WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 169

REVIEW OF URBAN CLIMATOLOGY 1973-1976

by

T. R. Oke
CoSAMC Rapporteur on Urban Climatology

WMO - No. 539

Secretariat of the World Meteorological Organization - Geneva - Switzerland

The WMO

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- To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
- To promote standardization of meteorological observations and ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture, and other human activities;
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CONTENTS

FOREWORD

In recent years the application of climatology to urban planning problems has received particular attention within the WMO Commission for Climatology and Applications of Meteorology*. In 1974 WMO published a Technical Note under the title "Review of Urban Climatology, 1968-1973", the text of which had been prepared by Professor T. R. Oke (Canada) who had been appointed by the Commission as Rapporteur on this subject. At its sixth session the Commission considered this subject and recognized the need to continue to follow the developments.

Professor Oke was accordingly invited once again to serve as a Rapporteur and, *inter alia*, to prepare a report to complement the material contained in the above Technical Note. The Commission at its seventh session (1978) commended Professor Oke for the excellent report prepared by him in response to this request and agreed that it should be published in the WMO Technical Note series. The present publication, entitled "Review of Urban Climatology, 1973-1976" contains this report.

I should like to take this opportunity of expressing the gratitude of the World Meteorological Organization to Professor T. R. Oke for his valuable report on a subject of great topical interest.

D. A. Davies

D. A. DAVIES
Secretary-General

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* Prior to 1979 this Commission was known as the Commission for Special Applications of Meteorology and Climatology.

SUMMARY

This publication reviews developments in the fields of urban climatology and meteorology in the period 1973-1976 inclusive. It therefore forms an addendum to WMO Technical Note No. 134 "Review of Urban Climatology 1968-1973" produced earlier by the author. The organization of the report follows that of the earlier one and the combined bibliographies along with that produced by Chandler (WMO Publication No. 276, 1970) provide a reasonably comprehensive coverage of literature in urban climatology.

The report is in two parts. The first concentrates on observational studies including research into the radiation, energy and water balances of cities, inadvertent modification of cloud and precipitation and the perturbation of wind, temperature and moisture fields by urban areas.

The second part deals with attempts to construct models (scale, statistical and theoretical) to simulate the atmosphere both below urban roof-level and in the overlying urban boundary layer. The models range from those aimed at statistical prediction of a single climatic variable to those attempting to simulate the three-dimensional characteristics of the urban boundary layer.

RESUME

Cette publication passe en revue les études faites dans le domaine de la climatologie et de la météorologie urbaines de 1973 à 1976. Elle constitue, donc, un additif à la Note technique N° 134 de l'OMM, intitulée "Review of Urban Climatology 1968-1973", déjà préparée par l'auteur. Ce rapport est présenté de la même manière que le précédent et les deux bibliographies combinées, avec celle qu'a établie Chandler (Publication WMO-No. 276, 1970), donnent un aperçu assez complet des ouvrages publiés au sujet de la climatologie urbaine.

Le rapport se divise en deux parties. La première est essentiellement consacrée à des études fondées sur l'observation, notamment les recherches concernant les bilans radiatif, énergétique et hydrique des villes, la modification involontaire des nuages et des précipitations et les effets perturbateurs des zones urbaines sur les champs de vent, de température et d'humidité.

La seconde partie traite des tentatives de construction de modèles (réduits, statistiques et théoriques) pour simuler l'atmosphère tant au-dessous qu'au-dessus du niveau des toits en ville. Les modèles vont de ceux dont le but est la prévision statistique d'une seule variable climatique à ceux qui s'efforcent de simuler les caractéristiques tridimensionnelles de la couche limite urbaine.

РЕЗЮМЕ

В данной публикации рассматриваются достижения в области городской климатологии и метеорологии за период 1973-1976 гг. включительно. Таким образом, эта публикация является дополнением к Технической записке ВМО № 134 "Обзор городской климатологии за 1968-1973 гг.", написанной этим же автором ранее. Структура данного отчета совпадает с построением предыдущей работы, а объединенная библиография вместе со списком литературы, приводимом Шандлером (Публикация ВМО № 276, 1970 г.), представляет собой достаточно широкий список литературы в области городской климатологии.

Отчет подразделяется на две части: первая концентрируется на исследованиях, основанных на наблюдениях, включая исследования радиации, энергетического и водного баланса городов, непреднамеренного воздействия на облачность и осадки и возмущений полей ветра, температуры и влаги, вызываемых городскими районами.

Во второй части предпринимаются попытки построения моделей (масштабных, статистических и теоретических) атмосферы как ниже уровня городских крыш, так и в пограничном слое, располагающемся над городом. Классы представленных моделей колеблются от тех, которые направлены на статистическое предсказание единичных климатических переменных,до моделей, предназначенных для моделирования трехмерных характеристик городского пограничного слоя.

RESUMEN

Esta publicación examina los acontecimientos que han tenido lugar en el sector de la climatología urbana y de la meteorología durante el período de 1973 a 1976 inclusive. Por lo tanto, constituye un aditivo a la Nota Técnica Nº 134 de la OMM "Examen de la climatología urbana, 1968-1973", preparada anteriormente por el autor. La organización del informe es la misma que la del anterior y las bibliografías combinadas así como la preparada por Chandler (Publicación Nº 276 de la OMM, 1970) constituyen una documentación bastante amplia sobre climatología urbana.

El informe consta de dos partes. La primera trata de los estudios de observación, incluidos la investigación en materia de radiación, energía y balance hídrico de las ciudades, la modificación involuntaria de la precipitación y de las nubes y la alteración del viento, de la temperatura y de la humedad por las zonas urbanas.

La segunda parte trata de los intentos de establecer modelos (a escala, estadísticos y teóricos) para simular la atmósfera más abajo del nivel de los techos urbanos y en la capa límite urbana más arriba de los techos. Los modelos se extienden desde los que están destinados a la predicción estadística de una variante climática única a los que tratan de simular características tridimensionales de la capa límite urbana.

LIST OF SYMBOLS

Symbol	Definition	SI units
D	diffuse-beam short-wave radiation flux density	$W\ m^{-2}$
K^*	net short-wave radiation flux density	$W\ m^{-2}$
$K\downarrow$	incoming short-wave radiation flux density	$W\ m^{-2}$
$K\uparrow$	reflected short-wave radiation flux density	$W\ m^{-2}$
L^*	net long-wave radiation flux density	$W\ m^{-2}$
$L\downarrow$	long-wave radiation flux density from the atmosphere	$W\ m^{-2}$
$L\uparrow$	long-wave radiation flux density emitted by the surface	$W\ m^{-2}$
Q	total heat input by a city to the atmosphere	$W\ m^{-2}$
Q^*	net all-wave radiation flux density at the surface	$W\ m^{-2}$
Q_E	latent heat flux density	$W\ m^{-2}$
Q_F	anthropogenic heat flux density	$W\ m^{-2}$
Q_G	sub-surface heat flux density	$W\ m^{-2}$
Q_H	sensible heat flux density	$W\ m^{-2}$
S	direct-beam short-wave radiation flux density	$W\ m^{-2}$
T	temperature	K (°C)
U	representative canyon wind speed	$m\ s^{-1}$
U_R	reference wind speed	$m\ s^{-1}$
V_G	gradient wind speed at the height z_G	$m\ s^{-1}$
W	canyon width	m
Z_o	roughness length for the canyon layer	m
a	power law wind profile index	
c_p	specific heat of air at constant pressure	$J\ kg^{-1}K^{-1}$
d	zero-plane displacement	m
h^*	height of the surface mixed layer	m

Symbol	Definition	SI units
h'	height above which building and street wind profiles are similar	m
h_b	building height	m
$\bar{u}$	mean horizontal wind speed	m s^{-1}
u'	instantaneous deviation of horizontal wind speed from the mean	m s^{-1}
$\bar{w}$	mean vertical wind speed	m s^{-1}
w'	instantaneous deviation of vertical wind speed from the mean	m s^{-1}
x	distance of urban fetch from the upwind urban/rural boundary	m
z	height	m
z_G	depth of frictional influence of the surface	m
z_R	reference height	m
z_o	surface roughness length	m
α	surface albedo	
β	Bowen's ratio	
Δ	finite difference	
ΔQ_S	rate of energy storage change by a volume per unit horizontal area	W m^{-2}
ρ	air density	kg m^{-3}
σ	Stefan-Boltzmann constant	W m^{-2} K^{-4}
θ	potential temperature	K (°C)
ε	surface emissivity	
ϕ	population of a city	

Subscripts

o	surface
u	urban
r	rural
z	height

REVIEW OF URBAN CLIMATOLOGY,

1973-1976

by

Professor T. R. OKE

Department of Geography, University of British Columbia,
Vancouver, B.C., Canada

INTRODUCTION

This report deals with developments in the field of urban climatology that have occurred subsequent to those covered in WMO Technical Note (TN) No. 134 (Oke, 1974). Figure 1 shows that the period since 1968 has been characterized by an exceptionally large outpouring of publications in the field. It shows the first real growth in the subject to have occurred in the 1920's, mainly in Europe (e.g. Ashworth, Ångström) followed by a major expansion in the 1930's especially in Germany and Austria (e.g. Albrecht; Kratzer; Lauscher; Peppler; Schmidt), also in France (Besson) and North America (Brooks). Following a relative hiatus in the Second World War there was steady growth in the 1950's and early 1960's on a much wider geographic basis (e.g. Arakawa; Chandler; Georgii; Landsberg; Mitchell; Sundborg). The sudden surge at the end of the 1960's through into the 1970's coincided with increasing concern over the state of the atmospheric environment, especially with regard to air pollution in cities.

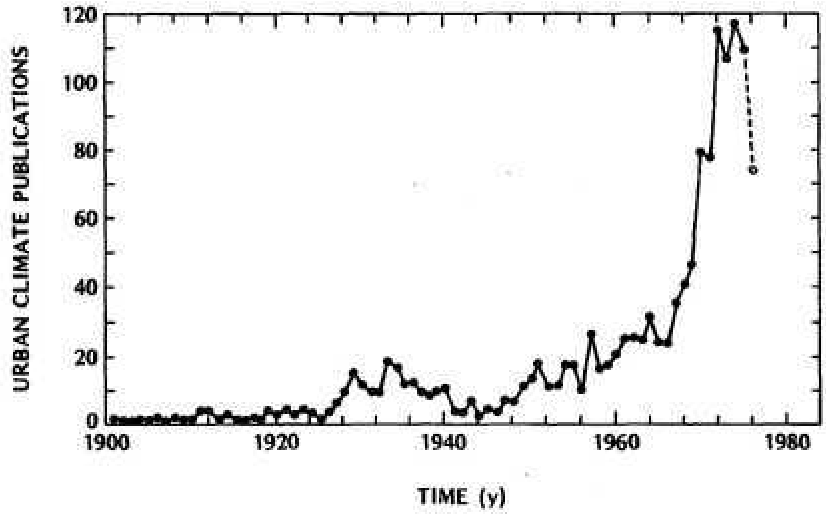

Figure *1 - Trend of total publications in urban climatology (excluding air pollution) in the twentieth century. [Compiled from Chandler (1970), WMO (1970), Oke (1974) and the bibliography of this report.]*

The upsurge was also associated with a change in methodology, away from the descriptive climatological tradition towards a more physically-oriented approach. The latter seems to have gained special impetus from the need to develop numerical models of the urban atmosphere which can be interfaced with air pollution dispersion models for predictive purposes. Munn (1973) suggests that the 1968 WMO Brussels Symposium on Urban Climates may have provided the stimulus for the step-change in research interest.

During the period under review there have been a number of conferences dealing at least in part with urban climates. These include:

CIB/WMO, "International Symposium on the Climatology of Building", Zurich, September, 1974.

AMS/WMO, "Symposium on Atmospheric Diffusion and Air Pollution", Santa Barbara, 1974.

AMS, "Fourth Conference on Weather Modification", Fort Lauderdale, 1974.

AMS, "Workshop on Modelling the Urban Boundary Layer", Las Vegas, May, 1975 (Lee et al., 1976).

UN Conference on Human Settlements (HABITAT), Vancouver, 1975.

AMS/USDA (Forest Service)/SUNY, "Conference on Metropolitan Physical Environment", Syracuse, August, 1975 (Herrington and Heisler, 1976).

NORDFORSK, "Workshop on Urban and Mesoscale Meteorology", Uppsala, October, 1975.

WERC/NSF, "Second US National Conference on Wind Engineering Research", Fort Collins, 1975.

WMO, "Symposium on Meteorology as Related to Urban and Regional Land-Use Planning", Asheville, November, 1975.

AMS, "Third Symposium on Atmospheric Turbulence, Diffusion and Air Quality", Raleigh, October, 1976.

WMO, "Meeting on Education and Training in Meteorological Aspects of Atmospheric Pollution and Related Environmental Problems", Research Triangle Park, January, 1977.

Royal Meteorological Society (Australian Branch), "Conference on Urban Meteorology", Sydney, February, 1977.

This review is organized in the same manner as TN 134 and is therefore an extension of it. The references from the two provide an almost complete bibliography of research in urban climatology from 1968 to 1976. There are two exceptions to be noted: first, TN 134 did not review the contents of TN 108 (WMO, 1970); second, this report may be deficient in respect of some publications in 1976 since the major abstract lists for this year were not available at the time of writing (April, 1977). This will be most noticeable for work in languages other than English.

During the period of concern there have been other reviews of the field. These include Bergstrom (1976), Berlyand and Kondrat'yev (1972), Braham (1975), Chandler (1967b), Daigo and Nagao (1972), Frisken (1973), Landsberg (1974b, c, 1976b), Lowry (1975), Oke (1976b, 1977a), Schmid (1974) and

Terjung (1974a, b). Several recent textbooks have also included summaries including Griffiths (1976), Kawamura (1977), Smith (1975) and Yoshino (1975). In addition Lowry (1977) has provided a most important analysis of methodological approaches employed in the estimation of 'urban effects' on climate. He examines the commonly used estimation procedures such as urban/rural differences, upwind/downwind differences, urban/regional ratios, analysis of time trends and weekday/weekend differences. He points out a number of weaknesses in these estimators and proposes that the only measure which can be used with confidence is one involving the difference between urban and pre-urban observations stratified by synoptic weather type. His analysis undoubtedly casts very real doubts concerning the existence or magnitude of certain 'urban effects' claimed in the literature. Readers of this review should bear these comments in mind.

Following Oke (1976a) the terms <u>urban canopy</u> and <u>urban boundary layer</u> are used to distinguish between the layers below, and above, roof-level respectively.

As with TN 134 this report does not provide a complete historical perspective, nor does it consider air or noise pollution in cities. The review is in two related parts: first, it considers observational studies aimed at a description of the processes and phenomena characteristic of urban climates; and second, it looks at attempts to model these features. The observational section considers work on the flows of energy and mass in the urban system and how these are manifest as urban temperatures, humidities, winds, cloud, etc. The modelling section examines developments in both scale and numeric simulation techniques. In each case it is only possible to highlight the most important advances in the text, but a comprehensive bibliography is provided at the end.

PART I - OBSERVATIONAL STUDIES

A. RADIATION BUDGET

1. Short-wave radiation

The short-wave (0.3 to 3.0 μm) radiation budget for a surface such as that represented by an urban area viewed from above roof-level is given by:

$$K^* = K\downarrow - K\uparrow \tag{1}$$

where, K^* - net short-wave radiation, $K\downarrow$ - incoming short-wave (global) radiation, and $K\uparrow$ - short-wave radiation reflected by the surface. The incoming term is composed of both direct-beam (S) and diffuse-beam (D) radiation, i.e.:

$$K\downarrow = S + D, \tag{2}$$

and the outgoing portion is a function of $K\downarrow$ and the surface albedo (α):

$$K\uparrow = (K\downarrow)\alpha. \tag{3}$$

It is well recognized that the more polluted urban atmosphere leads to an attenuation of $K\downarrow$ relative to that observed in cleaner rural air nearby, although it is often difficult to make true urban/rural comparisons because of the transport of pollutants downwind of the city. Further verification of this depletion has been provided by studies in Cincinnati (Bach, 1973), Hamilton, Ont. (Rouse et al., 1973), Windsor, Ont. (Sanderson et al. 1973; Sanderson 1974), Tokyo (Sekihara, 1973), Toronto (Yamashita, 1973, 1974), St. Louis and Los Angeles (Peterson and Flowers, 1974), Bet Dagan, Israel (Manes et al., 1975) and Adelaide (Lyons and Forgan, 1975). In almost all cases the reduction was noted to be quite variable depending on such factors as the wind direction, amount of cloud, time of year, and averaging period. Peterson and Flowers (1974) noted that on cloudless summer days at St. Louis $K\downarrow$ was decreased by about 2 to 3%, but when cloudy days were included the reduction was greater than 6% for a 28-day period. They suggest that this may be related to the effect of the city in producing more, or denser clouds. Manes et al. (1975) analyzed a 10-year record of $K\downarrow$ at Bet Dagan and found that there was a clear decrease (4%) using only summer data, but a greater reduction still (7%) if only cloudless summer data were included. They indicate that this seems consistent with increasing pollution transport from the Tel-Aviv area which lies upwind of Bet-Dagan. Presumably cloudless summer conditions are conducive to the build-up of photochemical products which are then advected downwind. Yamashita (1973) shows that the reduction of solar radiation can be related to SO_2 values by the cosine of the altitude of the Sun. This combines the facts that attenuation is affected by both the pollutant concentration and the path length of the solar beam through the urban layer.

In general, it appears as though urban-rural $K\downarrow$ differences are somewhat smaller than those reported in earlier studies (i.e. 2-10% rather than 10-20% reduction). This may be due to changes in the nature of aerosols as a result of different sources and/or the effects of pollution controls.

