L.O., 1969: "A numerical model of the urban heat island", Journal of Applied Meteorology, Vol. 8, pp. 908-918.

Nicholas, Francis, 1974: "Parameterization of the urban fabric: a study of surface roughness with application to Baltimore, Maryland", Ph.D. diss., University of Maryland.

Outcalt, S.I., 1972a: "The development and application of a simple digital surface climate simulation", Journal of Applied Meteorology, Vol. 11, pp. 629-636.

Outcalt, S.I., 1972b: "A reconnaissance experiment in mapping and modelling the effect of land use on urban thermal regimes", Journal of Applied Meteorology, Vol. 11, pp. 1369-1373.

Outcalt, S.I., 1972c: "A synthetic analysis of seasonal influences in the effects of land use on the urban thermal regime", Archiv. Met. Geoph. Biokl., Series B, Vol. 20, pp. 253-260.

Pease, R., J.E. Lewis and S.I. Outcalt, 1976: "Urban terrain climatology and remote sensing", Annals of Assoc. of Am. Geographers, Vol. 66, pp. 557-569.

Pease, R. and D. Nichols, 1976: "Energy balance maps from remotely sensed imagery", Photogrammetric Engineering and Remote Sensing, pp. 1367-1374.

Pease, R., C. Jenner, and J. Lewis, 1978: "The impact of land use on climate: an analysis of the Washington - Baltimore area that couples remote sensing with numerical simulation", U.S.G.S. Professional Paper, Reston, Va. (forthcoming).

RESEARCH IN URBAN CLIMATOLOGY AT THE UNIVERSITY OF CALGARY

by

Lawrence C. Nkemdirim*

Studies in urban climatology are not new to Calgary. Ten years ago when Yudcovitch completed a survey of Calgary's surface temperature field, he found that the city had a well defined urban heat island whose average intensity was about 3.7°C. Since then, Calgary's population has grown from just a little over 300,000 to the current half million. The limits of the built up area have spread outwards to engulf what used to be open prairie. The inner city has gone through and continues to experience large scale urban renewal with multi-storey towers replacing dilapedated single and two storey houses. The fabric of the city is rougher and its street geometry more complex. Calgary has grown and so has its heat island, one of the reliable gages with which the effect of urban growth on climate can be measured.

The current research effort began in 1974 with the following objectives:

(a) To study the morphology of the city's street level temperature field and the factors that control it. In this regard, a distinction was made between urban-rural temperature contrasts and the intra-urban differential.

(b) To develop an empirical model for the estimation of urban heat island intensities in the area from a few readily measured meteorological and environmental variables.

(c) To examine the size and form of the urban boundary layer within the city and the factors that influence these properties.

(d) To develop a model (theoretical or empirical) for the estimation of the mean depth and structure of the layer.

(e) To examine the mechanisms through which the surface and atmospheric features of the island are coupled and to model the coupling process.

---

* Lawrence C. Nkemdirim is Professor and Chairman of the Department of Geography at the University of Calgary, Alberta.

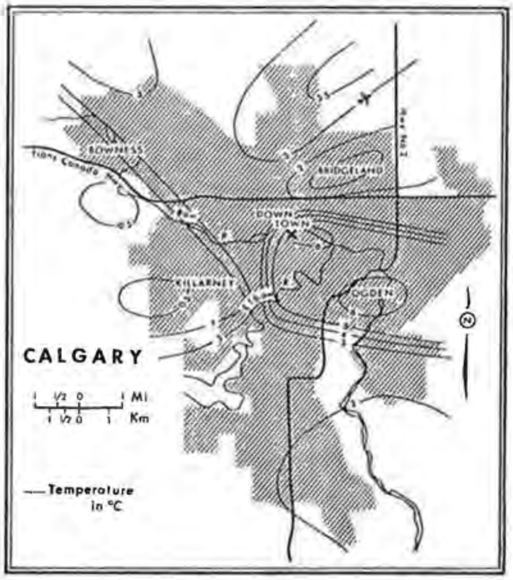


Fig. 1. Mean hourly pattern of Calgary's temperature field based on one year of hourly data.

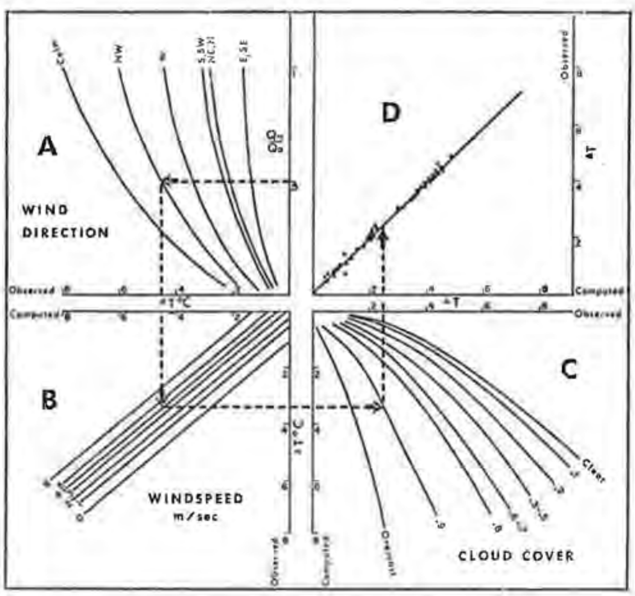


Fig. 2. A coaxial graphical correlation system.

These objectives are probably ambitious and may take years to accomplish assuming that we continue to receive financial support for our work. The most important task as we see it is the acquisition of a good data base which we have done by:

(a) Setting up a very dense network of temperature stations for a year round observation of temperature regimes within and outside the city.

(b) Conducting about 160 airbourne transects of temperature and wind under a variety of weather conditions. Helicopters, minisondes, radiosondes and pilot balloons have been employed for that purpose. More transects are being planned.

(c) Running a mobile unit equipped with radiometers for a complete energy budget determination in various parts of the city.

(d) Conducting diffusion studies in topographically complex environments.

(e) Participating in boundary layer experiments using acoustic sounders.

The following hard conclusions have been reached at this time.

1. Calgary has a well defined urban heat island which has been growing at an average rate of 6% per annum compounded over the past ten years. In 1975, the average intensity of the island was 6.7°C.

2. Although a heat island exists in the area throughout the year, the phenomenon is better defined in the cooler than in the warmer seasons.

3. The inner city - downtown and Ogden - is the warmest part of the city in every month of the year.

4. There are three districts where temperatures are consistently below the city average. These are Bridgeland, Killarney and Bowness (Fig. 1). Bridgeland is the coldest part of the city in the winter while Killarney is the coolest part in the summer.

5. The mean diurnal pattern of the urban-rural temperature difference has a double maximum. A primary maximum (8°C) occurs at about midmorning while a secondary peak (7.2°C) is observed about midnight Intensities are at a minimum in the late afternoon.