Recent studies on the reduction of ultra-violet radiation (approximately 0.30 to 0.40 μm) confirm that the urban atmosphere tends to preferentially filter out this waveband. Using one year of data in Cincinnati Bach (1973) found an average weekend/weekday difference of about 29%. He also compared measured ultra-violet irradiance with that calculated from theory for a 'clean' atmosphere under different meteorological conditions. Differences ranged from a 30% attenuation with good ventilation and low pollution, to more than 80% with light winds and smoggy conditions. These comparisons were made in the autumn when solar intensities should have been sufficient to trigger photochemical activity. In Los Angeles, Peterson and

Flowers (1974) observed a depletion of 25 to 35% in ultra-violet irradiance over a 2 month period in the autumn, although they noted considerable non-uniformity in time and space. They report a good correspondence between variations in the ultra-violet measurements and those of aerosols as indicated by nephelometer and turbidity data. In Tokyo, Sekihara (1973) found a decrease of 10 to 15% in ultra-violet, visible (approximately 0.40 to 0.70 μm) and a small portion of near infra-red radiation (0.70 to 1.2 μm). The similarity of behaviour at all wavelengths is somewhat surprising and may be fortuitous (for example due to a changing mix of pollutants with time). The point deserves more attention.

The Complete Atmospheric Energetics Experiment (CAENEX) is one of the major contributions made by scientists from the Soviet Union towards the Global Atmospheric Research Programme (GARP). In 1972 (CAENEX-72) (Kondrat'yev and Orlenko, 1972; Kondrat'yev, 1973; Kondrat'yev et al. 1973; Berlyand et al. 1974) the experimental location was the city of Zaporozhye. The work was mainly concerned with radiative transfer in a polluted urban atmosphere. In the context of GARP it was suggested that, in the absence of advection, the city might provide a good model of the influence of pollution upon the global climate. The radiative characteristics of the surface and atmosphere of Zaporozhye and a rural site 30 to 50 km away were observed using multi-level aircraft traverses (at heights of 0.5, 1.3, 2.85, 5.5 and 7.2 km) and ground-based stations.

CAENEX-72 data indicate that short-wave flux convergence in the total planetary boundary layer is greatest at midday. At this time short-wave convergence in the lowest 0.5 km of the urban atmosphere is about $0.1^{o}C\ h^{-1}$ greater than in rural air. The absolute all-wave convergence was about $0.4^{o}C\ h^{-1}$ of which the long-wave component contributed about $0.03^{o}C\ h^{-1}$ (Berlyand et al. 1974). The spectral characteristics of both incoming and outgoing short-wave radiation in the band 0.1 to 0.9 μm were also measured, and a 'spectral radiant heat flux' computed for the 0.5 to 7.2 km layer in both environments (Figure 2). This clearly shows the greater convergence in the urban case to apply at all wavelengths, and that the aerosols preferentially absorb the shorter wavelengths. Aspects of the albedo and long-wave radiation results from CAENEX-72 will be summarized later.

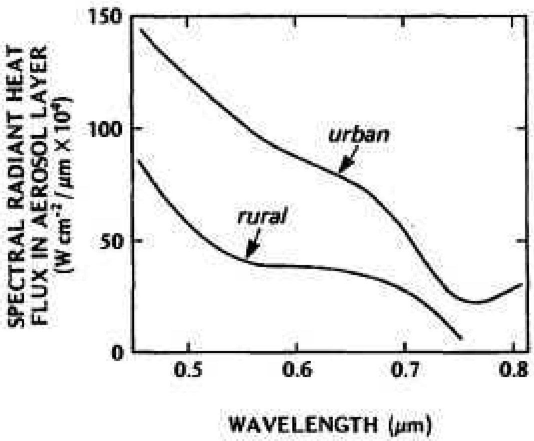

Figure *2 - Spectral radiant heat fluxes in the 0.5 to 7.2 km layer of the atmosphere over the city of Zaporozhye and a rural area 30 to 50 km distant. Time averages corrected for solar zenith angle during the daytime of August 22, 1972 (after Berlyand et al., 1974)*

Glazier et al. (1976) also investigated the role of aerosols in boundary layer heating and cooling. Instead of using measured radiative profiles they calculated the total convergence of heat below subsidence inversions in Britain using radiosonde ascents, and estimated the contributions due to sensible heat from the surface using energy balance measurements. Absorption and backscattering of short-wave radiation by aerosol was calculated from ground-level measurements of S, and long-wave convergence/divergence was estimated from charts using the radiosonde data. Their results suggest that aerosol absorption in stable air masses can be significant, and sometimes dominant in the radiative balance of the boundary layer. Averaging data for 5 summer days they find the following contributions to the daytime heating rate:

Process	Heating rate ($^{o}C\ h^{-1}$)
Convergence of short-wave:	
gases	1.1
aerosol	3.3
Divergence of long-wave:	-1.3
Sensible heat from ground:	5.2
Net heating	8.3

Thus aerosol can contribute 40% of the net heating during the day. It should also be realized that these are not urban results but refer to conditions found in a moderately turbid atmosphere. Although it might be initially assumed that in the urban case with higher pollution concentrations the aerosol warming effect would be greater, Glazier et al. (1976) point out that this may not necessarily be so. They note that the net thermal effect of aerosol consists of two distinct processes:

(i) the extra absorption leading to atmospheric warming

(ii) the decrease in sensible heat flux to the atmosphere (Q_H) caused by a decrease in the net all-wave radiation at the surface (Q^*), assuming the surface radiative properties remain constant.

Therefore for a given increase in aerosol the net effect will depend upon the surface albedo and the surface energy balance partitioning between sensible and latent heat. They suggest that over extensive moist surfaces (e.g. oceans and forests and farmland with free water availability) the net effect is likely to be warming, but over drier areas (possibly including conurbations) aerosol may actually decrease the net heat input to the atmosphere by suppressing the sensible heat flux. It should, however, be noted that long-wave radiative effects were neglected in the analysis, and that linear aerosol absorption and backscattering coefficients were employed.

There remains a great need for detailed studies on the radiative properties of aerosols. There is a considerable volume of work emerging on the planetary scale but it often relies on assumed coefficients for absorption and scattering. On the urban scale Lyons and Forgan (1975) compared $K\downarrow$, S and D from urban and rural sites of Adelaide and concluded that the major role of pollutants is to increase scattering rather than absorption. Their results are in agreement with those of Mani et al. (1974), but contrary to the suggestion by Lettau and Lettau (1969) that the ratio of aerosol absorption to scattering is greater than unity for a city. Using cloudless sky data Wesely and Lipschutz (1976) showed that with increasing turbidity S decreased and D increased. In extreme cases S was reduced by greater than 50% (solar zenith angles 55 to 65 degrees) compared with 'background' levels found with 'clean' skies. The gain in D compensated for the loss of S by an amount that varied from 58% of the loss at a solar zenith angle of 65 degrees to 70% at 37.5 degrees. Refinement of our understanding of the effects of pollutants upon short-wave radiation receipts also holds the promise of techniques to indirectly assess particulate and gaseous concentrations (Sprigg, 1974; Wesely, 1975), and possibly the mixing depth (Moses and Eggenberger, 1973).

Research into the albedo (α) characteristics of urban areas is progressing slowly but recent studies have enhanced our knowledge at a number of scales. Nunez (1975) took measurements in a north/south oriented urban canyon in Vancouver. When viewed from above, the average albedo of the total canyon-system exhibited a complex diurnal pattern. Further it was shown that the albedo of the canyon-system was always less than that of an equivalent surface area composed of similar materials, but placed in the horizontal. This tends to support the view that the effect of urban geometry is to increase short-wave radiation trapping and thereby to decrease the albedo. In the canyon surveyed this led to a 20 to 50% increase in absorption.

On the integrated urban scale, albedos have been measured from airborne platforms over St. Louis (Dabberdt and Davis, 1974a, b) and Zaporozhye

(Berlyand et al. 1974). In the St. Louis study urban/rural α differences were about 0.03 (older urban areas 0.13, rural 0.16). These values are in approximate agreement with the summary table of albedos presented in TN 134. Similarly the CAENEX-72 results for Zaporozhye show the city albedo to be lower by a maximum of 0.03 to 0.05 in the morning. At this time the urban albedo was 0.20, later α was noted to decrease with decreasing solar zenith angle. The urban/rural difference in albedo was only detectable to altitudes of 3 km. Further it was found that the reflectivity (spectral reflectance) of the central city is less than that of its suburbs at all wavelengths in the range 0.3 to 1.7 μm.

Finally, Lunde (1977) shows that the radiance of urban areas is different to that of rural areas using LANDSAT satellite imagery. The cities of Ames and Des Moines, Iowa show higher radiance in the band from 0.5 to 1.1 μm during the summer, and lower radiance in the winter when the rural areas are often snow-covered. The summer result appears to be at variance with the CAENEX-72 findings.

2. Long-wave radiation

The long-wave radiation (3 to 100 μm) budget for a surface is given by:

$$L^* = L\downarrow - L\uparrow \tag{4}$$

where, L^* - net long-wave radiation, $L\downarrow$ - incoming long-wave radiation from the atmosphere, and $L\uparrow$ - outgoing long-wave radiation emitted by the surface and given by:

$$L\uparrow = \varepsilon\sigma T_o^4 \tag{5}$$

where, ε - surface emissivity, σ - Stefan-Boltzmann constant, and T_o - surface temperature.

There are very few studies which demonstrate the magnitude of these terms for cities, probably because of the difficulty of obtaining representative measurements. Studies reviewed in TN 134 suggested that $L\downarrow$ is greater from the urban atmosphere. At night urban/rural differences appear to be small (Oke and Fuggle, 1972) but, at least in one study, the daytime differences were considerable with a peak at the time of low solar zenith angles (Rouse et al., 1973). Most recently, Sanderson (1974) and Brazel and Osborne (1976) report observations of $L\downarrow$ from an urban site in Windsor, Ont. Their results also exhibit a diurnal variation with a marked midday peak. Brazel and Osborne compared their observed values with those computed using empirical formulae and found the midday measurements were substantially underestimated. They partially attribute such deviations to the presence of urban pollutants.

The CAENEX-72 urban/rural overflights provide some of the first information available concerning $L\uparrow$ (Berlyand et al., 1974). They report that most of the city of Zaporozhye emits less $L\uparrow$ than its environs during the daytime, but this is reversed at night. These results appeared to agree with those from a radiation thermometer used to measure surface radiation temperatures (in the 8 to 12 μm band), which showed the city to be radiatively 'cooler' than its surroundings by day, but warmer at night. The differences were observable in flights up to an altitude of 3 km by day. The observation of higher radiation temperatures in the urban area at night is consistent with a number of similar studies (e.g. Dabberdt and Davis, 1974a, b; Tsuchiya, 1974; Landsberg, 1975b; Stock, 1975) but the daytime 'coolness' is less expected.

Yap (1975a) provides some interesting thoughts on the role of surface emissivities in net long-wave radiation differences between urban and rural areas at night. Using equations (4) and (5) for the two environments the urban/rural net long-wave raidation differential (ΔL^*_{u-r}), which equals the net all-wave difference (ΔQ^*_{u-r}) at night, is given:

$$\Delta L^*_{u-r} = \Delta L\downarrow_{u-r} - (\varepsilon_u \sigma T_u^4 - \varepsilon_r \sigma T_r^4). \qquad (6)$$

As already mentioned, $\Delta L{\downarrow}_{u-r}$ nearly always seems to be a small positive value at night, and if $\varepsilon_u = \varepsilon_r = 1$ (i.e. the urban and rural surfaces are acting as full radiators), then $(\varepsilon_u \sigma T_u^4 - \varepsilon_r \sigma T_r^4)$ is usually greater than $\Delta L{\downarrow}_{u-r}$, so that ΔL^*_{u-r} is negative. In other words, the greater loss from the warmer urban surface usually outweighs the slightly greater urban atmospheric input, resulting in a greater net loss in the urban area. However, if $\varepsilon_u < \varepsilon_r$ by a small amount (Yap uses $\varepsilon_u = 0.92$ and $\varepsilon_r = 0.98$) it is possible for ΔL^*_{u-r} to be positive so that the urban radiation losses are less than those from the rural surroundings. The size of these differences depends upon the absolute temperature and the urban/rural temperature differential (i.e. the urban heat island intensity, ΔT_{u-r}).

Evidence is also emerging on the role of long-wave radiative flux convergence and divergence in the thermal balance of urban air layers. Berlyand et al. (1974) discovered long-wave heating of the lowest 1.35 km of the urban atmosphere over Zaporozhye during the daytime. On some afternoon occasions they report that the warming (convergence) approaches that due to short-wave absorption. Weak heating was retained in the lowest 0.5 km in the evening but was replaced by cooling later in the night. Fuggle and Oke (1976) took long-wave flux divergence measurements in the layer 4 to 5.5 m above roof-level in Montréal. The study was restricted to nocturnal conditions and, on all occasions, the radiative cooling rate exceeded the measured air temperature changes. This situation is approximately in agreement with that in rural areas under similar weather conditions (mainly cloudless skies and weak airflow). On the other hand, a similar study within an urban canyon under these conditions showed quite different behaviour (Nunez and Oke, 1976). The radiative cooling of the canyon air volume was conspicuously less than the rates typical of the above-roof study. Such changes in the role of radiation could well lead to differences in the observed cooling rates between urban canyon, urban above-roof, and rural environments and have an important bearing upon heat island characteristics. With weak winds, air in the canyon becomes almost stagnant. Turbulence is therefore almost absent and air temperature change is dominated by radiative flux divergence (i.e. the radiative and actual cooling rates are almost equal). These studies do not yet provide an integrated view of the role of radiation in air temperature changes but they do hold promise of helping to elucidate cause-and-effect linkages.

3. <u>All-wave radiation</u>

Finally, if we combine equations (1) and (4) we obtain the surface all-wave radiation budget equation:

$$Q^* = K^* + L^*. \tag{7}$$

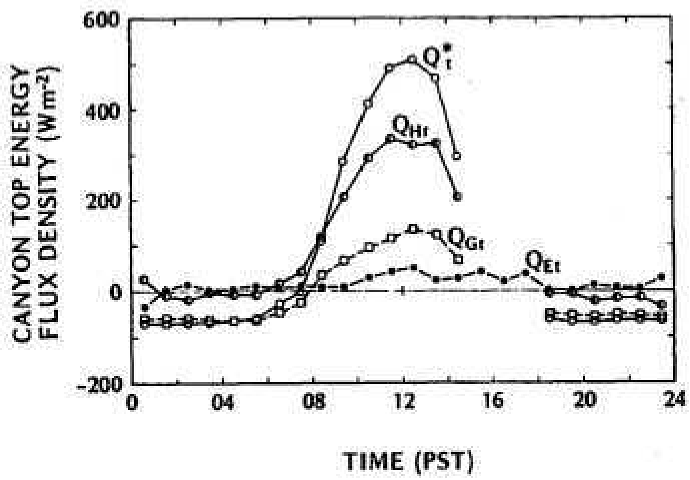

Figure 3 - *Diurnal energy balance of a canyon system expressed as equivalent fluxes through the canyon top. Mean hourly values for the 3-day period September 9-11, 1973 in Vancouver, B.C. Cloudless skies and light winds prevailed throughout the period (after Nunez and Oke, 1977)*

There are few recent observational studies of Q* in the urban context, and virtually none relating to ΔQ^*_{u-r}. Nunez (1975), and Nunez and Oke (1976, 1977) provide results within an urban canyon in Vancouver. They show that although the urban geometry causes phase shifts in the diurnal pattern of

Q^* for individual canyon components (walls and floor), the budget for the complete canyon system exhibits a reasonably smooth and symmetric distribution (Figure 3). The absolute magnitude of Q^* at the top of the canyon by day is similar to that observed in other studies above roof-level at the same time of year. The nocturnal budget shows a slightly smaller rate of radiative heat loss which may be due to reduced sky view factors. Tuller (1973) also provides measurements of the radiation budget components in residential and downtown locations of Victoria, B.C. He used sidewalk sites with predominantly north, south, east and west exposures. Results illustrate the complex pattern of receipt found in a canyon and the changes experienced by each of the component fluxes.

In terms of overall urban/rural comparisons there appears to be little reason to change the synopsis given in TN 134. This showed that although all of the individual radiation streams ($K\downarrow$, $K\uparrow$, $L\downarrow$ and $L\uparrow$) are modified by urbanization, the net effects are small because of a fortuitous off-setting arrangement. Thus although $K\downarrow$ is attenuated, surface short-wave absorptivity is increased and therefore net short-wave differences (ΔK^*_{u-r}) are likely to be small. Evidence suggests that for a large mid-latitude city in summer K^*_u is slightly smaller than K^*_r. The reverse is, however, quite possible if, for example, the city has a low pollutant loading (because of low emissions or excellent dispersion), or the albedo of the environs is relatively high (such as in winter when the rural snow cover is more complete than in the city, or if the city is set in a semi-arid landscape). Similar off-setting occurs in the case of long-wave budget comparisons (ΔL^*_{u-r}). Despite $L\downarrow$ being greater over the city, the greater warmth of the city also usually gives greater $L\uparrow$ (however, note that the daytime CAENEX-72 results suggest $L\uparrow_u < L\uparrow_r$). Normally it is expected that L^*_u is slightly greater than L^*_r. Combining these changes, it appears both qualitatively, and from observations reviewed in TN 134 that ΔQ^*_{u-r} is usually small but that there is a tendency for the city to have a slight radiative deficit in comparison with the countryside at all times.

B. ENERGY BALANCE

The energy balance for an extensive integrated urban 'surface' (e.g. a plane at about roof-level) may be written:

$$Q^* + Q_F = Q_H + Q_E + Q_G \tag{8}$$

where, Q_F - anthropogenic heat flux due to combustion, Q_H, Q_E - turbulent sensible and latent heat fluxes respectively, and Q_G - sub-'surface' heat conduction. If the energy balance applies to a soil/building/air volume (e.g. extending from roof-level down to a depth where heat fluxes are negligible over the time period concerned) then Q_G should be replaced by ΔQ_S representing the net rate of energy storage change in the volume.

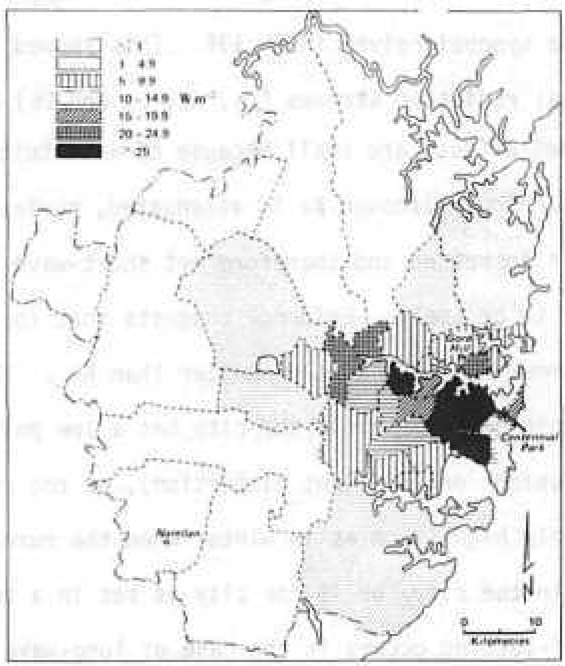

Figure 4 - *Spatial pattern of anthropogenic heat output for Sydney, Australia in July. Data are for 07 to 09 h on an average day (after Kalma, 1974)*

At all times the anthropogenic heat term represents a net energy source for the system. It is usually calculated on the basis of fuel consumption data. If the energy balance is being measured it enters into all of the other flux observations (radiant, turbulent and conductive). The magnitude of Q_F on a seasonal and annual basis was summarized in TN 134, and in the interim there have been a number of studies concerned with the possible climatic impact of these releases on the urban, regional and global scales (Geiger, 1974; Kalma, 1974; Kutzbach, 1974; Landsberg and Machta, 1974; Sawyer, 1974; Bolin, 1975 and Kalma and Byrne, 1976).

Kalma (1974) provides a map of the Q_F distribution for Sydney, Australia in winter (Figure 4) and used it to assess the thermal modification of the urban boundary layer for different fetch directions. Kalma and Byrne (1976) produced a similar map for Hong Kong. Geiger (1974) established that the energy releases from domestic and commercial uses in Munich follow an exponential decrease with distance from the city centre. Further he noted that similar relationships held for both 1960 and 1970 data with different slopes. Kalma and Byrne (1976) also show the diurnal variation of Q_F for Sydney. The pattern is characterized by a nighttime minimum and two daytime peaks at approximately 07 to 09 h and 15 to 17 h. Most authors agree that concentrated heat releases in urban areas are already capable of exerting a climatic impact, and by about 2050 AD it is possible that they may be sufficient to impart synoptic-scale modification (Kutzbach, 1974).

Research into the partitioning of energy into the terms on the right-hand side of equation (8) is not progressing rapidly. About the only recent measurements available to characterize the urban 'surface' are those of Yap and Oke (1974) from Vancouver, B.C.. Direct measurement of Q^* and Q_H above the city, and the use of roof heat flux plates to approximate Q_G (or ΔQ_S) left Q_E as a residual in the energy balance. Under ideal summer conditions (cloudless, winds < 6 m s^{-1}, moist soil) the diurnal partitioning was as in Figure 5. Probably the most interesting feature is the fact that $Q_E > Q_H$ throughout the day (i.e. Bowen's ratio $\beta = Q_H/Q_E$ is less than unity). In the Vancouver study Q_H dropped to as low as $0.25Q^*$ following rain, and increased to greater than 0.60Q* after a dry period. In the example given in Figure 5 Q_H was 0.34Q* over the period shown. The surface was probably

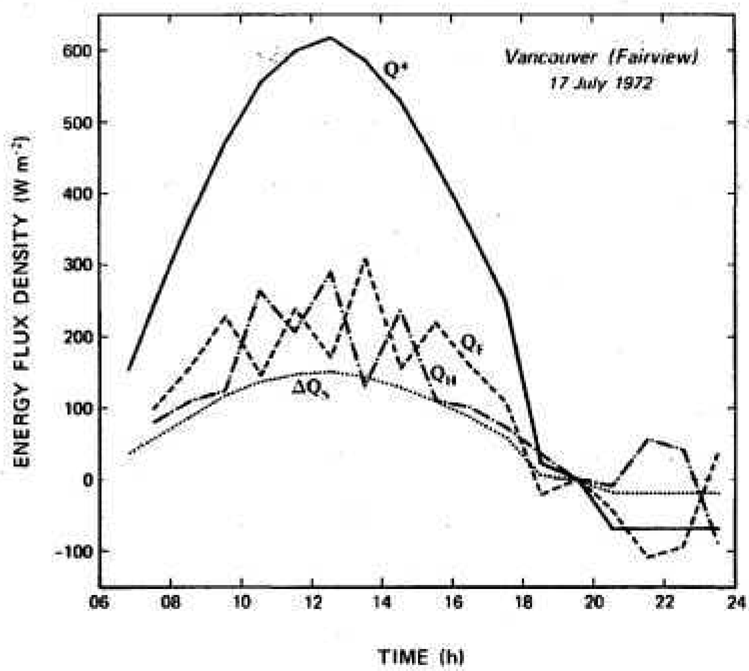

Figure 5 - *Urban energy balance variation on July 17, 1972 in Vancouver, B.C. (after Yap and Oke, 1974)*

moister than usual, due to a storm 5 days prior to these observations, but the study suggests that in general urban evapotranspiration is not negligible. This contradicts the view that cities are 'dry' (even desertic). Marotz and Coiner (1973) had earlier speculated that urban latent heat fluxes were being underestimated because most workers had a poor conception of the amount of natural surface area left in cities, and because of widespread urban irrigation.

Dabberdt and Davis (1974a, b) attempted to estimate urban energy partitioning in St. Louis using aircraft traverses supplemented by ground stations. These measured and parameterized data were used as input to a climatonomic model whose output included calculated values of the surface thermal admittance and the inverse Bowen ratio (β^{-1}). They conclude that the derived values are reasonable and that with improved aircraft operations the approach is worthy of further development. Rauner and Chernavskaya (1972) similarly provide a study of synthetic urban energy balances, and the thermal effects of varying urban green space, by parameterizing the fluxes in terms of net radiation and potential evapotranspiration over a variety of surfaces. Schüepp (1974) provides a general discussion of anticipated rather than measured energy balance changes attributable to urbanization.

Nunez and Oke (1976, 1977) provide the first measurements of the diurnal energy balance within an urban canyon. The radiant and conductive heat flows for the walls and floor and the evapotranspiration from the floor were measured directly, and the sensible heat flux to/from the air was solved by residual. The timing and magnitude of the energy régimes for the different surfaces were very different and were controlled by the influence of the canyon geometry on the radiation exchanges. The diurnal pattern for the canyon system on the other hand was relatively smooth and symmetric (Figure 3). By day, approximately 60% of the radiant surplus was dissipated as Q_H, 25 to 30% as Q_G and 10 to 15% as Q_E. Since the observations were made at the end of a dry period the balance is likely to represent close to the upper limit for sensible heat production. Only areas totally devoid of moisture sources are likely to show less latent heat use. At night, canyon winds were almost calm and therefore the radiant deficit was almost totally balanced by heat released from sub-surface storage. The magnitude of advective exchanges within the canyon were also assessed.

C. WATER BALANCE, CLOUD AND PRECIPITATION

Aspects of the urban water balance are dealt with by two groups: the hydrologist-engineer, and the atmospheric scientist. The former are most interested in the response of the city surface to storm input, the storage in groundwater, the supply of water from reservoirs and water quality. The latter are concerned with the city as a source or sink for atmospheric vapour and the possible effects of the city in enhancing precipitation. Unfortunately, it appears that the two groups do not mesh very easily and there is as yet no integrated study which properly relates all of the components.

In terms of urban climate the three most easily identifiable concerns are the nature of anthropogenic vapour releases, the change in the surface evapotranspiration régime, and effects upon precipitation. At present, research in these subjects is rather uneven. Anthropogenic vapour releases have recently been calculated from fuel inventories in New York (Tam and Bornstein, 1975), Edmonton (Hage, 1975), and St. Louis (Sisterson, 1975). In New York, releases were found to be sufficient to contribute to an urban moisture excess in the boundary layer. This also gave rise to a buoyancy excess which enhanced that provided by the heat island effect, and thereby strengthened the urban thermal circulation. In Edmonton, calculations suggest that anthropogenic releases can explain about 30% of the observed winter excess in humidity at night at temperatures of about $0^{o}C$. In the summer, the St. Louis anthropogenic sources were considered negligible by comparison with estimates of day-time potential evapotranspiration. At night, on the other hand, these releases were considered capable of contributing to an urban atmospheric moisture excess.

The subject of urban evapotranspiration was reviewed in connection with latent heat fluxes in section B. Basically the field remains poorly researched.

If one were to single out one field of urban climatology that has shown the most significant advance since the TN 134 review it would have to be that of urban precipitation, and the major thrust in this development has come from the Metropolitan Meteorological Experiment (Project METROMEX) centred on St. Louis. The field phase of this multi-institutional project covered the period 1971 to 1975. The analysis (interpretation and reporting) is continuing, but already there are many important findings. The present review relies heavily upon a METROMEX Update statement provided by the participants (Principal Investigators of Project METROMEX, 1976). The statement has been edited to include more recent work and to exclude preliminary reports and items not referring to cloud, precipitation or water resources if they are covered elsewhere in this review. The statement is organized under three sub-headings: definition and description of urban-related precipitation anomalies; process studies related to the development of anomalies; and impacts of anomalies.

1. Definition and description of anomalies

(a) There is a summer precipitation anomaly at St. Louis, varying between a 10 and 30% excess above background. The location and intensity of the anomaly vary with the prevailing seasonal storm motions and the general character of the summer weather (Huff and Changnon, 1973; Huff and Schickedanz, 1974; Changnon, 1976b). The anomaly trend has been upward and agrees with similar trends for Paris and Chicago over the last century (Dettwiller and Changnon, 1976).

(b) Some individual rain intensity centres of showers or thunderstorms that develop or pass over St. Louis and over the Alton-Wood River industrial area appear to be significantly enhanced by 94 and 73% respectively (Schickedanz, 1974).

(c) The major precipitation changes in, and east of, the urban industrial area seem to occur during squall line or squall zone conditions which would normally produce moderate to heavy rain even without inadvertent enhancement. Anomalies include an increase of at least 60% in the number of heavy rain days ($\geq$ 30 mm) (Huff and Schlessman, 1974), a 25% increase in thunderstorm activity, and an 80% increase in hailstorms and hail intensities in and just east of the city (Changnon and Huff, 1973). Radar studies show a region of maximum development of large thunderstorms extending 100 km northeast from the city (Braham et al., 1975; Dungey et al., 1974).

(d) The city has a marked heat island and a specific humidity deficit extending through the mixing layer to cloud-base level. Light wind flow is perturbed over the city producing convergence over or downwind of the urban centre.

(e) The source strength of Aitken condensation nuclei (ACN) for St. Louis is $5x10^5$ cm^{-2} s^{-1} with industrial sources up to $3x10^6$ cm^{-2} s^{-1} (Auer and Dirks, 1974; Auer, 1975b). The corresponding strength of cloud condensation nuclei (CCN) is 1 to $4x10^4$ cm^{-2} s^{-1} (Spyers-Duran, 1972a, 1974; Braham, 1974a; Auer, 1975b). The city does not seem to be a significant source of ice forming nuclei (IFN), in fact it may 'poison' the naturally occurring IFN (Braham, 1974a, 1975; Braham and Spyers-Duran, 1974a, b).

(f) Convective storms are significant mechanisms for removal and deposition of urban pollutants.

2. <u>Process studies related to the development of anomalies</u>

(a) Tracer materials released at the surface are taken into clouds and appear in subsequent rain areas 5 to 35 km downwind of the release point (Gatz, 1974).

(b) Lagrangian measurements of transformation of the St. Louis aerosol suggest that gas-to-particle transformations involving existing nuclei play an important role in the growth of mass in the urban plume (Alkezweeny, 1975).

(c) The urban effluent is ingested by clouds, and the enhanced CCN levels result in urban clouds having more uniform droplet sizes (Braham, 1974; Fitzgerald and Spyers-Duran, 1973; Spyers-Duran, 1972a, 1974).

(d) Urban aerosols and urban-induced changes in cloud structure have been found as far as 80 km downwind of St. Louis (Dytch, 1974a, b).

(e) The city and certain industrial areas appear to be preferential sites for the initiation of small cumulus clouds (Auer, 1974, 1976; Uthe and Russell, 1974). The initiation of radar echoes and precipitation cells in summer cumulus indicates rapid initiation of the warm rain process and urban enhancement of it, probably as a result of giant nuclei from urban sources (Schickedanz, 1974; Semonin and Changnon, 1974a; Dytch, 1974a; Dungey et al., 1974; Braham et al., 1975).

(f) Convective cloud bases are generally higher by 300 to 600 m over the city (Cateneo, 1973a).

(g) Storms that have passed over St. Louis produce more large rain drops, and larger and more numerous hailstones. These results suggest alteration of the microphysical and dynamic processes leading to the storage of more water aloft in large cumulus clouds (Semonin and Changnon, 1974a).

(h) Day-time mixing heights are 'domed' up over the city, and the morning growth rate of this layer is faster than over rural areas (Spangler and Dirks, 1974; Ackerman and Appleman, 1974; Uthe and Russell, 1974). The typical diurnal variation of the mixed layer shows it to be typically < 1 km deep in the morning, rising to 2 km in the midday convection period, and lowering in the late afternoon or evening. Nearly 80% of the added rain in, and east of, the city occurred with mixing heights > 2 km (Semonin and Changnon, 1974a).

(i) Urban temperature and absolute humidity anomalies can bring about a decrease in the intensity of thunderstorms in the vicinity of the urban area (Boatman and Auer, 1974).

(j) Under certain synoptic conditions urban surface temperature anomalies can raise the mixing layer and displace it downwind, and in some instances can initiate local convection, clouds, and rainfall (Ochs, 1974, 1975; Auer and Dirks, 1974; Dirks and Wong, 1975).

3. Impacts of anomalies

(a) The increases of summer rainfall in downwind areas (10-30%) produce an average increase of 15% in streamflow (Changnon, 1973), and greater infiltration of ground water.

(b) Groundwater contamination has increased rapidly due in part to the deposition of pollutants scavenged from the urban plume (Changnon, 1973).

(c) There has been an increase in the annual average crop yields in the downwind zone (Changnon, 1973).

(d) Crop losses due to hail are greater in the area to the east of St. Louis (Changnon, 1973).

This wealth of new information requires careful synthesis so that the general picture is not obscured by detail. No doubt this is one of the aims of the principal investigators as the analysis draws to a conclusion. The METROMEX study has clearly established that an anomaly exists, and has reasonably defined its magnitude for St. Louis. It has also provided a large amount of evidence concerning the nature of the processes contributing to the anomaly. We are probably now on the threshold of providing a rational framework for causation of the anomaly, at least for the case of St. Louis. Two important papers that hypothesize upon causation are those of Braham (1975) and Changnon et al. (1976). The latter suggests that the greater frequency of rain initiation over urban and industrial areas is tied to three urban-related factors:

(i) thermodynamic effects which lead to more clouds, higher cloud bases and greater cloud instability,

(ii) mechanical and thermodynamic effects that produce confluence zones where clouds and rain initiate,

(iii) the enhancement of the cloud droplet coalescence process due to the addition of giant nuclei.

These factors appear to combine to initiate more cloud cells over urban-industrial regions in summer; this, in turn, increases the probability of cell merger (because there are more cells per unit area) and the likelihood of heavier rain.

Project METROMEX dominates the field of urban precipitation and cloud studies partially because of the sheer size of the undertaking, but most interesting work is also being undertaken elsewhere. For example Harnack and Landsberg (1975) and Atkinson (1975) studied selected case studies of convective precipitation in the vicinity of Washington, D.C. and London, U.K., respectively. In the Washington study, three rain events were selected to demonstrate the importance of thermal factors (heat island effects) in triggering events which probably led to anomalous rainfall distributions (determined from historical records). Parcel theory, using urban surface temperature and upper air soundings, permitted comparison between predicted and observed cloud behaviour. In all cases, urban thermal effects seemed to be the likely trigger force for shower development. Vertical wind data and cloud energetics led to the correct positioning of rainfall in eight of nine cases. In London, on the other hand, one rain event was intensively studied to determine the role of urban mechanical effects in triggering increased precipitation. Mechanical effects include the deepening of the boundary layer, increased forced convection, uplift due to frictional retardation, changes in airflow directions, etc. Analysis revealed a clear perturbation of the wind field over the city sufficient to produce uplift of about $0.1\ m\ s^{-1}$. This was capable of lifting the surface layer (which contained higher humidities and probably greater CCN than the rural air) through a height of 1 km in 2.5 h. This was sufficient to raise air in the lowest layers to saturation causing them to become absolutely unstable, and leading to a localized increase of precipitation. The Washington and London studies therefore converge with those from St. Louis since Braham (1975), in summarizing the METROMEX findings, states "it seems to me most likely that any urban effects upon rainfall are associated with cloud dynamical effects associated with the heat island and surface roughness."

Detwiler (1974) and Lyons (1974), both, show ERTS satellite images which clearly show urban-industrial effects on cloud form downwind of the Chicago-Hammond-Gary complex at the southern end of Lake Michigan. Detwiler shows several cumulus bands being spawned over these areas during a typical summer lake breeze period. On the other hand, Lyons shows that cumulus cloud formed over the relatively warm lake in early winter has cloud streets which are aligned with industrial plumes. In neither case is it possible to isolate the causative factors (such as additional heat, moisture, IFN or CCN) but the visual link with urban-industrial areas is useful additional proof of inadvertent weather modification.

D. WIND FIELD

Steady-state winds in the planetary boundary layer are governed by a balance of the horizontal pressure gradient force, the frictional stress, and the virtual force associated with Coriolis acceleration. Winds traversing urban areas encounter changes in the characteristics of the surface, and the atmosphere, which necessitate a new balance of forces compared with upwind (and downwind) rural areas. In particular, the existence of an urban heat island imposes a three-dimensional deformation of the pressure field and the rougher surface increases the frictional drag exerted on the airflow. These changes (and others) combine to cause modification of the wind speed (horizontal and vertical), wind direction, turbulence and other characteristics of boundary layer motions.