6. The average diurnal pattern is preserved in all weather conditions, although, mean values are higher under anticyclonic than under cyclonic systems. The chinook is highly disruptive to the mean pattern; the amplitude of the diurnal wave of heat island intensity being about five times the normal size under a chinook.

7. Wind direction and speed, the level of heat emission from fuel burning, atmospheric stability and cloudiness appear to be the most important determinants of the variability in heat island intensity.

8. Elevation by itself does not appear to exert a major influence on the mean temperature field in Calgary but the general relief of the region, especially the valley location of the inner city, is considered to be extremely important in the evolution of the surface field.

9. An empirical model based on a coaxial graphical correlation has been developed for the assessment of intensities of heat island in the area (Fig. 2). The graph is used by entering the appropriate energy ratio Qm/Qa, where Qm is the heat emission from man-made sources and Qa, the incoming all wave radiation, and wind direction in Chart A and the windspeed and cloud cover in Charts B and C respectively. The estimated value of the urban-rural differential (ΔT) is read off the horizontal scale of Chart D. Chart D shows a comparison between observed and estimated values.

It is obvious from this report that present understanding of the urban heat island in Calgary is limited to the surface feature. Most of the conclusions outlined above could have been obtained from the extensibe literature on urban climate. But, there are a few new facts that have emerged from the study; the most important of which are (a) that a maximum intensity of heat island can and does occur in the daytime and (b) that a double maximum can and does occur in the diurnal pattern of heat islands.

Our next report will focus on the boundary layer characteristics and hopefully, we can lay the foundation for the ultimate aim of our project - the coupling of the surface and atmospheric features.

Publications

Nkemdirim, L.C., G. Lunn and R.D. Rowe 1975: "COH stratification and concentration in an urban heat island", Water, Air and Soil Pollution, Vol. 4.

Nkemdirim, L.C., 1976: "Dynamics of an urban temperature field: a case study", Journal of Applied Meteorology, Vol. 15, pp. 818-828.

Nkemdirim, L.C., P. Truch and K. Leggat, 1977: "Calgary's urban heat island, 1975", University of Calgary, Weather Research Monograph No. 1, 102 pp.

Nkemdirim, L.C., 1977: "Urban heat island in Calgary, Diurnal pattern and time trends", Proceedings of the Alberta Climatological Association, Symposium on the application of climatological data, Edmonton, April, 1977 (in press).

Nkemdirim, L.C. and E.C. Rhodes, 1977: "Climatological research in Calgary", Proceedings of the Alberta Climatological Association, Symposium on the application of climatological data, Edmonton, April, 1977 (in press).

Nkemdirim, L. C. and P. Truch,1977 : "Variability of temperature fields in Calgary", Atmospheric Environment (in press).

Nkemdirim, L.C. and K. Leggat, 1977: "The effect of the Chinook on urban heat island intensity and air quality in Calgary", Water, Air and Soil Pollution (in press).

RESEARCH IN URBAN CLIMATOLOGY AT THE UNIVERSITY OF ALBERTA

by

Keith D. Hage*

Introduction

Elucidation of urban influences on weather and climate is a problem of unsteady airflow over inhomogeneous terrain and, as such, is an example of a major class of unsolved problems in micrometeorology. In some respects the city is an outdoor laboratory - not a controlled laboratory, but one with several well-defined and measurable characteristics. The complex, and often subtle, interactions between the atmosphere and cities provide opportunities for both theoretical and experimental studies that may help to solve some of the mysteries of the planetary boundary layer.

Several small studies of urban climatology were completed at the University of Alberta between 1969 and 1977. Although all were concerned with the city of Edmonton because of its proximity, and because of its relatively uncomplicated setting on a fairly uniform level plain, it is hoped that the major findings will be applicable elsewhere.

For purposes of this summary the Edmonton studies have been classified as climatological, experimental, and theoretical. The climatological studies were based on historical weather data from Edmonton Municipal Airport (YXD - urban), and Edmonton International Airport (YEG - rural). The experimental studies were based on data from special short-term weather stations. The theoretical study involved the development and application of a one-dimensional, higher-order closure turbulence model.

---

* Keith D. Hage is Professor of Meteorology in the Department of Geography at the University of Alberta.

Climatological Studies

Urban-rural temperature differences on nights best suited for heat-island development were studied in an attempt to eliminate other causes of large temperature variations. Data from an urban tower, from a network of thermographs, and from the rural and urban airports were used for this purpose. The annual cycle in urban-rural differences was found to be remarkably steady with weak maxima in January and June. Maximum diurnal differences occurred 3 to 4 hours after sunset in all seasons. The urban vertical temperature gradient on these selected strong heat island nights reached maximum values of 2C per 100 m in summer and 3C per 100 m in winter in the lowest 100 m shortly after midnight.

Several notable features were found in a comparison of urban and rural absolute and relative humidities based on 13 years of airport data. In all but winter months the city experienced lower relative humidities than the rural airport at all hours with mean monthly differences of more that 10 percent in summer at night. Urban absolute humidities were lower by day but higher at night than those in the country in the warm season. In winter both relative and absolute humidities were highest in the city - a result which is at variance with findings elsewhere, and which is attributed to high vapour output in combustion at low temperatures.

Annual maxima in absolute humidity differences were found at night in March and August (city moist) and by day in July (city dry). The March peak was attributed to urban snowmelt on nights when rural temperatures were below freezing. The August maximum difference at night was attributed mainly to rural dewfall. The times of maximum cooling and maximum absolute humidity in the city varied appreciably with wind speed and it was concluded that vertical radiative and heat-flux divergences as well as advection are important in establishing the time and magnitude of maximum heat-island intensity.

Ice fog is rare in Edmonton but it does occur in severe winters when it can be a hazard to transportation and an annoyance to the urban population. What influences, if any, will urban growth have on the frequency and density of ice fog? Intuitively, such growth is expected to be accompanied by increased heat island intensities, greater vertical mixing in a shallow surface layer, and increased air water content from combustion in winter. The first two factors favour less ice fog and the last favours increased fog. A simple advective model and comparative ice-fog statistics from the severe winters of 1949-50 and 1968-69 were used in an effort to evaluate the relative importance of these factors.

A seven-fold increase in the total amount of water vapour added to the air by the city on cold winter days resulted in dense low-temperature fog at temperatures 5C higher in 1969 than in 1950. Model calculations showed that further increases in the temperature at which fog forms can be expected if fuel consumption continues to increase but that the rate of increase of this temperature with population growth should diminish.