The increase in roughness is obvious and can be relatively easily modelled in wind tunnels but, as pointed out in TN 134, it is not easy to obtain reliable quantitative estimates of the surface roughness length (z_0) from urban measurements. Since that report, Shklyarevich (1974) reports that for Leningrad z_0 = 0.3 to 0.7 m, but that these figures may be low because the city is often characterized by weak instability rather than neutrality (the latter condition being necessary for proper specification of z_0 from wind profiles). Duchêne-Marullaz (1976) showed that z_0 at a suburban site in Nantes was strongly dependent upon the direction of fetch. His values encompassed the range from 0.4 to 2.3 m. Taken overall it seems that reasonable values for suburban terrain are about 1 to 1.5 m, and for central urban areas about 2 to 4 m (Table 1). Considering the problems associated with logarithmic wind profile analysis over urban areas it is

TABLE 1. Typical Values of the Power Law Parameters (z_G and a) for Three Categories of Surface Roughness (z_0) Based upon Measurements with Strong Winds and/or Neutral Stability

Terrain	z_0[1] (m)	z_G[2] (m)	a[1]
Open countryside	0.01-0.2	275	0.13-0.16
Woodland, suburbs, small towns	1.0 -1.5	400	0.20-0.23
Dense urban, city centre	2.0 -4.0	500	0.25-0.40

[1]Counihan (1975), see also Figure 6

[2]Penwarden and Wise (1975)

not surprising that for engineering purposes the simpler power law expression has gained favour (Newberry and Eaton, 1974; Counihan, 1975; Penwarden and Wise, 1975):

$$\bar{u}_z = V_G(\frac{z}{z_G})^a \tag{9}$$

where, $\bar{u}_z$ - mean horizontal wind speed at the height z, V_G - gradient wind speed at the height z_G (i.e. depth of frictional influence), a - empirical coefficient which depends on surface roughness (Table 1) and stability. Counihan (1975) provides an excellent review of the relation between a number of boundary layer wind characteristics including the relationship between the coefficient a and z_o in neutral stability (Figure 6). He further shows that in adiabatic conditions the intensity of longitudinal turbulence $((\sqrt{(\overline{u'^2})}/\bar{u})_{30m}$, where the prime indicates an instantaneous deviation from the mean wind) and the Reynolds stress $(\overline{u'w'}/\bar{u}^2_{z_R}$, where z_R is some reference height, and w is the vertical wind speed) can be related to z_o by the simple empirical form:

$$a = (\sqrt{(\overline{u'^2})}/\bar{u})_{30m} = (\overline{u'w'}/\bar{u}^2_{z_R})10^2$$

$$= 0.096 \log_{10}z_o + 0.016 (\log_{10}z_o)^2 + 0.24 \tag{10}$$

as shown in Figure 6. These relationships have been criticized for not using available theory but for practical use in the urban atmosphere, which is almost always close to being adiabatic, they seem useful.

Field evidence of the structure of turbulence over cities is limited although the recent work of Brook (1974a, b, 1975) in Melbourne, Arakawa and Tsutsumi (1975) in Tokyo, and Duchêne-Marullaz (1975a, c and 1976) in Nantes are beginning to make progress. The latter study involves direct measurements from 60 m masts at a suburban location. Derived terms include the power law index, intensity of longitudinal turbulence and turbulence spectra. Their characteristics can be related to height above ground and the upwind roughness, which varies with fetch. Preliminary results show agreement with Counihan's relationships involving z_o (equation 10). Panofsky (1975) provides computations of vertical diffusion coefficients as a function of height and time in the Los Angeles boundary layer. He finds that the diffusion coefficients increase rapidly with height in the surface layer, are extremely large in the layer from 50 m to about half of the mixing depth, and then decrease with height up to the top of this layer.

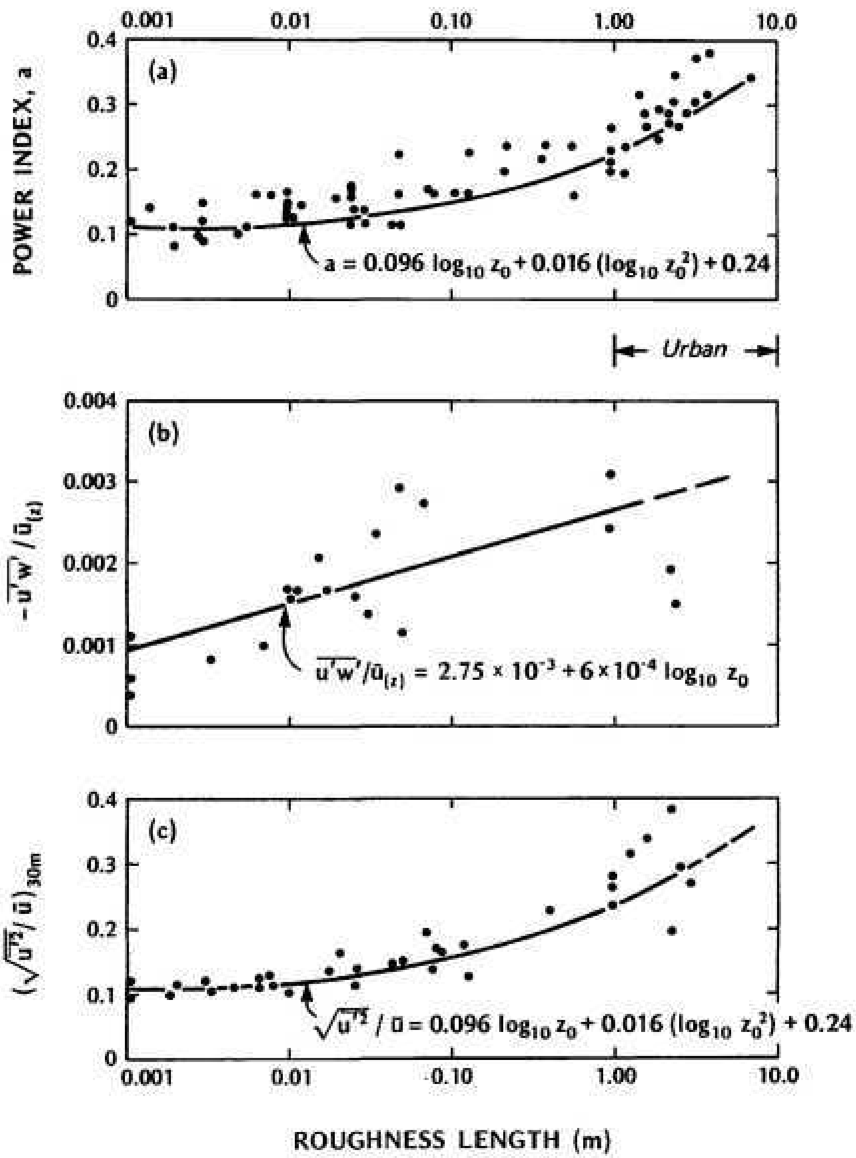

Figure 6 - *Variation of (a) power law index, (b) Reynolds stress and (c) longitudinal turbulent intensity with the surface roughness length. Curves are empirical fits to observations in neutral stability (modified after Counihan, 1975)*

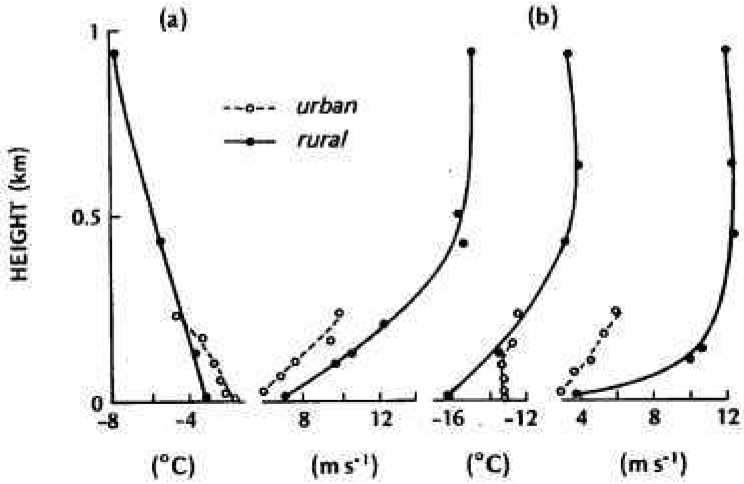

Figure 7 - *Simultaneous average wind and temperature profiles at Voyeykovo Station (rural) and Leningrad Television tower (urban) in (a) neutral and (b) inversion conditions (after Shklyarevich, 1974)*

In terms of the mean wind field, the increased drag caused by the rougher urban surface usually results in reduced wind speeds in the lowest layers. This effect is best seen with reasonably strong airflow, as illustrated in Figure 7 which compares urban/rural wind profiles in Leningrad. Further confirmation of deceleration is provided by the tower measurements of Johnson and Bornstein (1974) and Duchêne-Marullaz (1975b), and by the pilot balloon data of Albert et al. (1973) amongst others. Johnson and Bornstein extended an earlier study (Bornstein et al., 1972) of the wind field over New York City. The original analysis of nocturnal wind data showed that the city retarded airflow when upwind rural speeds were greater than 3.6 m s^{-1}, but for cases below this critical value urban speeds were greater. The new study shows the same situation to occur during the day-time. The explanation appears to be that strong flow is decelerated by increased friction, but weak flow is accelerated due to the horizontal pressure gradient force associated with the urban heat island. The heat island is always best expressed in weak flow conditions. These conclusions merge with a related study of the effect of the New York City area upon the movement of slow-moving synoptic cold fronts (Loose and Bornstein, 1976).

Preliminary results suggest that in non-heat island periods frontal movement is retarded by at least 50% over the central urban area compared with upstream speeds. The slowing was attributed to increased surface drag. Conversely, during periods with well-developed heat islands fronts were retarded over the upwind half of the city as before, but speeded up by at least 25% over the downwind half of the city. The increase was felt to be due to the heat island pressure field.

The urban wind speed profile is often rather complex, especially in light wind conditions at night. Under these circumstances it is quite common to find a low-level wind speed maximum ('jetlet') in both urban and rural areas, but the urban one tends to occur at a higher elevation (Albert et al., 1973; Ackerman 1974b, c; Moses, 1974). Urban winds also exhibit greater temporal variability, or 'unsteadiness', than their rural counterparts; and, even though deceleration may be occurring at low-level, it is quite common to observe a relative acceleration of airflow at higher levels over the city (Albert et al., 1973).

The decelerations in windy conditions, and accelerations when the heat island is well-developed, lead to adjustments in the balance of forces. As a result, the wind direction also changes. With strong winds, the deceleration causes a decrease in the Coriolis deviating force; and, since the pressure gradient force may be assumed constant, the flow must turn towards lower pressure (i.e. cyclonically). With acceleration the opposite will occur, leading to anti-cyclonic curvature. Excellent examples of these responses are now available. Angell et al. (1973) and Angell and Bernstein (1975) analyzed tetroon flights across Oklahoma City in strong wind conditions (speeds of greater than 12 m s^{-1} at 400 m). Figure 8 gives the average trajectories of tetroons crossing the city at three times during the day at a height of about 400 m. The city induced an average cyclonic turning of 5^{o}, with a maximum of 10^{o} in the morning and 4^{o} in the afternoon. In the evening, the effect was negligible. Note that downwind of the city

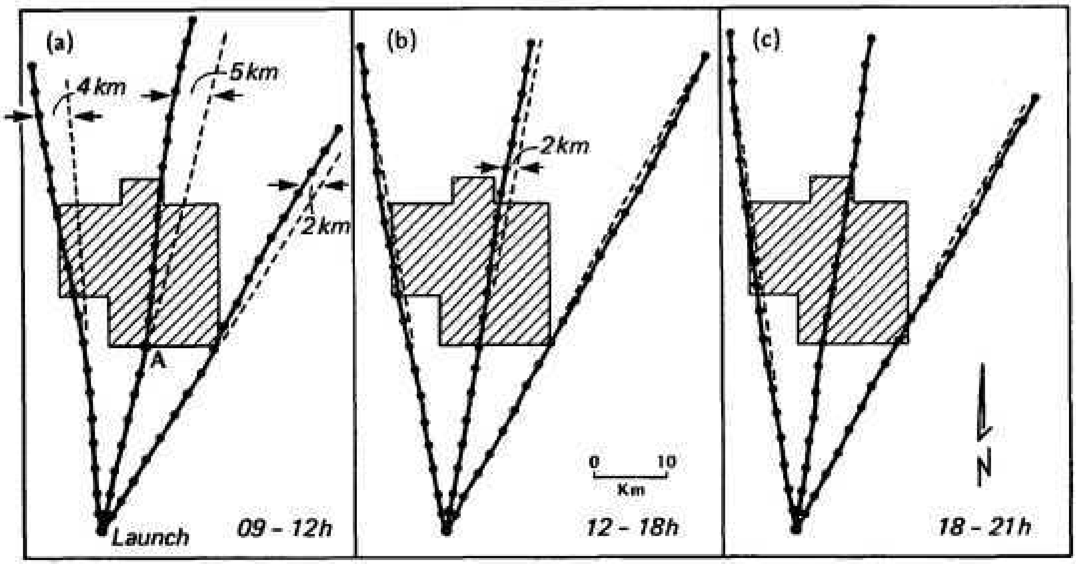

Figure 8 - *Mean tetroon trajectories across Oklahoma City during (a) mornings (b) afternoons and (c) evenings with strong southerly flow. The dashed lines are a linear extrapolation of the initial trajectory (i.e. the expected path with no urban influence) (after Angell et al., 1973)*

the direction readjusted to resume a trajectory parallel to (but offset from) that upwind. The diurnal variability is thought to be related to the depth of the urban mixing layer. In the morning, the tetroons were just within the relatively shallow urban layer where the frictional effects were concentrated. By the afternoon, these influences were spread through a much deeper (approximately 1 km) layer and were thereby diluted. In the evening, the tetroons were flying above the urban boundary layer and were not affected by the frictional effect, but they are seen to curve around the city from both sides (see also the afternoon). This lateral perturbation is thought to be due to the urban area acting as an obstacle to the flow which is not entirely compensated for by vertical motion. Hence the air tends to bend around the city rather like the flow of water around a rock.

Frictionally-induced turning of the wind in moderate to strong flow conditions has also been reported for St. Louis (Albert et al., 1973; Moses, 1974; Auer, 1975a), New York City (Johnson and Bornstein, 1974) and London (Atkinson, 1975). It also follows from continuity considerations that deceleration will cause convergence over the city giving rise to a tendency for uplift. The Oklahoma City tetroon and pilot balloon studies (Angell et al., 1973; Angell and Bernstein, 1975) illustrate these features also. In the earlier study based on tetroons the city was seen to act as a source for a 'plume' of ascending air which extended to at least 30 km downwind. Urban/rural comparisons revealed a mean upward velocity of 0.4 m s^{-1} at 10 km downwind. Superimposed on this mean pattern, however, were areas with descending motion. These areas tended to be on the outskirts of the city. In the latter study it was clearly shown that at times the upward motion caused by the barrier (or heat island) effect over the city also resulted in descending motions in the lee of the city. This was thought to explain an observed maximum wind speed downwind of the urban area, by transporting air with higher momentum from aloft down towards the surface.

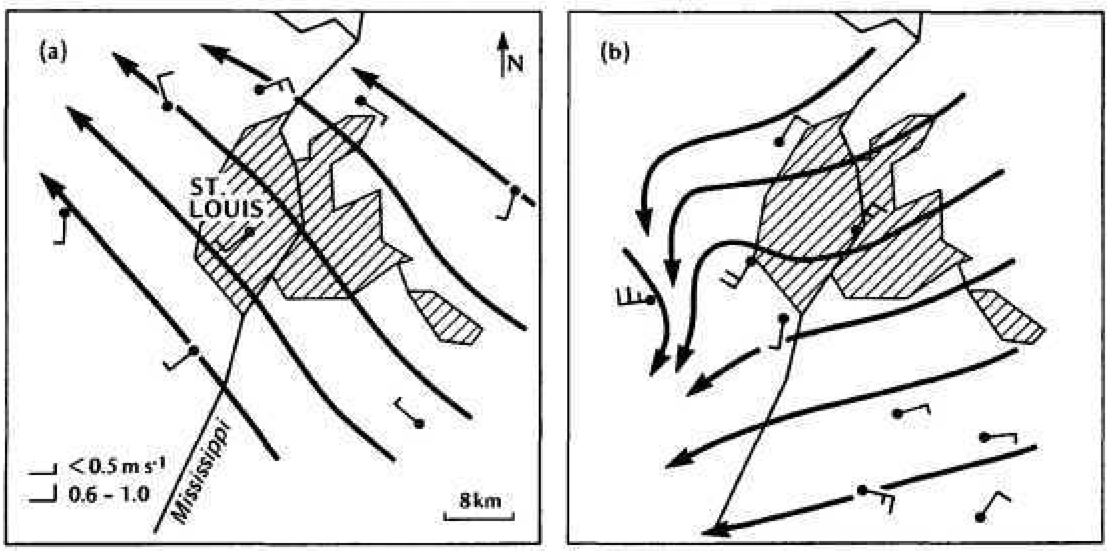

Figure 9 - *Mean streamlines in the lower boundary layer over St. Louis with light winds. (a) At 150 m on August 10, 1972 at 1510-1730 CTD; and (b) at 100 m on August 17, 1971 at 2120-2240 CDT, both with cloudless skies. The streamlines are based on the time-averaged winds at each site, and the wind barbs give the vector deviation of the site winds from the average velocities at all sites (after Ackerman, 1974b)*

In light wind conditions the role of the heat island becomes more important in determining urban airflow. The deeper mixing layer over the city encourages vertical momentum exchange and when added to the heat island pressure field gives higher urban wind speeds than at the same height in surrounding rural areas, as already mentioned. With moderate regional airflow, the urban inflow becomes a component added vectorially to the wind. The observed streamlines then exhibit anticyclonic turning at the upwind edge of the city and re-curve cyclonically downwind of the city centre (Figure 9). Similarly, Johnson and Bornstein (1974) show anticyclonic turning over New York City with light winds (i.e. when acceleration was noted). Ackerman (1974a, b) calculates that these changes lead to convergence in the lower portion of the boundary layer of the order of 5 to 10 x 10^{-5} s^{-1}, and divergence aloft. The convergence should lead to a mean uplift at about 0.1 m s^{-1}, and local updrafts of about 1.0 m s^{-1} have been observed.

A particularly interesting study of the wind field over St. Louis is presented by Auer (1975a) using a Doppler navigation system onboard an aircraft. Horizontal divergence was evaluated by flying around the city limits of St. Louis in a closed pattern and comparing the area enclosed by such a path with that of the 'distorted' area produced by joining the ends of wind vectors (each based on 15 one-second values) corresponding to the displacement of air during the time necessary to complete one circuit. This was repeated at 3 levels (460, 760 and 1340 m) in mid-afternoon in August with average winds of about 5 m s^{-1} at all levels. Results showed convergence at the lowest and middle levels (2.8 and 3.6 x 10^{-5} s^{-1}, respectively) but divergence at the top level (6.1 x 10^{-5} s^{-1}). Derived vertical velocities in the mixing layer were -0.01 m s^{-1} and were sufficient to explain most of the 260 m 'doming' of the mixing layer observed over the city (e.g. Fig. 10). It was hypothesized that the low-level convergence and 'doming' due to the related vertical velocities result from a reduction in wind speed as air passes over the city.

If synoptic-scale winds are absent, the urban heat island is able to develop a completely self-contained thermal circulation system. This has recently been studied in St. Louis (Dannevik et al., 1974) and Milan (Santomauro, 1976). The low-level portion of the system has been verified in a number of locations, but only indirect evidence of the required counter flow aloft is available. Dannevik et al. (1974) provide a useful set of characteristic dimensions for the St. Louis circulation (Table 2).

TABLE 2. Characteristic Features of the Urban Heat Island Circulation of St. Louis, Missouri. Compiled after Dannevik et al. (1974)

Feature	Characteristic Value
(a) Intensity of surface heat island	$\geq 2.20^{\circ}C$
(b) Gradient-level (90 kPa) wind speeds	≤ 5 m s^{-1}
(c) Diameter of area of surface inflow	30 km
(d) Depth of circulation (incl. in- and outflow)	1 km
(e) Diameter of updraft	7 km
(f) Duration of circulation	1 to 4 h
(g) Velocity of surface inflow	2 m s^{-1}
(h) Vertical velocity of updraft	0.3 m s^{-1}
(i) Vertical volume flow rate in the updraft	10^6 m^3 s^{-1}

At the city-block or street scale, understanding of wind patterns remains rather qualitative. Much of our knowledge relies upon scale modelling in wind tunnels (see Part II). These will become even more useful if more full-scale comparisons are undertaken such as those of Newberry et al. (1973), Isyumov and Davenport (1975) and Penwarden and Wise (1975). Limited information on winds in urban canyons can be found in Malissa et al. (1975) and Nunez and Oke (1977).

Finally, in this section, we should note that a rather novel technique has been developed to determine horizontal urban wind fields through the analysis of condensation plumes visible in air photography (Bourque 1974, 1976). The technique is limited to use in areas with cold winters and in cities with many plumes; but, in a test using surveys from Ottawa, the method was found to be capable of identifying urban trajectories and the influence of topography and land use upon winds.

E. TEMPERATURE (HEAT ISLAND)

The heat island effect of a city (its relative warmth compared with pre-urban conditions, or as approximated by the present urban/rural difference) remains one of the central research foci in urban climatology. Table 3 lists most of the recent observational studies published on this phenomenon. Since most of these deal with the unique form and magnitude of the heat island in each city, it is difficult to provide a detailed review. Therefore, as with TN 134, this section will seek to synthesize where possible, and to pinpoint any significant general advances. Reviews of the heat island have also been produced by Nishizawa (1973), Garstang et al. (1975) and Oke (1976b, 1977a).

1. Urban boundary layer

Thermal modification of the urban boundary layer has been studied with the aid of various tall towers, helicopters and fixed-wing aircraft. Their results largely confirm previous findings. Figure 7 is an example from Leningrad where both Vdovin (1973) and Shklyarevich (1974) have used temperatures from a television tower in the city to compare with those from radiosonde ascents in the surrounding countryside. It is clear from Figure 7 that when rural areas are characterized by neutral conditions the urban boundary layer is slightly unstable, and with stable inversion conditions the city is neutral or slightly unstable. In the neutral case, the modified layer is about 230 m deep. With an inversion, it contracts on average to 160 m. The erosion of stability by the heat island is also shown by Yap

TABLE 3 Summary Listing of Urban Heat Island Studies Published 1973-76. Those Marked with an Asterisk Include Vertical Temperature Information.

Author(s)	Location	Author(s)	Location
1973			
Arseni-Papadimitriou	Athens	Landsberg	Columbia, Md.
Ball et al.	Winnipeg	Neaçsa	Bucharest
Clarke and Peterson; *Ludwig and Dabberdt	St. Louis	Oke	10 Québec settlements
Daniel and Krishnamurthy	Poona; Bombay	Oujezdsky; Peschier	Austin, Tex.
Fogelberg et al.	Helsinki	Rastorgueva	Irkutsk; Lipeck; Sverdlovsk; Cita
Grønskei et al.	Oslo		
Herrmann	Giessen, GDR	*Rouse et al.	Hamilton, Ont.
Hirt and Shaw;	Toronto	Sanderson et al.	Windsor, Ont.
Hufty	Liége	Sasaki	Sendai
Jauregui	Mexico City	Spar and Mayer	New York
Kossowska	Warsaw	*Vdovin	Leningrad
1974			
*Auer and Dirks;*Braham(a) Dabberdt and Davis (a, b) Dannevik et al.; Dirks (a, b); *Miller, *Spangler and Dirks; *Uthe and Russell	St. Louis	Goldreich (a)	Johannesburg
		Hosokawa	Small towns in Miyagi Prefect.
		Lyons (a, b); Lyons and Cutten	Adelaide
Balke	Cologne	*Machalek	Vienna
*Berlyand et al.	Zaporozhye	Nemeth	Budapest
Changnon (a)	Urbana, Ill.	*Olsson et al.	Stockholm
Eagleman	Kansas City, Topeka, Lawrence	Padmanabhamurty and Hirt	Toronto
		*Shklyarevich	Leningrad
		Tsuchiya	Tokyo
1975			
Benson and Bowling	Fairbanks	Nkemdirim et al.	Calgary
De Marrais	31 US cities	Nübler	Freiburg
Duchêne-Marullaz	Nantes	Oke and Maxwell	Montréal; Vancouver
Hage	Edmonton	Sekiguti and Kawakami	Takiyama; West-Ageo
Landsberg (b)	Columbia, Md.	Stock	Dortmund
Lee	London	Unwin and Brown	Nottingham
Martin and Evans	Akron, Ohio	*Yap (a)	Toronto
*Miller; *Sisterson	St. Louis	Yap (b)	Edmonton
1976		Karl; *von Strobel Woods	St. Louis
Börngen and Dobierzin	Leipzig	Millward and Motte	Plymouth
Bowling et al.	Fairbanks	Mukherjee and Daniel; Prahdan et al.	Bombay
Cech et al.	Houston, Tex.	Nicol	Inuvik, N.W.T.
*Conrads	Utrecht	Nkemdirim	Calgary
Hannell	Quito	Oke (a, b)	Vancouver
Harlfinger	Freiburg	Zanella	Parma

(1975a) in Toronto using urban/rural towers, and by Machalek (1974) in Vienna using an urban church steeple and a suburban-park tower. The latter study also reports that the 'cross-over effect' (the situation where urban air is cooler than rural air at the same height) is related to wind speed. It is suggested that with winds less than 4 m s^{-1} a heat island forms, but with winds of 5 to 10 m s^{-1} a cold layer forms over the city. This is at variance with some previous work which shows the 'cross-over effect' even at low wind speeds.

Helicopter and aircraft surveys have the great advantage of providing spatial probing in the horizontal as well as the vertical. In Leningrad, Vdovin (1973) used a helicopter to study the heat island. In rural inversion conditions, flow across the city resulted in weak lapse over the city with a heat island depth of 200 to 250 m at the centre. Downwind of the city there was an isothermal layer up to a height of 450 m. After 4 to 5 km of downwind fetch a thin surface inversion began to re-form giving an elevated 'urban heat plume'.

Fixed-wing surveys over St. Louis as part of METROMEX have mapped the magnitude and extent of its heat island, especially during the summer (Auer and Dirks, 1974; Braham, 1974a; Dirks, 1974a, b; Sisterson, 1975; Sisterson and Dirks, 1975a; Spangler and Dirks, 1974). Their results (Figure 10) show that the thermal anomaly extends to a height of at least 1 km and on some occasions to 1.5 km. The urban temperature excess therefore extends throughout the day-time mixing layer up to cloud-base level, and is also capable of 'doming' the base of the normal boundary layer capping inversion. The effects were detectable to at least 30 km downwind.

One of the most important reasons for studying the vertical structure of the heat island is that its upper boundary normally coincides with an elevated inversion and therefore it also defines the effective depth within which pollutants may be dispersed. Summers (1964) first proposed a simple model which related the mixing depth (h^*) and the intensity of the urban heat island (ΔT_{u-r}) at the surface to the rural lapse rate ($(\Delta\theta/\Delta_z)_r$, where θ is potential temperature), the wind speed through the mixing layer ($\bar{u}$), the heat input from the city (Q) and the distance of fetch across the city (x), so that in the centre of a circular city where x equals the radius:

$$h^* = \left[\frac{2xQ}{\rho c_p \bar{u}(\Delta\theta/\Delta z)_r}\right]^{\frac{1}{2}} \tag{11}$$

and,

$$\Delta T_{u-r} = \left[\frac{2xQ(\Delta\theta/\Delta z)_r}{\rho c_p \bar{u}}\right]^{\frac{1}{2}} \tag{12}$$

where, ρ - air density and c_p - specific heat of air at constant pressure.

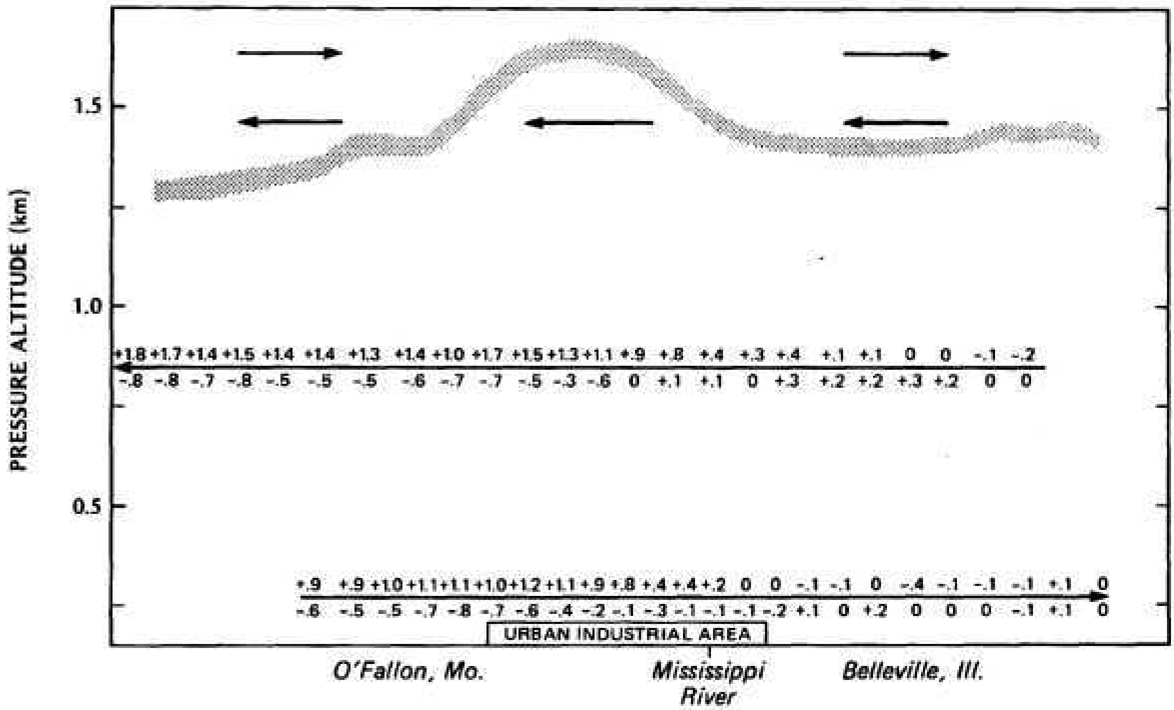

Figure *10 - Cross-section of temperature (above line, ^{o}C) and moisture (below line, g kg^{-1}) anomalies with respect to upwind values in the St. Louis area. Data from aircraft traverses (at heights given by arrows) at 1550 to 1650 CDT on August 10, 1972 with winds south-east (right to left) at 3 m s^{-1}. Data points are ~4km apart, shading represents observed height of mixing layer (after Dirks, 1974a)*

It has since been shown (TN 134; Grønskei et al., 1973; Lee, 1975) that ΔT_{u-r} is correlated with $(\Delta\theta/\Delta z)_r$. Using this, and other simplifications Ludwig and Dabberdt (1973) arrived at an equation to determine h*. Comparison with lidar and balloon soundings showed reasonable agreement in the pre-dawn hours in St. Louis.

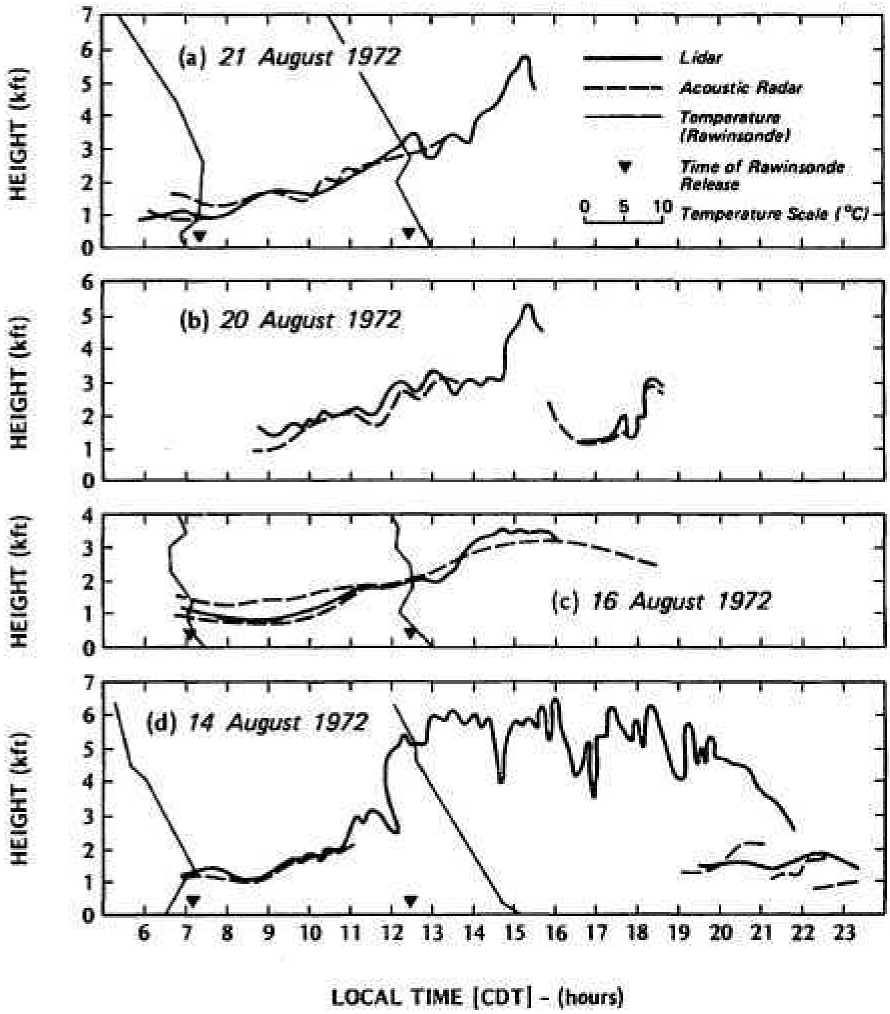

Figure 11 - *Comparison of urban mixing depths (h*) inferred from concurrent acoustic sounder (sodar) and laser (lidar) observations in St. Louis in August 1972. Temperature profiles from rawinsonde ascents at a station about 5 km away (after Russell et al., 1974)*

Both Summers (1974) and De Marrais (1975) suggest that the commonly used technique for estimating morning urban mixing depth (Holzworth, 1967) which assumes a constant value of ΔT_{u-r} should be used with caution. They suggest that better modelling of ΔT_{u-r} (by incorporating x, Q and $\bar{u}$ as in equation 12) would lead to more realistic h* values.

Valuable insights into the spatial and temporal variations of urban h* are now becoming available through the use of remote sounding techniques (especially lidar and sodar, see section G for details). Figure 11 shows a time-section of the St. Louis mixing depth in summer using both approaches. The diurnal cycle exhibits a stable period through the night with h*≈ 0.3 km. The layer begins to expand in the period after sunrise and then rapidly grows at midday. The depth grows to 1.5 to 2 km in the afternoon and is characterized by relatively large variability associated with well developed convection cells. This would correspond to the period of urban 'doming' seen in Figure 10. Later in the evening the layer contracts and becomes more quiescent again.