A comparative study of daily maximum, minimum, and mean temperatures for 36 years ending in 1965 at Edmonton Municipal Airport and Wetaskiwin, 60 km south of Edmonton, was carried out by Malcolm Berry. In this time period the population of Edmonton increased from 85,000 to 215,000. After corrections for latitude and elevation differences a substantial increase of 1.2C in Edmonton-Wetaskiwin minimum temperature differences was found with the largest increases at low temperatures. The average increase in maximum temperature differences was estimated to be 0.4C with the largest increase in early winter and smallest increases in spring.

Experimental Studies

Special low-threshold anemometers were constructed and erected on four sides of the city by Jay Campbell in an attempt to measure urban effects on surface air flow. Seven trials were completed on clear nights in July and August. Horizontal convergence was observed on all nights on the upwind side of the city and was found to increase in magnitude with increases in heat island intensity. On the downwind side divergence occurred with strong winds and convergence with light winds. The wind field consistently exhibited positive vorticity (vertical component) on the upwind side of the city and near-zero values on the downwind side.

A comparative study of low-level turbulence was conducted by J. David Steenbergen using vectorvanes operated simultaneously at a rural site and in the central business district. Data were recorded on analogue tape during 6 trials in September in a variety of wind speed and stability conditions.

Turbulence intensities for all three components of the wind were found to be 3 times as great in urban air as in rural air. Some evidence of large-scale horizontal meanders of wavelengths between 500 and 1000 m was found in the lateral component. The vertical velocity spectra exhibited maxima at non-dimensional frequencies of 0.3 (rural) and 0.1 (urban) indicating violation of similarity theory and a shift of energy to longer periods in the city air. It must be kept in mind, however, that important assumptions of similarity theory were not valid at the urban observation site.

Theoretical Study

A time-dependent, one-dimensional, higher-order closure boundary-layer model similar to Level C of the hierarchy of Mellor and Yamada was formulated and extended to include water vapour by Claude Lelievre. Soil heat flux, vertical turbulent fluxes of sensible and latent heat, and radiative processes were included. A log-linear vertical grid-point array of high resolution was used in the atmospheric layer.

Computations of successive diurnal cycles were carried out with changes in roughness height, soil thermal conductivity, and wind speed. Soil thermal conductivity was found to be a very important factor in establishing the amplitude of the diurnal temperature wave. Unfortunately, resources did not allow computations with water vapour included. Detailed displays and discussion of diurnal variations of computed mean and turbulent variables as functions of height were presented in Lelievre (1976).

Future Plans

Experimental studies of the temperature field and airflow in a cross-section of the North Saskatchewan River Valley in downtown Edmonton are planned for 1977. It is expected that the urban heat island will strengthen valley inversions that form on clear nights. Does the valley air participate in the heat island or is it uncoupled by a strong inversion layer? Are there significant local circulations at night in a narrow urban valley?

Although no specific plans have been formulated it is hoped that further development and extensions can be made to the numerical model mentioned above. In particular, an extension to two dimensions would be desirable for simulation of the urban boundary layer.

List of Publications and Theses

Berry, M.O., 1970: "The effects of urban expansion on temperatures in the city of Edmonton, Alberta", unpubl. M.Sc. Thesis, University of Alberta, Edmonton, 139 pp.

Campbell, J.E., 1972: "The meso-scale circulation induced by the city of Edmonton, Alberta", unpubl. M.Sc. Thesis, University of Alberta, Edmonton, 119 pp.

Hage, K.D., and R.W. Longley, 1970: "Ventilation and mixing in Alberta cities", Man and his Environment 1, Pergamon Press, Oxford, pp. 99-113.

Hage, K.D., 1972a: "Nocturnal temperatures in Edmonton, Alberta", Journal of Applied Meteorology, Vol. 11, No. 1, pp. 123-129.

Hage, K.D., 1972b: "Urban growth effects on low-temperature fog in Edmonton", Boundary-Layer Meteorology, Vol. 2, pp. 334-347.

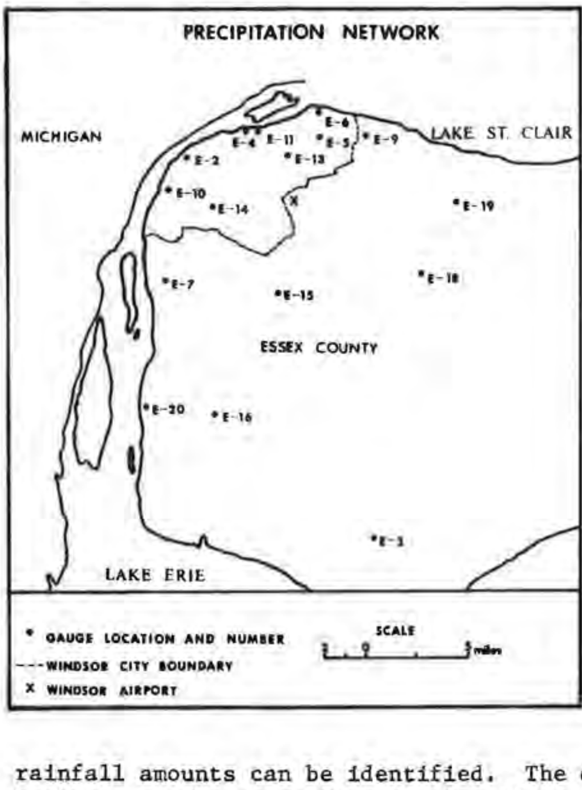
Hage, K.D., 1975: "Urban-rural humidity differences", Journal of Applied Meteorology, Vol. 14, No. 7, pp. 1277-1283.

Lelievre, C., 1976: "One-dimensional model of the urban heat island", unpubl. M.Sc. Thesis, University of Alberta, Edmonton, 230 pp.

Steenbergen, J.D., 1971: "Comparison of urban and rural turbulence statistics at Edmonton, Alberta", unpubl. M.Sc. Thesis, University of Alberta, Edmonton, 86 pp.

SHORTER CONTRIBUTIONS

I. Research in Urban Climatology, Department of Geography, University of Windsor. Contributed by Marie Sanderson.



Research in urban climatology at the University of Windsor has focussed mainly on the effect of the large metropolitan area of Detroit-Windsor with its 4.5 million people, on micro-precipitation patterns and on the radiation balance.

In 1970, 18 Belfort recording precipitation gauges were installed in Windsor and adjacent Essex county (see Fig.) and data are exchanged with the SEMCOG (South Eastern Michigan Council of Governments) network of some 100 gauges in and around Detroit. The Canadian network is operated by volunteer observers in various industries and utilities and by individual farmers. The daily charts are sent to the University of Windsor and a computer print-out giving hourly and daily summaries are mailed to all interested observers. Actually, 15 min. rainfall amounts can be identified. The data bank has been used in several bachelors and masters theses and articles listed below. The network is currently sponsored by the Essex Region Conservation Authority.