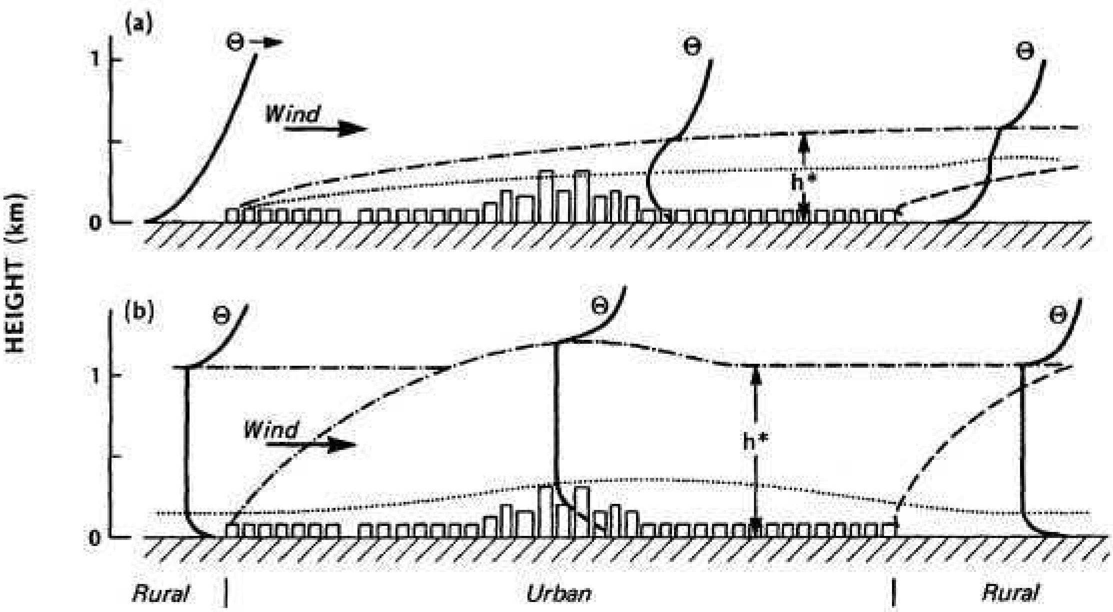

Figure *12 - Schematic diagram of the (a) nocturnal, and (b) daytime form of the potential temperature (θ) profile and mixing depth (h*) in the vicinity of a large mid-latitude city in fine summer weather (after Oke, 1977a)*

Figure 12 is an attempt to summarize the form of the temperature structure and mixing depth over a large mid-latitude city in summer. In the nocturnal case the rural boundary layer is stable, but as it advects across the urban area its stability is eroded due to the extra heat input from below and the increased mechanical mixing which re-distributes heat in the vertical. Typically the lowest layer is neutral or unstable, and there is a transition layer in the upper portion of the urban modified layer where the air is slightly stable. Downwind of the city a stable rural layer begins to reform at the surface. In the daytime case both the urban and rural surface layers are unstable and the remainder of the boundary layer is neutral due to convective mixing. The enhanced vigour of this mixing over the urban area creates a domed perturbation in the overlying inversion. The exact causation of the excess warmth in the urban boundary layer remains to be shown, but Table 4 summarizes the most likely processes. These include not only heat input from below, but also from above (due to greater entrainment from the overlying inversion), and short-wave absorption. It should, however, be noted that the picture depicted in Figure 12 is highly schematic. At any given location in the city, the depth and thermal structure of the urban boundary layer may be highly variable (e.g. Figure 11) or even absent.

2. Urban canopy layer

The canopy layer heat island is that measured by most conventional station networks or by automobile traverses. Its detailed morphology has long been recognized to consist of two basic scales: first, its overall outline is related to the shape of the urban region and its unique geographic features (topography, water bodies, etc.); second, its internal pattern is strongly controlled by micro-scale features especially relating to urban land uses and building density. Recently, there has been increased interest in assessing the role of the site factors. As reported in TN 134, Clarke and Peterson (1973) used an eigenvector analysis to study the relationship between the heat island and land use in St. Louis. Goldreich (1974a) working with data from Johannesburg defined an 'urban factor' on the basis of the difference between urban and rural regressions of temperature versus a series of station descriptors. When the 'urban factor' was regressed against meteorological parameters, the resulting equation was an improvement compared with just using ΔT_{u-r}. Finally, Unwin and Brown (1975) working in Nottingham undertook a statistical analysis of the 'heat island relative temperature' (deviation of a site temperature from the areal mean for the city) and a measure of urban structure (land use characteristics within 50 m of the site combined to give one measure via principal components analysis). Regression yielded a relation between the relative heat island and the logarithm of urban structure which explained 44% of the variance.

TABLE 4. Mechanisms Hypothesized to Cause the Urban Heat Island Effect (after Oke, 1976b, 1977a)

1.	URBAN BOUNDARY LAYER
(a)	Anthropogenic heat from roofs and stacks
(b)	Entrainment of air scoured from warmer canopy layer (for mechanisms see below)
(c)	Entrainment of heat from overlying stable air by the process of penetrative convection
(d)	Short-wave radiative flux convergence within polluted air
2.	URBAN CANOPY LAYER
(a)	Anthropogenic heat from building sides
(b)	Greater short-wave absorption due to canyon geometry
(c)	Decreased net long-wave loss due to reduction of sky view factor by canyon geometry (incl. reduced nocturnal radiative flux divergence)
(d)	Greater daytime heat storage (and nocturnal release) due to thermal properties of building materials
(e)	Greater sensible heat flux due to decreased evaporation resulting from removal of vegetation and surface 'water proofing'
(f)	Convergence of sensible heat due to reduction of wind speed in the canopy

Note: Mechanisms are not listed in any order of priority.

The question of the effect of city size upon the magnitude to ΔT_{u-r} was addressed by Oke (1973). Using data from 10 settlements in Québec (with populations from 10^3 to 2×10^6 inhabitants) he finds that under the limiting conditions of cloudless skies, and at the time of the maximum heat island (about 3 h after sunset):

$$\Delta T_{u-r} = 0.25 \frac{\phi^{1/4}}{\bar{u}^{1/2}} \tag{13}$$

where, ϕ - population of the settlement. The relationship explained greater than 70% of the variance, and the standard error of the estimate of ΔT_{u-r} was $\pm 1.6^{\circ}$C. Equation 13 was later found to provide a good description of an independent data set for Vancouver (Oke, 1976a). In fact, it performed better than equation 12 which is otherwise physically superior and dimensionally correct. It was suggested that the advective approach was inappropriate for canopy layer heat islands where micro-scale site factors are probably most important. In the statistical model (equation 13) ϕ may be a surrogate for the physical structure of the centre of cities (including such features as the sky view factor, type of materials, degree of shelter, area of greenspace, anthropogenic releases, etc.). In the limit when $\bar{u}$ approaches zero (calm), the maximum heat island ($\Delta T_{u-r(max)}$) is recorded in almost all cities. Under these conditions Oke (1973, 1976a) shows that $\Delta T_{u-r(max)}$ is highly correlated with the logarithm of ϕ, with different slopes for North American and European cities (Figure 13). Conrads (1976) adds further data in agreement with the European relation, and Landsberg (1975b) shows that the North American model also fits the case of a growing settlement (Figure 13). Eagleman (1974) showed similar types of relationships between urban/rural temperature (and temperature-related) differences for three cities in Kansas. There is, however, some concern over the size of the data set used (Changnon, 1976a).

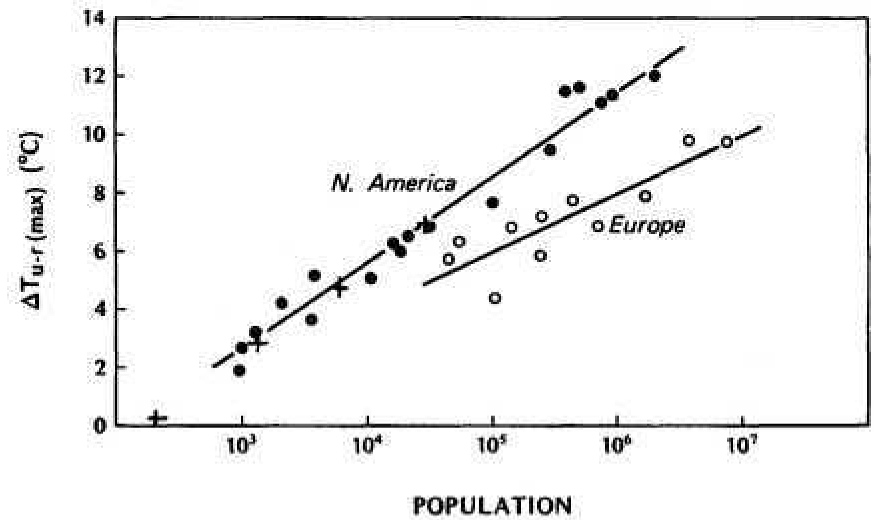

Figure *13* - *Relation between the size of the maximum heat island intensity ($\Delta T_{u-r(max)}$) and population (ϕ) for European and North American settlements. The equations of the lines are:*

N. America $\Delta T_{u-r(max)} = 3.06 \log \phi - 6.79$

Europe $\Delta T_{u-r(max)} = 2.01 \log \phi - 4.06$

The crosses are values from the growing new town of Columbia, Md. in the years of 1967, 1970, 1972 and 1974 (modified after Oke, 1973)

Tropical city heat island studies have been published for Bombay and Poona (Daniel and Krishnamurthy, 1973; Mukherjee and Daniel, 1976; Prahdan et al. 1976), Mexico City (Jauregui, 1973) and Quito (Hannell, 1976). Early morning studies in the Indian cities showed heat islands to be well displayed. In both cities the largest heat islands had an intensity of 6°C with calm winds and cloudless skies. Similar early morning surveys in Mexico City found heat islands of up to approximately 9°C under ideal conditions. Heat island intensity was noted to be related to the strength of the rural inversion, and was inversely related to wind speed with virtually no anomaly forming if winds were greater than 4 m s^{-1}. Isotherms followed the built-up outline of the city, and the peripheral 'cliff' became most pronounced when katabatic winds converged on the city from the surrounding hills and mountains. Thus, in large measure, the nocturnal heat island characteristics of these tropical cities in varied topographic (Poona, Mexico City) and coastal (Bombay) locations show similarity with mid-latitude experience. On the other hand, the results from Quito are apparently distinctly different. The heat island was reported to be a maximum (up to $4^{o}C$) at midday and a minimum after sunset, and daytime heat islands remained substantial even with winds of 9 to 11 m s^{-1}. The lack of a nocturnal heat island was suggested to be the result of a strong cold air drainage from surrounding terrain. The high day-time values are speculated to be the result of reduced albedos in the city although no data are available to support this. Intra-urban variations of temperature showed that parks formed very distinct cool cells within the heat island.

At the other extreme, the results of arctic studies are rather sparse. In Fairbanks, Alaska (Benson and Bowling, 1975; Bowling et al., 1976) the heat island can attain 10 to $12^{o}C$ under ideal conditions in winter, and $8^{o}C$ in summer. The winter value is exceptionally large for this size of settlement. In Inuvik, N.W.T. (Nicol, 1976) the heat island is usually less than $3^{o}C$ in winter. In both cases, it becomes extremely difficult to establish the 'rural background' temperature, and to eliminate the effects of topography because 'rural' inversions are so intense that small changes in elevation produce large changes in temperature.

As an interesting side effect it should be noted that Balke (1974) has found that the heat island extends down into the ground below a city. Based on measurements of groundwater temperature in Cologne, W. Germany the spatial pattern of the heat island is evident and, in the central city, the temperature is 2 to $3^{o}C$ warmer down to depths of at least 25 m.

There has been discussion of the differences between air temperatures measured near the ground and on roofs. In the most recent study (Armstrong, 1974) it is concluded that using standard observations for climatological purposes there is surprisingly little difference.

The exact cause of the canopy layer heat island at any time in a given city remains unsolved in detail. Table 4 lists those mechanisms that are likely to be involved. Further process work integrated with heat island measurement will be required before a realistic model can be constructed.

F. HUMIDITY

At the time of TN 134 the effect of the city on atmospheric moisture was somewhat confused and lacking in research. In the interim there have been few studies but their results are encouragingly more consistent.

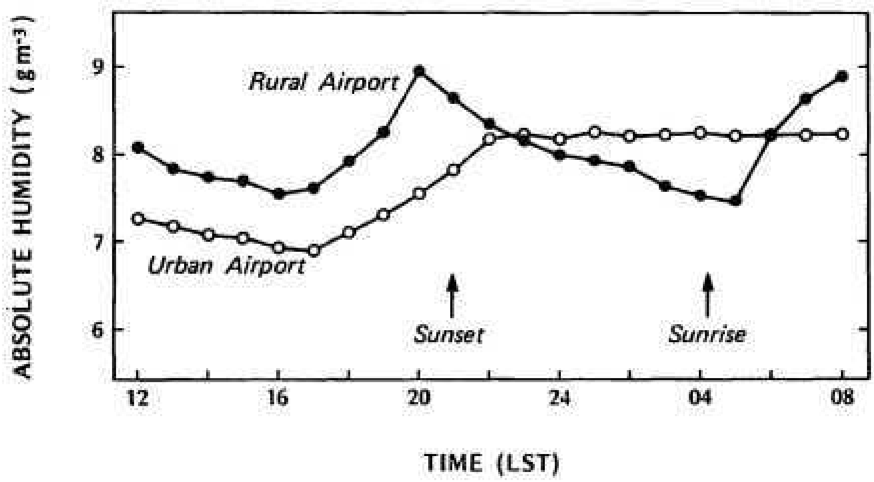

Figure *14 - Diurnal variation of urban and rural absolute humidities on 30 fine summer days in and near Edmonton, Alberta (modified after Hage, 1975)*

Most of the urban boundary layer work has originated in St. Louis (Auer and Dirks, 1974; Dirks,1974a, b; Sisterson, 1975; Sisterson and Dirks, 1975; Spangler and Dirks, 1974; von Strobel Woods, 1976). In the summer, there appears to be an identifiable anomaly in the urban mixing layer with specific humidity deficits of about 1 g kg^{-1} found over and downwind of the city during the day-time. In Figure 10, deficits of the order of 0.5 g kg^{-1} are observed up to heights of at least 0.85 km. On individual occasions deficits as large as 2.5 g kg^{-1} have been found over the central city. On the other hand, at night and in the morning before significant convection develops, the urban boundary layer may be more moist than in surrounding regions.

Exact reasons for this situation are not yet fully clear but most investigators suggest the day-time deficit is due to reduced surface evapotranspiration in the city, and the entrainment of drier air into the boundary layer from above by the enhanced convective development. The nocturnal surplus is often ascribed to continued evaporation and less dewfall in the city, and to the addition of anthropogenic moisture.

Concensus also appears to be emerging regarding the effect of the city upon canopy layer humidities, at least in the mid-latitudes. In general there appears to be a correspondence between the situation in the boundary layer with that in the canopy layer. In summer, the urban atmosphere is drier by day but more moist at night. This pattern is particularly well displayed by the Edmonton results of Hage (1975) in Figure 14. The rural temporal variation exhibits a double 'wave' characteristic of continental locations. The peak prior to sunset is due to vapour convergence in the lower layers as evapotranspiration continues to add moisture to a stable atmosphere. Values decline through the night as dewfall depletes the moisture store. After sunrise humidites initially increase because the rate of input from surface evapotranspiration exceeds the transport to higher levels, if convection is not yet well developed. Throughout the rest of the day-time, values decrease as diffusion to higher layers is very efficient in an unstable atmosphere. The same pattern is not evident in the city. The reduction in urban evapotranspiration and the enhanced urban mixing combine to keep humidities below those of the countryside throughout the day-time. At night, there is a gradual increase in the city which is possibly due to continued evapotranspiration and anthropogenic inputs to the atmosphere and/or to the downward mixing of moisture from above the urban boundary layer. A similar diurnal reversal was found by Kopec (1973) in Chapel Hill, N.C. and by Auer and Dirks (1974) and Sisterson (1975) in St. Louis. Kopec's maps also reveal that the greatest range of values, and the most complex areal patterns occur in the late afternoon. They also show that, although the overall urban/rural pattern is well differentiated, the micro-scale association between surface character and absolute humidity is unclear.

In the winter, Hage (1975) found that the Edmonton urban area was more moist at all times of the day. This could be due to the preferential source of anthropogenic vapour in the city at a time when rural surface evaporation is negligible (snow covered, dormant vegetation). This is likely to increase in importance as conditions become colder due to the increased fuel consumption for space heating. It is also likely that moisture is added from above. Rural radiosonde ascents showed that, on average, water vapour increases with height during the winter. The enhanced mixing over the rougher, warmer city may therefore bring about a net increase in downward transport. Comparison of data from two periods (1961-66 and 1967-73) showed that the urban effects are increasing as the city grows.

Results from Johannesburg (Goldreich, 1974b) do not entirely conform to the above picture. On good inversion nights the urban area appears to be more moist than its environs in agreement with mid-latitude studies. The day-time situation, however, is unusual. In the summer (rainy season), most of the urban area is drier but in the core area the air is more moist. In the winter (dry season), the whole city is more humid and indeed the anomaly is better expressed than on inversion nights.

G. OTHER

Although it is somewhat outside the scope of this report to deal with the bioclimatic implications of urban climates, it should be noted that several recent studies have been produced. The energy balance of humans in urban environments has been dealt with by Morgan and Baskett (1974), Stark and Miller (1975) and Tuller (1975), and aspects of human comfort in urban locations by Penwarden (1973), Arens (1975), Bernatzky (1975), Huckaby and Rouch (1975), Joyner and Reiter (1975), Rowntree and Plumley (1975) and Mayer and Gietl (1976).

Substantial input of climatic information into the design of settlements seems to remain a basic but largely unrealized goal. There would appear to be no lack of enthusiasm but tangible results appear to be sparse. Chandler (1976a, b) and Page (1976) have provided excellent overviews of the present knowledge in this field. Landsberg (1973a, c) paints his idea of the utopian city from an atmospheric standpoint but as he says "although the facts are well known, at least to the meteorologists, they are only slowly seeping through to the planners." Givoni (1973) and Oke (1976b) outline some of the reasons for this situation including the lack of the right kind of information, poor communication, and the fact that urban climatology has tended to be dominated by descriptive and comparative studies rather than analytic research which would lead to the development of a truly predictive science. More serious attention will have to be paid to a genuine interfacing of planners and atmospheric scientists.

The dimensions of the urban boundary layer impose a number of physical constraints upon measurement. Helicopter and fixed-wing aircraft have been used frequently and to a lesser extent tethered balloons. These are usually rather expensive to operate and/or encounter limitations due to air traffic regulations. Minisonde and other balloons have also been used successfully (e.g. Frenzen, 1972; Gage and Jasperson, 1974, 1976). But,without doubt, the most promising recent developments relate to the use of remote sensing systems such as lidar (Johnson et al., 1973; Olsson et al., 1974; Pal et al., 1974; Russell et al., 1974; Uthe and Russell, 1974; Russell and Uthe, 1975), sodar (Bennett and List, 1974; Miller, 1974, 1975; Olsson et al., 1974; Russell et al., 1974; Uthe and Russell, 1974; Russell and Uthe, 1975) and a radio acoustic sounding system, RASS (North et al., 1973). Much of the lidar and sodar work is experimental in nature at this point. In particular it has been necessary to interpret the data from these devices in conjunction with that from more conventional techniques. The lidar transmits laser light pulses and the back-scattered returns produce a signal that is related to the aerosol concentration in the air. The sodar transmits audible sound and measures the back-scattered returns that are related to temperature fluctuations caused by turbulence in the atmosphere. As shown in Figure 11, these techniques are capable of giving continuous measurements of boundary layer characteristics including the mixing depth (h*). Russell et al. (1974) conclude that both systems are well suited to tracing the growth of h* in the morning period when aerosols are concentrated beneath an elevated nocturnal inversion. But, in the midday period when convection is strong, the lidar is superior because it is able to use surface-generated aerosol tracers to considerable heights; whereas the sodar signal is saturated by low-level thermal turbulence. In the evening, when h* declines, the sodar is the better because this feature is first seen as a thermal discontinuity not an aerosol one.

The subject of urban observational networks has been dealt with by Munn (1973) and Changnon (1975). Munn considers observing requirements and recommends that first-order urban reference stations be established at sites away from major point sources of pollution in areas where land uses are not likely to change markedly in the next 50 years. He also mentions that it is a misconception to assume that small cities need considerably fewer observing stations than large cities. In level terrain the urban climate patterns in towns are miniature copies of those for large settlements, with their intensities varying only slightly with the city's dimensions. Therefore, sampling stations must be closer together in a small city, if the main features are to be detected. Changnon outlines the design of the very detailed METROMEX mesoscale network. In many ways this represents a model for future studies on this scale. Finally, Page (1972) comments upon the common problem of forecasting the climatological properties of an existing or proposed site in a built environment using information from standard (non-urban) stations, more work along these lines would be of considerable practical value.

PART II - MODELLING STUDIES

A. CANOPY LAYER

1. Statistical models

The simple regression of urban/rural climatic differences against one or more meteorological parameters is one of the oldest forms of urban climate model. As we have seen in Part I, section E, modifications to this approach continue to be pursued, but it is felt that this is not a very fruitful area for further research unless more meaningful variables are used (Goldreich, 1974a; Unwin and Brown, 1975; Conrads, 1976). However, until satisfactory theoretical models are developed some of these relationships possess merit in providing approximate estimation procedures (e.g. Ludwig and Dabberdt, 1973; Oke, 1973).

2. Theoretical and semi-empiric models

There have been some recent developments in modelling energy and mass exchanges inside typical urban canyon configurations. Radiative exchanges are most amenable to analysis. Terjung and Louie (1973) developed a model to calculate the absorption of short-wave radiation by buildings and streets. Their methodology involved the definition of a 'radiation neighbourhood' (a strip extending from the top of one building, along the canyon walls and floor, to the top of the building on the other side of the street) whose form is repeated throughout the urban area, but whose dimensions (such as height and width) can be kept flexible. Using view-factor algebra and multiple integration the direct- and diffuse-beam short-wave radiation received and reflected by components of the 'neighbourhood' were obtained. The general model was then applied to an hypothetical 'synthetic city' of given shape, structure and dimensions, for different latitudes and seasons. In all cases it was shown that the central areas of the city absorbed more strongly than locations on a surrounding horizontal plain. This was entirely due to changes in surface geometry. The output also suggested that by day the maximum heating due to solar absorption will occur around the margins of the downtown area, and not in the centre itself. It is suggested that this may be due to shading by tall structures and conforms with the idea of negative heat islands at midday in cities with very tall buildings in their core. The authors point out that although geometry may result in very much enhanced absorption by building systems this may not necessarily apply at street-level and therefore observations near the ground in canyons could lead to erroneous conclusions.

An analogous approach was undertaken by Arnfield (1976) who modelled the albedo of a canyon, including the effects of multiple reflection. Various height-to-width ratios, solar geometries, and albedo mixes were modelled. The author points out that this approach permits the construction of maps of surface radiative properties for any city from urban land use maps and surveys. Arnfield also develops a parallel model for calculating the long-wave emissivity of a canyon, although it was not tested. It should be noted that this much neglected field of long-wave radiation modelling for non-horizontal surfaces is gaining impetus especially due to the work of Unsworth (1975) and Cole (1976a, b).

Terjung and Louie (1974) took their short-wave model, simplified it to use average view factors for sunlit and shaded areas, and added sub-models to compute the long-wave, heat storage and turbulent transport terms. These latter exchanges were related to an equilibrium surface temperature, or to empirical relations derived in other studies. Evaporation from wet surfaces was calculated using the Penman-Monteith combination model with assigned aerodynamic and surface resistances.

Nunez (1975) modelled the solar radiation exchanges in an experimental canyon theoretically, and used parameterizations to obtain the net all-wave radiation (Q^*), sub-surface storage (Q_G) and turbulent sensible heat (Q_H) exchanges. Good agreement was achieved between theory and direct measurements of solar radiation input ($K\downarrow$) and absorption (K^*). It was found possible to relate K^* to Q^*, and Q^* to Q_G and thereby to solve for Q_H in dry conditions where latent heat could be neglected.

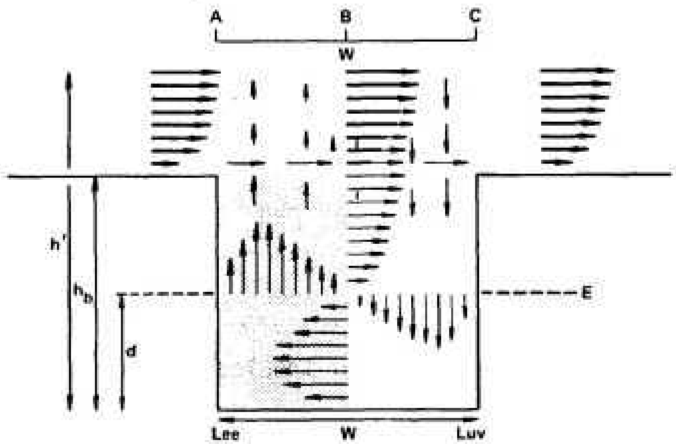

Figure *15 — Theoretical wind profiles above and within an urban canyon with wind perpendicular to the street. Heavy arrows - wind profile above buildings; light arrows - $\bar{u}$ wind vectors in and above the canyon. Length of arrows proportional to wind speed. The vector sum of all light arrows is zero due to continuity. W - canyon width, E - line along which in the ideal case $\bar{u}=0$; d - zero-plane displacement; h' - height above which profiles are the same over both buildings and streets; h_b - building height (after Nicholson, 1975)*

The vortex circulation that forms in canyons when airflow is perpendicular to their axial orientation, and the jetting flow when winds are parallel to this axis, were modelled by Nicholson (1975). It was assumed that the characteristic general wind profile for the urban area consisted of a logarithmic section above roof level, and an exponential section in the obstructed (canopy) layer beneath. For the vortex situation (Figure 15) the upward flow ($+\bar{w}$) between A and B was derived from mass continuity considerations to be:

$$\bar{w} = \frac{2(h'-h_b)}{W}([\bar{u}]_B - [\bar{u}]_A) \tag{14}$$

and also from continuity it was assumed that the downward flow ($-\bar{w}$) between B and C was equal to the same value. For flow parallel to the canyon, the primary flow remains horizontal and is given by the integration of the exponential law from the street up to the building height (h_b) so that:

$$U = \frac{U_R Z_o}{h_b} \left(1 - e^{h_b/Z_o}\right) \tag{15}$$

where, U - representative canyon wind speed, U_R - reference wind speed, Z_o - roughness length for the canyon layer. These vertical and horizontal transport equations were then incorporated into a model to predict volume-average concentrations of carbon monoxide from automobile sources in the canyon.

3. Scale models

As mentioned in section D much of our knowledge of airflow at the building scale has been derived from wind tunnel studies on scale models. The work is usually concerned with the effects of an individual (usually large) building in an urban context (e.g. Newberry et al., 1973; Isyumov and Davenport, 1975; Penwarden and Wise, 1975), but there are also studies of the flow patterns in street canyons which could be of great importance in understanding the linkage between the urban canopy and boundary layers especially for heat and pollution exchange (e.g. Cermak et al., 1974; Hoydysh et al. 1975).

B. BOUNDARY LAYER

The following review of numerical models at the urban scale is broken down into the categories suggested by Gutman and Torrance (1975), viz: energy balance models (one-dimensional, time dependent); advective integral models (two-dimensional); dynamic differential models (two- and three-dimensional, time dependent). Some of the outstanding problems in this field have been reviewed by Taylor (1974) and Lee et al. (1976).

1. Energy balance models

Bergstrom and Viskanta (1973a, b) devised a one-dimensional, time dependent model of the atmospheric boundary layer mainly to study the effects of pollutant concentrations upon the thermal structure and their feedback upon atmospheric stability and pollution dispersion. The model consisted of a 'natural' atmosphere, a 'polluted' boundary layer and a soil layer. In the natural atmosphere, variables were considered to be time dependent; in the polluted layer velocity, temperature and pollutant concentration were functions of height and time; and, in the soil, temperature varied with depth and time. The atmosphere was assumed to be horizontally homogeneous and advection was neglected. The boundary conditions at the top of the atmosphere were specified by requiring all quantities to be constant, and similarly for temperature at the base of the soil. A surface energy balance equation was used to predict surface temperature, and surface specific humidity was prescribed by Halstead's moisture parameter. Radiant flux divergence in the polluted atmosphere was included for the solar portion of the spectrum via a solution of the equation of transfer using a spherical harmonics approximation (Bergstrom and Viskanta, 1973a, 1974). Long-wave divergence was predicted using observed water vapour and carbon dioxide emissivity data. Turbulent diffusivities were calculated using similarity theory. They were expressed as functions of stability and assumed valid throughout the boundary layer except near the top where the decay of turbulence was allowed for by replacing height by a length scale. Model computations were compared with measured rural data before conducting a series of simulations of the thermal structure of an 'urban' atmosphere for summer and winter conditions, with and without an elevated inversion.

Simulations suggested that pollutants would lead to a decrease of solar radiation reaching the surface resulting in a lower surface temperature but a higher atmospheric temperature. They also increased the long-wave flux to the surface from the atmosphere which therefore tended to offset the solar effects. Atmospheric changes also affected stability.

More recently, Venkatram and Viskanta (1967a, b, c) have simplified the solar radiation sub-model in the Bergstrom and Viskanta model (to save computer time) and greatly expanded the turbulence portion. Solar fluxes were computed according to the two-stream method and turbulence was accounted for by a turbulent kinetic energy model. Results from this model showed that the predominant influence of pollutants was to produce surface warming despite the reduction in the surface receipt of short-wave radiation. Note that this is the reverse result to that predicted by the earlier model and illustrates the importance of accurately incorporating the role of the surface energy balance (especially evaporation) and turbulence (cf. Glazier et al., 1976). In the atmosphere, the thermal effects of pollutants led to an increase of stability by day and a decrease at night.

A similar type of model was constructed by Ackerman (1977) to study the effects of aerosols on urban climate. It included a four-stream radiative transfer sub-model based on Ackerman et al. (1976) which treated both solar and long-wave fluxes, and a boundary layer heat transfer model incorporating a surface energy balance equation and a variable mixing depth. The energy balance, however, contained an assumed Bowen ratio value, and no anthropogenic heat. The model was tested against rural observations. Model vs measured radiative and temperature characteristics were considered reasonable but sensible heat flux comparisons were rather poor. The model was initialized using urban data from Los Angeles. Sensitivity tests showed that the model was most sensitive to the surface properties (especially the albedo and Bowen ratio). Results strongly suggest that the surface-atmosphere system is characterized by self-compensating feedbacks which combine to reduce the impact of pollutants on climate. For example, if radiation is absorbed by pollutants it reduces the sensible heat transfer from the surface thereby tending to keep boundary layer temperatures about the same.

Lal (1975, 1976) tested modified forms of Pandolfo's one-dimensional model against data from Jodhpur and Toronto. His results suggest a marked reduction of surface temperature at midday in a polluted atmosphere, minor changes in minimum temperatures and major changes in stability.

In review, there appears to be considerable discrepancies both between the output of the different models, and between predictions and observation. There is uncertainty in the choice of the optical properties and concentrations of pollutants, and in the surface properties of urban areas (Ackerman, 1977). Therefore the warning by Oke and Fuggle (1972) that modelling is in danger of outstripping the data base and our physical insight into the workings of the urban-atmosphere system, seems worth repeating. Effective advances in parameterizing surface conditions have been made by Nappo (1975) and Nickerson and Smiley (1975) but much remains to be accomplished especially with regard to surface moisture (evaporation) conditions, sub-surface storage, and recognition of the role of the canopy layer. Until this is done, it is difficult to see how such models can be used with confidence to predict the effects of varying one or other term, such as anthropogenic heat (Torrance and Shum, 1976).

2. Advective integral models

Kalma (1974) used models based on the original two-dimensional advective approach formulated by Summers (1964) to study the height of the mixing depth (h^*), and the temperature increase downwind of Sydney, Australia in winter. Reasonable agreement with observations was achieved, and a sensitivity analysis performed.

3. Dynamic differential models

A number of two-dimensional models that were in their preliminary stages at the time of TN 134 have been further developed and in some cases applied to specific cities. These include the models of McElroy, Wagner and Yu, Bornstein, Vukovich, and Atwater. The most salient aspects will be summarized here again.

The model of McElroy (1973) was a two-dimensional steady state model developed from the one-dimensional model of Estoque. It included a constant flux layer and a transition layer in the boundary layer. Non-pollutant radiative effects were modelled and the diffusion coefficients (assumed equal for heat, water vapour and momentum) were computed in the constant flux layer and then allowed to decrease to zero at the top of the transition layer (set at 2.05 km). Sub-surface thermal characteristics were specified as boundary conditions for inclusion in a surface energy balance equation which was used to compute the surface temperature. Information on surface roughness, relative humidity, thermal properties and anthropogenic heat were specified at positions along an urban/rural cross section. Boundary conditions were also set for the upwind rural area.

The model was used to simulate the nocturnal thermal boundary layer over Columbus, Ohio during periods in September and May when extensive experimental data were available. An example of the comparison between simulated and observed thermal structure is given in Figure 16 where it can be seen that good agreement was achieved.

Yu (1973) and Yu and Wagner (1975) presented a similar model to simulate the nocturnal urban boundary layer. The model consisted of two layers: a soil layer, and an atmospheric layer. The former allowed for horizontal variation of surface roughness and thermal properties but ignored the effects of surface moisture. Air/surface coupling was achieved via a surface energy balance equation which included an anthropogenic heat term but no latent heat. The atmospheric layer did not include a constant flux layer or the radiative effects of pollutants or water vapour. A case study of an hypothetical city was presented to characterize the effects of stable rural air flowing across a rough city. It was shown that increased mixing over the city was capable of re-distributing heat in the vertical and gave rise to a heat island.

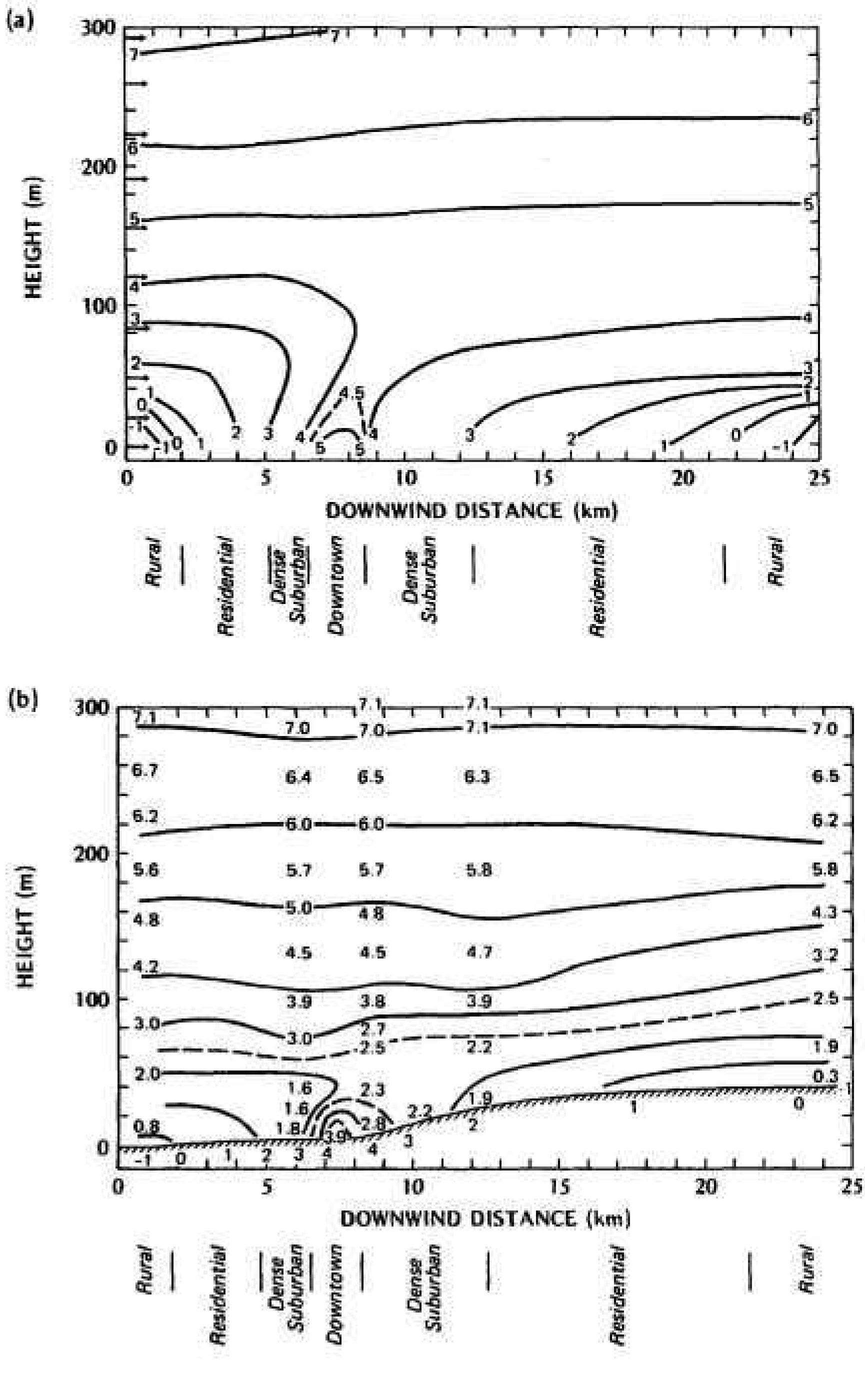

Figure *16 - (a) Simulated, and (b) observed temperature structure across Columbus, Ohio near sunrise on March 23, 1969. Arrows on vertical axis of (a) indicate computation heights (after McElroy, 1973)*

Additional simulations showed that the heat island was directly proportional to increasing stability and to increased anthropogenic heat input, but was inversely related to geostrophic wind speed.