A research project also related to precipitation has been the collection of bulk precipitation samples and the chemical analysis of precipitation. Three samplers obtained from the Canada Centre for Inland Waters were installed in 1971 in Windsor and Essex County and monthly samples were analyzed for sulphate, sulphite, phosphate, nitrogen, chloride, sodium, conductivity, magnesium, calcium and potassium. Several years of these analyses were carried out. In 1975 in connection with the

PLUARG study (Pollution from Land Use Activities Reference Group) for the International Joint Commission, two samplers were installed near Leamington in the eastern part of the county. Analysis of bulk precipitation was made until June 1977 of the above parameters, plus some analyses of heavy metals and P.C.B.'s. The report of this research will appear in 1978 in the general PLUARG report to the I.J.C.

The radiation research has involved the continuous recording of incoming solar radiation with an Eppley pyranometer on the roof of Essex College since 1971. This data on incoming solar radiation provided urban radiation information which can be compared with data from instruments recently installed in Harrow at the Agricultural Research Station and on Pelee Island at the University of Windsor weather station. These data have also provided material for several theses and articles listed below.

Publications

Published Articles

Sanderson, M., I. Kumanan, T. Tanguay and W. Schertzer, 1973: "Three aspects of the urban climate of Detroit-Windsor", Journal of Applied Meteorology, Vol. 12, No. 4, pp. 629-638.

Sanderson, M., 1974: "A preliminary radiation climatology of Windsor, Ontario", McGill University, Climatological Bulletin, No. 16, pp. 1-12.

Sanderson, M. and R. Gorski, (in press): "The effect of metropolitan Detroit-Windsor on precipitation".

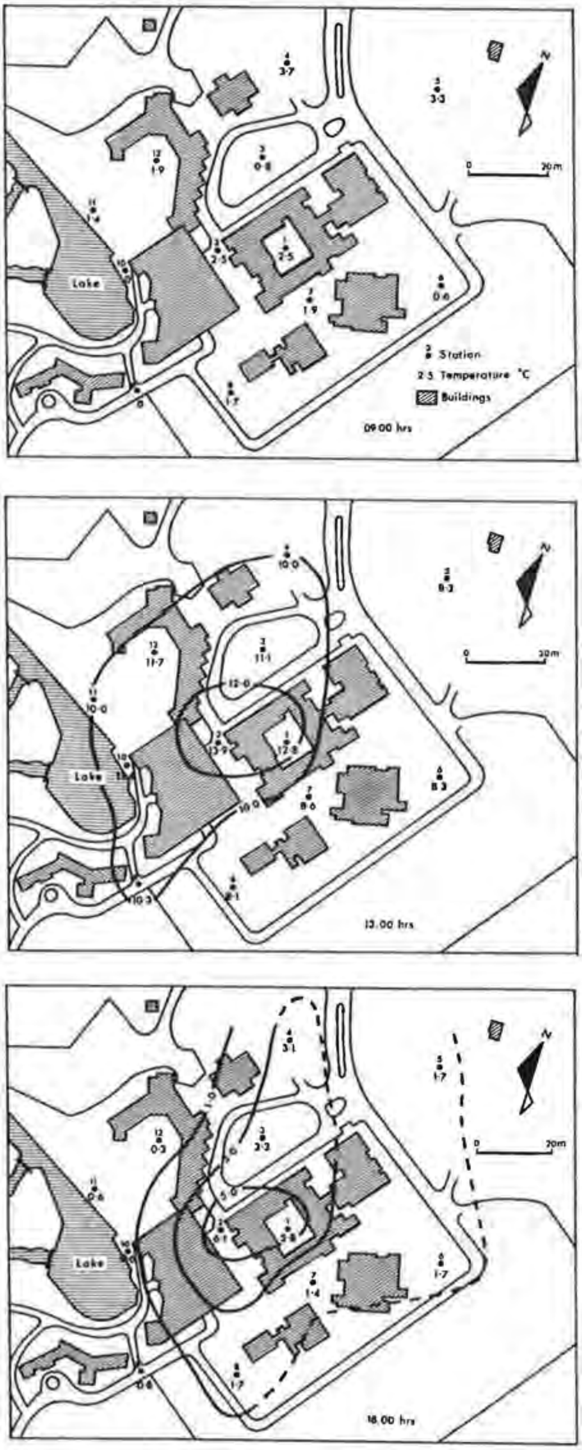
Sanderson, M., 1977: Annual Progress Report Task Group C. PLUARG, "Precipitation Quantity and Quality", Industrial Research Institute, University of Windsor.

Master's Theses

Kumaman, I., 1970: "Toward an understanding of the urban heat island in the Detroit-Windsor Area", Department of Geography, University of Windsor.

Osborne, R., 1976: "An investigation of factors affecting total sulfate supply and sulfate concentrations in individual rainfalls at Windsor, Ontario", Department of Geography, University of Windsor.

II. Research in Urban Geography at Lakehead University: "Temperature fields adjacent to small groups of buildings". Contributed by David D. Kemp.



Since 1975 temperature measurements have been taken at a series of locations around Lakehead University campus in order to study temperature fields adjacent to small groups of buildings. Twelve locations (see Fig.) were chosen to provide a variety of surface conditions and exposures and readings have been taken at various times of the day and at different seasons of the year. Stations 1, 2, and 7 are close to the core of the group of buildings on concrete walkways and surrounded by structures from one to five storeys high. The other stations, on lawns, walkways and adjacent to the lake are peripheral to the core group. Temperatures have been recorded morning, mid-day and evening with a complete series of readings obtained within a period of 20-30 minutes each time. Because of the availability of student assistants most of the readings have been taken during fall, winter and spring, but summer readings will be added to these at the original 12 locations plus an additional five.

The temperatures are measured using a Leeds and Northrup, 8694-2 Temperature Potentiometer and a shielded thermocouple attached to a survey pole to give readings at 1.5 m above the ground surface. A three-cup, hand anemometer has recently been added to the unit to allow wind speed at the time of reading to be measured. These instruments were purchased with a small grant made available from Lakehead University Senate Research Committee funds.

The most obvious element is the preponderance of higher temperatures at stations 1 and 2 at all times of the day and all seasons of the year. Temperatures at these locations are commonly 2 - 3 C higher than at the next warmest station and as much as 5 - 6 C higher than at the coolest station. It seems likely that the higher temperatures at stations 1 and 2 are a function of their location at the core of the group of buildings. Station 7, the other station in the core area, does not record similar consistently higher temperatures perhaps because of its greater exposure and the funnelling of air between the two buildings situated to the south-east of it. There seems to be no station that regularly records lower temperatures than all of the others.

The first figure illustrates the conditions that prevailed on October 29, 1975. The temperature distributions may be considered typical inasmuch as they show the build up of higher values in the core area during the day and their persistence into the early evening. A further examination of this phenomenon with an increase in the number of stations and readings later into the evening and early morning is planned.

III. Research in Urban Climatology at Concordia University. Contributed by David B. Frost.

The Department of Geography at Concordia University established a small climatological station in downtown Montreal in May 1973 and daily records have been maintained since that time. The intensely urban character of the Sir George Willimms Campus of Concordia precluded selection of a normal observational site and necessitated use of a second floor sundeck. The station permits Climatology students to gain experience with observational procedures and also seeks to provide information on a long term basis of the climate within an urban canyon.

The geometry of the canyon is complex with ground surfaces including back lanes, gardens, parking lots and a major urban routeway. The majority of the nearby buildings are three to four storey, but also include three high-rise towers, one of 33 storeys. Sunlight is accordingly limited to 7 3/4 hours at mid-summer (07.00 - 14.45 hours, EST) and to only 1 1/4 hours at mid-winter (10.15 - 10.55 and 14.15 - 14.50 EST).

The station comprises standard thermometers, hygrothermograph, sunshine recorder, pyrheliometer, rain gauge and recording rain gauge, Class A pan, totalizing anenometer at 50 cm and an anenometer and wind vane at 14 m. The instruments are read once daily, at 0930 EST and values are calculated according to the A.E.S. type 6 station procedures.

The station lies one kilometer southwest of the McGill University station whose situation can best be described as an urban parkland. A preliminary analysis of the temperature records for the two stations indicates that the canyon is on average 0.5C warmer than the parkland throughout the year. This value corresponds to 40% of the difference between the parkland and the surrounding countryside. There is no systematic difference in summertime precipitation, but in winter the canyon receives much additional snow blown off surrounding roofs.

Besides continuing analysis of existing data, further instruments will be installed both in the canyon and in the buildings nearby, to investigate the extent to which the internal building environment is coupled to external conditions.

Berkowicz, S., 1977: "An investigation of aspects of the urban climate of the Montreal region; January and July, 1976", unpubl. B.A. thesis, Department of Geography, Concordia University, 120 pp.

Zowtonizka, H., 1977: "A study of the internal temperature of 2090 Mackay Street, Montreal", unpubl. B.A. thesis, Department of Geography, Concordia University, 205 pp.

IV. Research in Urban Climatology at the University of Western Ontario - Summary of the Ground Level Wind Environment in Built-Up Areas.
Contributed by Dr. N. Isyumov and Prof. A.G. Davenport, Faculty of Engineering Science.

Changes in the profile of modern cities with the advent of high rise construction have significantly aggravated the city wind environment. In fact, in many cases the presence of tall buildings has created inhospitable and even dangerous ground level wind conditions. As a result an acceptable wind environment in outdoor public areas has become a major design consideration for new building complexes and a concern for existing areas which have been found undesirable by public opinion. Essentially this presents two major questions. First, how can the magnitude of wind speeds in public precints be predicted. This is a question of both building aerodynamics and wind climatology, as the occurrence of certain wind speeds and directions in full scale can only be expressed in probabilistic terms. Wind tunnel model studies currently offer the principal means of providing quantitative predictions of wind speeds around buildings for particular magnitudes and directions of wind at some reference location. The requirements for such simulations are discussed in detail below. Methodologies for developing statistical descriptions of the reference velocity, most conveniently taken as the velocity at gradient height, and the integration of wind tunnel results with meteorological data to provide predictions of the relative frequency of occurrence of particular events are available. Having obtained an estimate of the ground level windspeed environment, the second question becomes the choice of suitable criteria for evaluating its acceptability. This in many respects is a more difficult question, as it involves not only considerations of safety and the impediment to performing various tasks, but also the more subjective consideration of human comfort.

Indications that the question of the ground level wind environment is now no longer a secondary design consideration are the many articles on this subject in the current literature. Quoting Wise (1965), the Building Research Station has received some 200 inquiries about the wind environment for existing or projected buildings since 1964, when work was started in this area, of which some 10 % have been studied in the wind tunnel. Some 20 investigations of the wind environment in major plazas have been carried out at the Boundary Layer Wind Tunnel Laboratory in recent years. In fact, studies of the plaza level wind climate have become an essential ingredient of all current studies of wind effects for major buildings carried out at this laboratory. Furthermore, the seriousness of the matter is demonstrated by attempts of municipal planners to provide design recommendations or even by-laws to safeguard the environment in built-up urban areas from further deterioration. For example, proposed guidelines for the development of the Toronto core area include pedestrial level wind considerations (City of Toronto Planning Board, 1974).

Both the definition of the ground level wind speed environment around buildings and building complexes and criteria for its evaluation are discussed in this paper. In presenting specific results, the authors have drawn largely from the experience with a number of plaza wind studies carried out at the Boundary Layer Wind Tunner Laboratory of the University of Western Ontario (BLWTL).

References

City of Toronto Planning Board, 1974: "Core Area Interim Criteria for evaluating developments which require exemptions from provisions of the core area holding by-law", October.

Wise, A.F.E., D.E. Sexton and M.S.T. Lillywhite, 1965: "Studies of air flow round buildings", Architects Journal, Vol. 141, May.

CANADIAN URBAN CLIMATES - LITERATURE SURVEY UPDATE

by

G.A. McKay*

McGill University's Climatological Bulletin No. 5 contained a survey of literature on Canadian Urban Climates, by M.K. Thomas. A pre-emptory review of the list confirms the exponential growth pattern found throughout most scientific endeavours. The publications since 1969, when Bulletin No. 5 appeared, are almost double to the number listed by Thomas. Atmospheric Environment Service has continued to index urban and other climatic reports and these files have provided the bulk of items contained in the list attached to this update report.

Apart from exponential growth, a review of the literature appearing since 1969 discloses other interesting trends. There has been a decided shift from the analysis of elemental point values to that of areal and spatial patterns. More detailed studies of the boundary layer, radiation and heat islands have emerged (30 vs 7 prior to 1969). The total number of papers on air pollution is up, but the percentage is constant. Land-use planning papers have made their appearance, as did papers relating to the urban energy. Water balance papers are a notable omission. Also meteorologists showed a surprising lack of interest in the human element and operating problems within urban areas. This separation of meteorology from urban problems was evident at the August 1975 Conference on the Urban Physical Environment at the University of Syracruse. Only one urban planner attended the conference which was attended by urban meteorologists, foresters and land scientists.

The World Meteorological Organization's Symposium on "Meteorology as Related to Urban and Regional Land-use Planning" (Ashe-

---

* G.A. McKay is Director, Meteorological Applications Branch of the Atmospheric Environment Service in Toronto.

Urban Publications and Year of Issue. Publications are Identified According to Sector of Major Interest Except in Few Instances of Split Purpose.

Class / Year	Sun-shine	Heat Flux Rdn.	Wind	Air Flow	Pcpn.	Ice Snow	Fog Smoke	Temp.	Hum-idity	Air poln.	Poln Mdls	Syn-optic	Bdry Layer	Ener-gy Bal.	Water Bal.	Heat Is-land	Bio-Met.	Land Use Plan	Lit. Sur-vey	Hand Books	Areal Cli.
1936								1					1								
1954						1		1													
1955								1								1	1				
1956										1											
1958				1																	
1959										1											
1960										1											
1961						2,1*	1S			1											
1962							3S	1													
1963				1									1								
1964		1								2			2*								
1965					1			1													
1966					3		1S	1		1											1
1967								1								1					
1968			1	1																	1
1969					1			1		4			1			2			2	1	
1970	1	3		1	1	1				1	--	1 -	2	--	--	1					1
1971				1		1					1		1								
1972		1		1	1	1,1*	2F			2			1			3	1	1	1		1
1973			1		1*	1,1*			1	1			1			1		1	1		
1974	1*	2											1					1			
1975			1*		2	1		1*	1	4	1			1*		3					
1976		1			1								2						1		1
1977	1*	1											2								
Sub Classification Identification	*Turbidity		*Tornado		*TSTM Days	*Ice Storm	S-Smoke F-Fog H-Haze	*Soil Temp.					*Inversion	*Space Heating			*Pollen				

ville, 1975) provides further evidence of this problem, and changing trends. Cities and land are inseparably linked. The cities' food supply, water, recreation and forests are provided by adjacent lands. Furthermore, the way the land is used within the city is of critical importance to the health and social well-being of its inhabitants, as well as to the economic prosperity of the city. An interesting observation concerning building and urban climatology was that although the state of the science has advanced to the point where significant contributions can be nade to urban planning, the information has not been communicated to urban planners in an effective manner. To overcome this problem the Symposium recommended the formulation of simple, practical relationships, linking meteorological and urban parameters that would express the meteorological information in a way that is easily recognized by the planner, and highly usable.

The Asheville Symposium provided a basis for WMO's participation at Habitat 1976. Unfortunately the role of meteorology was barely visible among the social and cultural issues that dominated that conference. Nevertheless, it was encouraging to know that meteorology was there. Two items that stand out are: the WMO presentation by Dr. Landsberg that showed the pervasiveness of meteorology in all of man's activities, and an excellent film "Urban Climate and Urban Development" prepared by the Federal Republic of Germany. The film dramatically depicted, through the example of Stuttgart, how the planner could achieve a superior use of space (topography, buildings, industrial areas, residential areas, etc.), and avoid serious planning errors through an understanding of the meso-scale climate.

Urban meteorology/climatology has shared in the exponential growth of all sciences. It is now moving rapidly and positively to aid mankind in facing up to the environmental implications of urban growth.

SELECTED REFERENCES TO PAPERS CONCERNING
CANADIAN URBAN CLIMATES

1969 CATCHPOLE, A.J.W.

"The solar control of diurnal temperature variation in Winnipeg", The Canadian Geographer, Vol. 13, No. 3, pp. 255-268.

DIDUCH, O.J. and C.E. KLAPONSKI

"A preliminary analysis of gusts over Montreal", McGill University, Montreal, Climatological Bulletin, No. 5, pp. 26-34.

EAST, C.

"Pollution atmosphérique et île de chaleur", McGill University, Montreal, Climatological Bulletin, No. 5, pp. 21-26.

MUNN, R.E., D.A. THOMAS and A.F.W. COLE

"A study of suspended particulate and iron concentrations in Windsor, Canada", Atmospheric Environment, Vol. 3, No. 1, pp. 1-10.

MUNN, R.E., R.W. LONGLEY, W.C. BELL, A. HYFTY and F.G. HANNELL

"Research in urban climatology in Canada", McGill University Montreal, Climatological Bulletin, No. 5, pp. 35-63.

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

"A climatological study of the urban temperature anomaly in the lakeshore environment at Toronto", Journal of Applied Meteorology, Vol. 8, No. 3, pp. 411-422.

OKE, T.R.

"Towards a more rational understanding of the urban heat island", McGill University, Montreal, Climatological Bulletin, No. 5, pp. 1-20.

POWE, N.N.

"The climate of Montreal", Dept. of Transport, Met. Br. Climatological Studies, No. 15, 51 pp. (Also available in French as "Le climat de Montréal").

THOMAS, M.K.

"Canadian urban climates - a brief literature survey", McGill University, Montreal, Climatological Bulletin, No. 5, pp. 54-61.

1969 WEISMAN, B., D.H. MATHESON and M. HIRT

"Air pollution survey for Hamilton, Canada", Atmospheric Environment, Vol. 3, No. 1, pp. 11-23.

WRIGHT, J.B.

"An investigation into the problem of air pollution at Kamloops, B.C.", Dept. of Transport, Met. Br., TEC-708, January 15, 7 pp.

WRIGHT, J.B.

"Greater Vancouver precipitation", Dept. of Transport, Met. Br., TEC-722, September 10, 22pp.

YAP, D., K.L. S. GUNN and C. EAST

"Vertical temperature distribution over Montreal", Naturaliste, Can., Vol. 96, pp. 561-580.

1970 BRINKMANN, W.A.R.

"The chinook at Calgary (Canada)", Arch. Meteorol., Geophys., Bioklimatol., Ser. B, Vol. 18, pp. 269-278.

COLEMAN, M.D. and J.M HAVENS

"A climatography of London, Ontario - observations of bright sunshine, 1925-1968", Ontario Geography, Vol. 5, pp. 18-27.

DRIEDGER, H.L. and A.J.W. CATCHPOLE

"Estimation of solar radiation receipt from sunshine duration at Winnipeg", Met. Mag., Vol. 99, No. 1179, pp. 285-291, Oct.

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

"Infra-red flux divergence and the urban heat island", in Urban Climates, Technical Note 108, WMO No. 254, TP. 141, pp. 65-69.

MARSHALL, J.S. and C.D. HOLTZ

"Pattern analysis of one summer's multilevel map of Montreal rain", Mon. Weath. Rev., Vol. 98, No. 5, pp. 335-345, May.

MAYBANK, J. and J.L. BERGSTEINSSON

"Climate of Saskatoon", in Physical Environment of Saskatoon, Canada, Saskatchewan Research Council of Canada, Ottawa, pp. 22-36.

1970 MUNN, R.E.

"Meteorology and air pollution" in Man and His Environment, Vol. 1, Proceedings of the First Banff Conference on Pollution, May 16 and 17, 1968, Pergamon Press, Oxford, pp. 89-97.

MUNN, R.E.

"Airflow in urban areas", in Urban Climates, Technical Note 108, WMO No. 254, TP. 141, pp. 15-39.

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

"The form of the urban heat island in Hamilton, Canada" in Urban Climates, Technical Note 108, WMO No. 254, TP. 141, December, pp. 15-39.

TRUEMAN, M.E.H.

"Montreal's great snowstorm of '69", Weatherwise, Vol. 23, No. 6, pp. 270-273.

WILSON, H.J.

"Meteorological conditions in Windsor, Ontario, during the passage of a ridge of high pressure", Atmosphere, Vol. 8, No. 3, pp. 73-78.

1971 BAUMANN, D.D. and C. RUSSELL

"Urban snow hazard: Economic and social implications", University of Illinois, Water Resources Center, Final Report of a Contract, April.

BOWNE, N., A.E. BOYER and D.G. COOPER

"A simulation model of air pollution over Toronto", paper presented at Fifth Canadian Meteorological Congress, May, 12, (unpublished).

OKE, T.R. and C. EAST

"The urban boundary layer in Montreal", Boundary-Layer Meteorology, Vol. 1, No. 4, April, pp. 411-437.

VUKOVICH, F.M.

"Theoretical analysis of the effect of mean wind and stability on a heat island circulation characteristic of an urban complex", Mon. Weath. Rev., Vol. 99, No. 12, pp. 919-926.

1972 BOULERICE, M. and W. BRABANT

"La qualité de l'air à Montréal", Québec Science, Vol. 10, No. 7, Avril, pp. 14-21.

1972 CAMPBELL, J.E.

"The mesoscale circulation induced by the City of Edmonton, Alberta", the University of Alberta, M.Sc. Thesis, 119 pp.

EMSLIE, J.H.

"Surface temperature field - Greater Vancouver, B.C.", Dept. of the Environment, Atmospheric Environment Service, TEC-768, May 5.

HAGE, K.D.

"Nocturnal temperatures in Edmonton, Alberta", Journal of Applied Meteorology, Vol. 11, No. 1, pp. 123-129.

HAGE, K.D.

"Urban growth effects on low temperature fog in Edmonton", Boundary Layer Meteorology, Vol. 2, pp. 334-347.

HENDRICKS, J.R.

"Precipitation in Regina in June", Dept. of the Environment, Atmospheric Environment Service, TEC-772, July 18, 6 pp.

LIST, R., R.C. BENNETT and U. RENTSCH

"Acoustic echo soundings in urban Toronto", Atmosphere, Vol. 10, No. 3, pp. 73-79.

MUNN, R.E.

"Air quality: Local, regional and global aspects", Canada, Science Council, Special Study No. 24, 35 pp.

MUNN, R.E.

"Urban meteorology: Some selected topics", presented at the Conference on Urban Environment, American Meteorological Society, Oct 31-Nov 2, Philadelphia, Pa.

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

"The application of meteorology to land-use planning in south-western Ontario", International Geography, Univ. of Toronto Press, pp. 219-222.

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

"Comparison of urban/rural counter and net radiation at night", Boundary Layer Meteorology, Vol. 2, pp. 290-308.

PADMANABHAMURTY, D.

"A study of biotropism of climate in two Canadian cities", International Journal of Biometeorology, Vol. 16, No. 2, pp. 107-117.

1972 SMITH, R.

"A climatological study of Toronto", Dept. of the Environment, Atmospheric Environment Service, Meteorological Applications Branch, Project Report No. 8, (Internal), 85 pp.

SMITH, R.

"Characteristics of the urban heat island at Georgetown, Ontario", Dept. of the Environment, Atmospheric Environment Service, Meteorological Applications Branch, Project Report No 7 (Internal), 28 pp.

TYNER, R.V.

"Extreme values of annual and monthly snowfall amounts at Halifax, N.S.", Dept. of the Environment, Atmospheric Environment Service, TEC-778, Sept. 14, 8 pp.

WRIGHT, J.B.

"Fog occurrence at Calgary International Airport, Alberta", Dept. of the Environment, Atmospheric Environment Service, TEC-770, April 19, 7 pp.

1973 CHAINE, P.M.

"Glaze and its misery: The icestorm of March 22-23, 1972, north of Montreal", Weatherwise, Vol. 26, No. 3, pp. 124-127.

CHILTON, R.R.

"Climatic summary for greater Victoria region", in An Inventory of Land Resources and Resource Potentials - A Report to the Capital Regional Distric (British Columbia), May, pp. 5-21.

GUTZMAN, W.L.

"The heavy snowstorm at Montreal, Canada, March 4-5, 1971", Weather, Vol. 28, No. 7, pp. 281-288.

HENDRICKS, J.R. and T.G. MEDLICOTT

"The frequency of thunderstorm days at Regina", Dept. of the Environment, Atmospheric Environment Service, TEC-799, Dec. 4, 8 pp.

MUNN, R.E.

"A study of suspended particulate air pollution at two locations in Toronto, Canada", Atmospheric Environment, Vol. 7, Nos. 1-6, pp. 311-318.

MUNN, R.E.

"Secular increases in summer haziness in the Atlantic Provinces", Atmosphere, Vol. 11, No. 4, pp. 156-161.

1973 OKE, T.R.

"City size and the urban heat island", Atmospheric Environment, Vol. 7, pp. 769-779.

PADMANABHAMURTY, R. and R.E. MUNN

"A case study of mixing-height variations in the Toronto area", Atmosphere, Vol. 11, No. 1, pp. 21-25.

SANDERSON, M., I. KUMANAN, T. TANGUAY and W. SCHERTZER

"Three aspects of the urban climate of Detroit/Windsor", Journal of Applied Meteorology, Vol. 12, No. 4, June, pp. 629-638.

1974 ELEY, F.J.

"Mesoscale climatic study of Norman Wells, N.W.T.", Environmental-Social Committee, Northern Pipelines, Task Force on Northern Oil Development, Report No. 74-24, Ottawa, 56 pp.

SANDERSON, M.

"A preliminary radiation climatology of Windsor, Ontario", McGill University, Montreal, Climatological Bulletin, No. 16, Oct., pp. 1-12.

YAMASHITA, S.

"Comparative study of turbidity in an urban and rural environment at Toronto", Atmospheric Environment, Vol. 8, No. 5, May, pp. 507-518.

YAP, D.

"A preliminary investigation of winter air pollution potential at Fort Simpson, N.W.T.", Atmosphere, Vol. 12, No. 2, pp. 62-68.

YAP, D., T.A. BLACK and T.R. OKE

"Calibration and tests of a yaw sphere-thermometer system for sensible heat flux measurements", Journal of Applied Meteorology, Vol. 13, No. 1, February 1, pp. 40-45.

YAP, D. and T.R. OKE

"Sensible heat fluxes over an urban area - Vancouver, B.C.", Journal of Applied Meteorology, Vol. 13, No. 8, December, pp. 880-890.

1975 DeFREITAS, C.R.

"Estimation of the disruptive impact of snowfalls in urban areas", Journal of Applied Meteorology, Vol. 14, No. 6, September, pp. 1165-1173.

1975 FLUTO, K.A. and P.B. LEMIEUX

"The 1974 Victoria Day rainstorm in Winnipeg and vicinity", Dept. of the Environment, Atmospheric Environment Service, TEC-824, November 27, 5 pp.

HAGE, K.D.

"Urban-rural humidity differences", Journal of Applied Meteorology, Vol. 14, No. 7, October, pp. 1277-1283.

LEAHEY, D.M.

"An application of a simple advective pollution model to the city of Edmonton", Atmospheric Environment, Vol 9, pp. 817-823.

MUNN, R.E.

"The oxidant climatology of Canada in photochemical air pollution formation, transport and effects", National Research Council, Ottawa, Report 14096, pp. 53-70.

MUNN, R.E.

"Suspended particulate concentrations: Spatial correlations in the Detroit/Windsor area", Tellus, Vol 27. pp. 397-405.

NKEMDIRIM, C., G.R. LUNN and R.D. ROWE

"Pollutant concentration and stratification in urban heat island", Water, Air and Soil Pollution, Vol. 4, No. 1, March, pp. 99-112.

OKE, T.R.

"The urban heat island in Vancouver, B.C. - form, controls and models", Simon Fraser University, Burnaby, pp. 58-61.

OKE, T.R. and G.B. MAXWELL

"Urban heat island dynamics in Montreal and Vancouver", Atmospheric Environment, Vol. 9, No. 2, pp. 191-200.

OUELLET, C.E.

"Soil and air temperatures at Ottawa", Agriculture Canada, Publication 1541, 29 pp.

PAUL, P.

"La stagnation des fronts chauds, l'hiver, à Montréal et ses effects sur la pollution de l'air", Feuillet Météorologique, Vol. 28, No. 5, pp. 74-82.

1975 ROETE, E.H.

"The severe storm of April 3rd, 1974, at Windsor, Ontario", Dept. of the Environment, Atmospheric Environment Service, TEC-821, August 25, 6 pp.

SAVDIE, I.

"Effect of urban expansion on fuel consumption for space heating", Dept. of the Environment, Atmospheric Environment Service, Meteorological Applications Branch, Project Report No. 17 (Internal).

YAP, D.

"Seasonal excess urban energy and the nocturnal heat islant, Toronto", Archiv. für Meteorologie, Geophysik und Bioklimatologie, Series B, Vol. 23, No. 1-2, pp. 69-80.

1976 BRAZEL, A.J. and R. OSBORNE

"Observations of atmospheric thermal radiation at Windsor, Ontario, Canada", Archiv. für Meteorologie, Geophysik und Bioklimatologie, Series B, Vol. 24, pp. 189-200.

FINDLAY, B.F.

"Climatological studies in urban areas", Canada Committee on Ecological (Bio-physical) Land Classification, Proceedings of the Toronto Workshop on Metropolitan Ecology, November.

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

"Long-wave radiation flux divergence and nocturnal cooling of the urban atmosphere", Boundary Layer Meteorology, Vol. 10, pp. 113-120.

HAY, J.E. and T.R. OKE

"The climate of Vancouver, B.C. ", Geographical Series No. 23, The University of British Columbia, Dept. of Geography, Vancouver, B.C., 49 pp.

LAWFORD, R.G.

"A study of the precipitation events of August 27 and 28, 1976 in Toronto, Ontario area", Dept. of the Environment, Atmospheric Environment Service, Internal Report, SSU-76-S, 39 pp.

NKEMDIRIM, L.C.

"Dynamics of an urban temperature field - a case study (Calgary)", Journal of Applied Meteorology, Vol. 15, No. 8, August, pp. 818-828.

1976 NUNEZ, M. and T.R. Oke

"Long-wave radiation flux divergence and nocturnal cooling of the urban atmosphere, Boundary Layer Meteorology, Vol. 10, pp. 121-135.

OKE, T.R.

"Inadvertent modification of the city atmosphere and the prospects for planned urban climates", Proceedings of the WMO Symposium on Meteorology as Related to Urban and Regional Land-Use Planning, WMO, No. 444, p. 150-177.

OKE, T.R. and J.E. HAY

"Climate of Vancouver", in The Vancouver Book (C. Davis, Ed.), Vancouver, B.C., pp. 118-122.

OKE, T.R.

"The distinction between canopy and boundary-layer urban heat islands", Atmosphere, Vol. 14, pp. 268-277.

VENKATRIM, A.

"A model for internal boundary-layer development", Boundary Layer Meteorology, Vol. 4, pp. 1-19.

1977 NUNEZ, M. and T.R. OKE

"The energy balance of an urban canyon", Journal of Applied Meteorology, Vol. 16, No. 1, pp. 11-19.

VENKATRIM, A.

"Internal boundary-layer development and fumigation", Atmospheric Environment, Vol. 11, pp. 479-482.

McGill University

Department of Geography

CLIMATOLOGICAL RESEARCH SERIES

No. 1 Two Studies in Barbadian Climatology, by W.R. Rouse and David Watts, 65 pp., July 1966, price $6.50

No. 2 Weather Conditions in Nigeria, by B.J. Garnier, 163 pp., March 1967, out of print.

No. 3 Climate of the Rupununi Savannas - A Study in Ecological Climatology, by David B. Frost, 92 pp., December 1967, price $8.50.

No. 4 Temperature Variability and Synoptic Cold Fronts in the Winter Climate of Mexico, by J.B. Hill, 71 pp., February, price $7.50.

No. 5 Topographic Influences on a Forest Microclimate, by R.G. Wilson, 109 pp., September 1970, price $10.00.

No. 6 Estimating the Topographic Variations of Short-Wave Radiation Income: The Example of Barbados, by B.J. Garnier and Atsumu Ohmura, 66 pp., December 1969, price $7.50.

No. 7 The Remote Sensing of Surface Radiative Temperatures Over Barbados, by B.J. Garnier, 52 pp., May 1972, price $6.50.

No. 8 Moisture Conditions in the Savanna Region of West Africa, by Kala Swami, 106 pp., December 1973, price $8.50.

No. 9 Solar and Net Radiation Over Snow, by D.E. Petzold, 77 pp. November 1974, price $7.50.

No. 10 Snowmelt Runoff Processes in a Subarctic Area, by Anthony G. Price, 106 pp., June 1977, price $8.50

No. 11 Potential Evapotranspiration in Different Climatic Regions of Guyana, by Chander Persaud, 101pp., October, 1977, price $9.50.

Prices of Research Series vary, but subscribers to the Bulletin are entitled to a 50% reduction on the published price, provided they hold or held a current subscription for the year in which the relevant number of the Research Series appears. Send orders and inquiries to:

Department of Geography (Climatology)
McGill University
805 Sherbrooke Street West
Montreal, Quebec, Canada
H3A 2K6

Lithographed in Canada by Forrest Lithographing Limited, Montreal, Quebec.