Bornstein (1975) based his URBMET urban boundary layer model on finite difference solutions to the vorticity and energy equations in a vertical plane oriented in the direction of a constant geostrophic wind. The vertical fluxes of heat and momentum were assumed to be constant with height in a lower layer, and allowed to decrease with height in an upper transition layer. Surface boundary formulations followed those of Pandolfo, but the radiative effects of pollutants and water vapour were omitted. Simulations were carried out for day-time flow over a rough city, and nocturnal flow over a rough, warm city. In the latter case surface temperature was specified by use of observed cooling rates.

The model reproduced many of the observed features of the urban boundary layer. In strong wind conditions speeds were reduced by the urban roughness, but with a well-developed heat island urban speeds were increased. Vertical velocity patterns associated with horizontal speed changes were also in agreement with observation. The advection of cool rural air over the warm city produced an almost adiabatic mixing layer and simulated temperature profiles agreed well with data from New York and Montréal. More recent versions of URBMET have included the effects of anthropogenic moisture (Tam and Bornstein, 1975), anthropogenic heat (Dieterle, 1976) and a surface energy balance equation (Ellefsen et al., 1976).

Vukovich et al. (1976) presented a three-dimensional primitive equation model and applied it to the specific case of the St. Louis urban heat island. The model included basic forcing functions to characterize the city including the spatial distributions of topography, building height, surface roughness and the surface temperature field. These features were entered on a 144 x 144 km nested grid of the city and its surrounding area. There were 8 vertical levels up to a height of 4 km. The heat and momentum fluxes were determined through simultaneous solution of the boundary layer profile equations using 'friction' or 'scaling' quantities for velocity and temperature. These are proportional to the surface momentum and heat fluxes. Vertical eddy diffusivities were calculated using mixing lengths related to stability functions. The initial wind and temperature conditions were specified and then used to integrate the equations of motion.

The influence of a stable atmosphere was investigated using different synoptic wind speeds and wind directions. It was found as expected that the heat island intensity, and its circulation decreased with increasing wind speed and shear, and its heat plume extended further downwind. An example of the results for the weakest wind case is given in Figure 17. It will be noted that the thermal anomaly is centred on the city and extends to about 300 m in the vertical. Similarly the wind anomaly remains centred over the city with a pronounced zone of convergence and cyclonic curvature. Strongest winds are found upwind of the city centre (where the heat island pressure gradient produces acceleration), and weaker winds are experienced downwind. At 300 m (not shown) there was strong divergence. Also the city centre was characterized by upward vertical velocities extending to about 1 km. In simulations with stronger winds, the heat island circulation changed from one with cyclonic rotation (Figure 17c) to one characterized by a convergence line. Just as the heat plume extended downwind at higher speeds so did a tongue of positive vertical motion. Changes in the heat island due to wind direction were largely attributed to the effects of topography.

A three-dimensional model has also been developed by Atwater from an original model by Pandolfo (Atwater, 1974, 1975; Atwater and Pandolfo, 1975). It was based on the Eulerian conservation equation for momentum, heat, water vapour and pollutants in the atmosphere, heat in the soil and momentum, heat and salinity in water. The model extended from below the surface to a height of about 3 km. Finite difference solutions were defined for a three-dimensional space grid and a given time step. The dependent variables of temperature and velocity, and the heat fluxes were continuous at the surface.

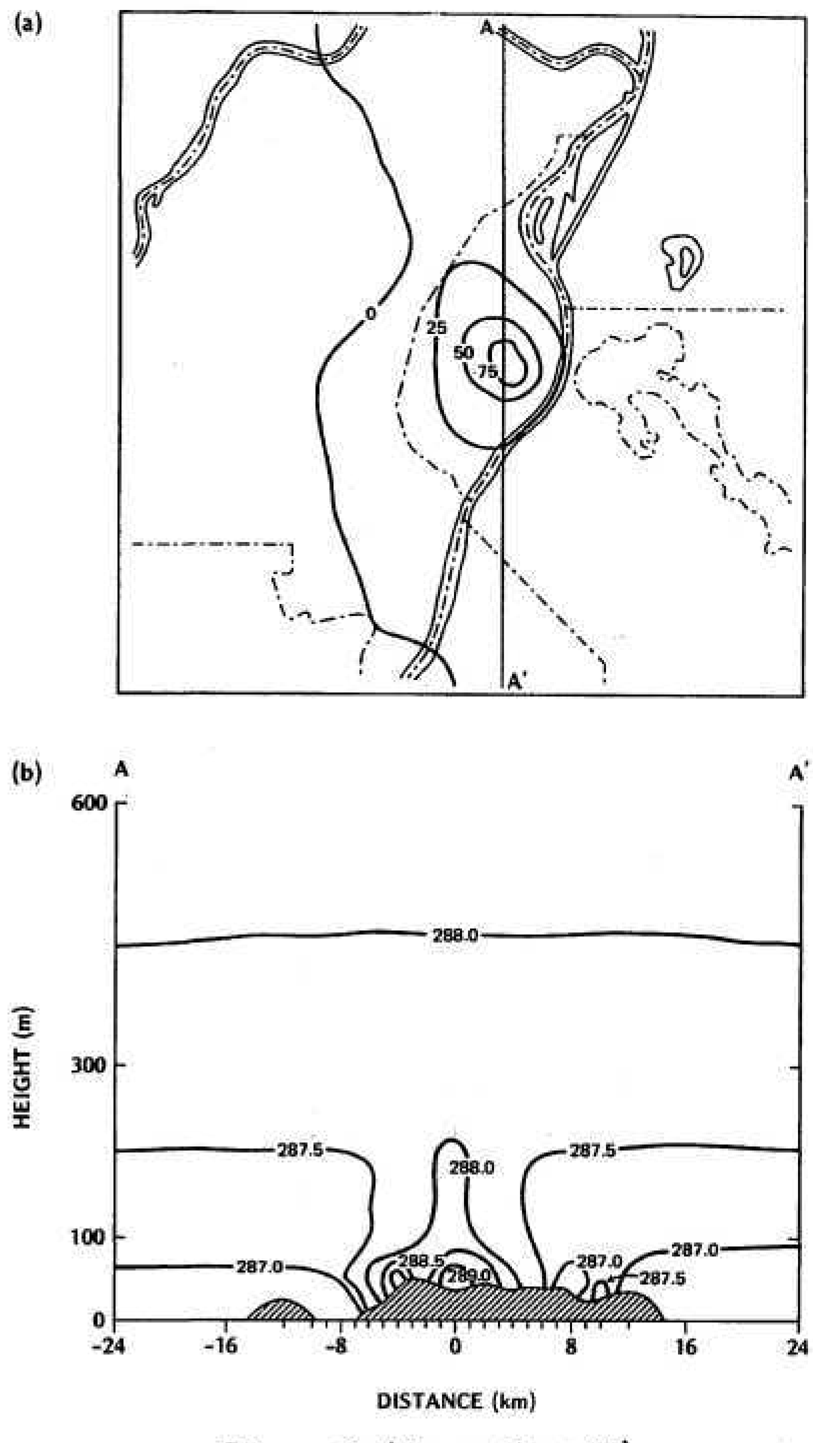

Figure 17- (See caption p. 66)

Radiative divergences due to pollutants and water vapour were computed in the atmosphere. The interface temperature was derived from an iterative solution to the surface heat balance equation which included an anthropogenic heat term.

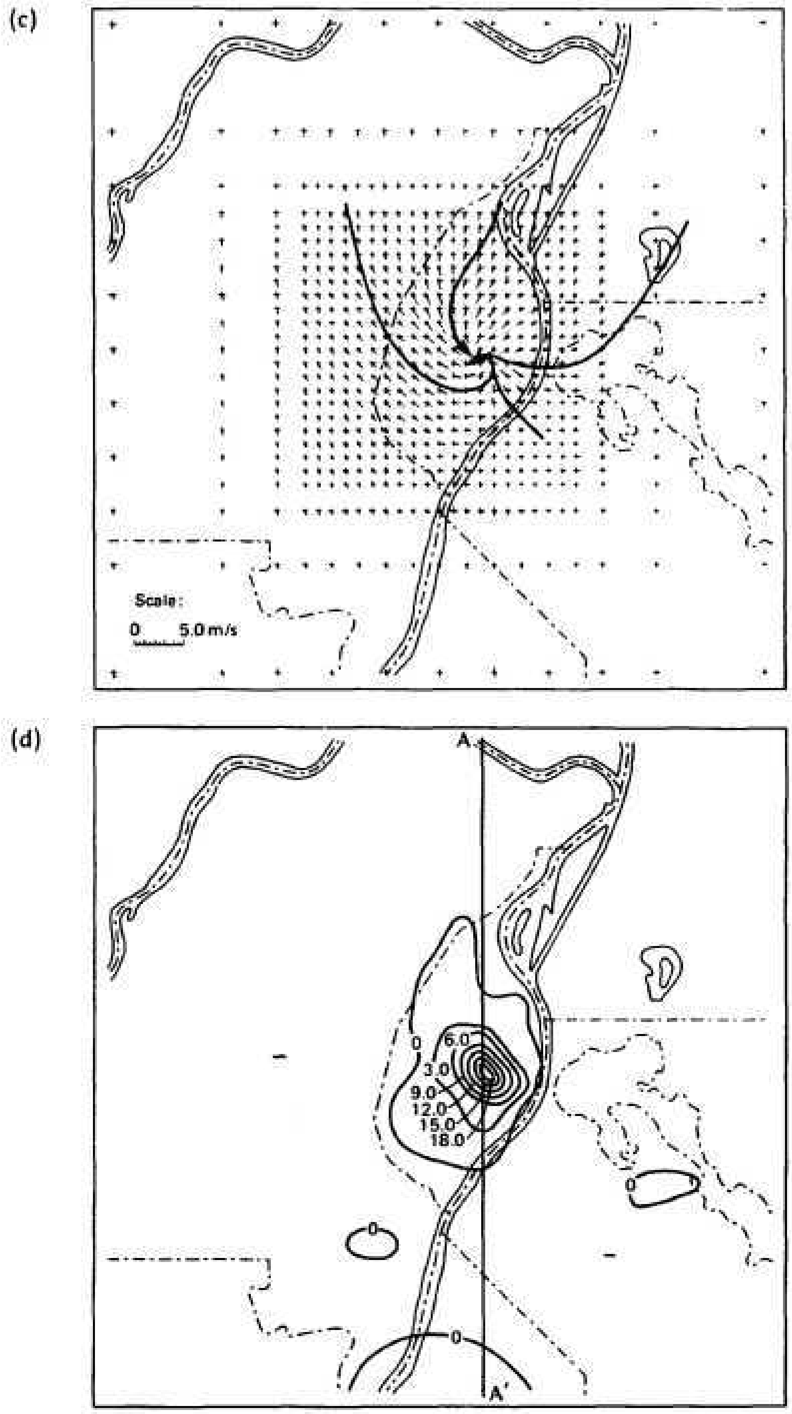

Figure 17 - (*See caption p. 66*)

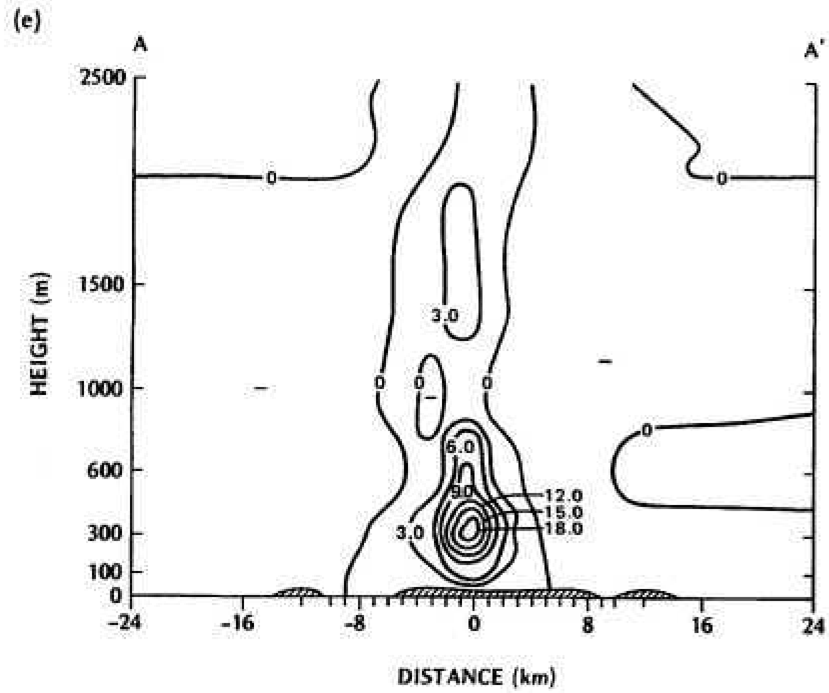

Figure *17 - Results of simulations from St. Louis using weak, stable airflow from the north:*
(a) spatial distribution of the temperature perturbation at 100 m,
(b) potential temperature (K) cross-section along line AA' in (a),
(c) spatial distribution of the horizontal wind vector at 100 m,
(d) distribution of the vertical velocity (positive upward, cm s^{-1}) at 300 m, and
(e) cross-section of vertical velocity (cm s^{-1}) along the line AA' in (d) (after Vukovich et al., 1976)

The model was used to simulate conditions in an arctic city surrounded by tundra but without pollutants (Atwater and Pandolfo, 1975), and for an hypothetical mid-latitude city in summer and winter (Atwater, 1975). In the arctic case it was noted that results were not dissimilar to those found in the mid-latitudes. The major difference seemed to be that arctic summer heat islands were more strongly negative by day. In the more general case it was found that the inclusion of pollutants had only a minor effect upon the heat island intensity, and on the vertical thermal structure. The major thermal change was an increase in stability. Model predictions for the vertical distribution of urban/rural temperature differences agreed well with observations in New York and Montréal.

Gutman (1974) and Gutman and Torrance (1975) presented a two-dimensional model which included water vapour effects on radiation and a surface energy balance equation with an anthropogenic heat term and an evaporative flux depending upon surface moisture. They investigated the winter-time nocturnal heat island case and made direct comparisons against observations from Montréal. Agreement at the surface and aloft was good. The thermal structure of the heat island was found to be more sensitive to anthropogenic heat changes than to surface roughness changes. Lee and Olfe (1974), using non-linear two-dimensional calculations, investigated the temperature and velocity changes induced in air flowing over a heat island. They modelled the destruction of a nocturnal inversion, and the 'cross-over' effect above the city.

During the period covered by this review there have been major developments in modelling the mixing height, especially the time development of h^* during the day-time as a result of the convergence of sensible heat in the boundary layer. Heat is thought to converge both from below due to the normal upward heat flux from the radiatively heated surface, and above due to 'penetrative convection' (entrainment of heat from the overlying inversion). Most of this work has been over rural terrain and cannot be covered here for lack of space, but Barnum and Rao (1974, 1975) have incorporated these ideas into a two-dimensional model for urban mixing heights. With the aid of this model and various analytical techniques, the dependence of h^* on such factors as horizontal advection, penetrative convection, lapse rate in the stable layer, etc. was delineated and compared with observations from St. Louis during selected summer days.

4. Scale models

Probably the most extensive scale modelling of the flow over cities has been conducted at the Colorado State University facility (Cermak, 1975;

Sethuraman, 1973, 1976; Sethuraman and Cermak, 1974a, b, 1975). The wind tunnel allows stratified boundary layers to be simulated. In a number of experiments stable flow across a heated 'city' was investigated. The heat island was simulated by the use of electrical heaters and, in some cases, roughness elements (aluminum blocks) were arranged on the heated area in a street-block pattern. Flow was visualized with the aid of a passive smoke source; mean and fluctuating temperatures were measured with an array of thermocouples; and, in some experiments, the mean wind speed and the longitudinal component of turbulence were monitored with temperature-compensated hot-wire probes.

Results suggested that the heat island was characterized by two large circulation cells, one upwind and one downwind. The former was associated with downward motion near the upwind edge, and the latter with upward motion extending over about one-fifth of the heat island and downwind. It was thought that these cells would be symmetric about the heat island centre, if general flow was absent. There was low-level horizontal convergence and uplift over the 'city' and upper-level horizontal divergence. The reverse situation applied in areas surrounding the heat island. Longitudinal turbulence intensities were greatly enhanced over a rough heat island and showed a minimum along the sides of the 'city' where lateral convergence produced longitudinal roll vortices. An elevated heat plume was seen downwind and it was suggested that buoyancy forces caused larger perturbations in the flow than the greater roughness. An empirical relationship to predict the height of the modified layer was devised and tested.

Cook (1973) discussed a method of simulating the characteristics of the adiabatic urban boundary layer in a wind tunnel, and carried the methodology through to apply the approach to a specific site for wind loading purposes (1974). Reasonable agreement with observation was achieved in respect of such properties as the mean velocity profile, turbulence intensity, stress, and gust velocity. Similarly Counihan (1973) reported simulations of adiabatic flow over urban terrain. In general, reasonable agreement was achieved in comparison with full scale data. Characteristics studied included the profiles of mean velocity and turbulence intensity, power spectral density, cospectra of stresses, and the power law index.

REFERENCES AND BIBLIOGRAPHY

ABAKUMOVA, G.M. and Z.P. SEMYONOVA, 1975: "Vliyaniye Moskvy na integral'nuyu prozrachnost' atmosfery", Meteorol. i Gidrol., No. 6, 38-44 (Engl. transl. in corresp. issue Meteorol. and Hydrol., Wash., D.C.).

ACKERMAN, B., 1974a: "Wind fields over the St. Louis metropolitan area", J. Air Pollut. Control Assoc., 24, 232-236.

ACKERMAN, B., 1974b: "Wind fields over St. Louis in undisturbed weather", Bull. Amer. Meteorol. Soc., 55, 93-95.

ACKERMAN, B., 1974c: "Wind profiles and their variability in the planetary boundary layer", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 19-22.

ACKERMAN, B., ALBERT, R.E., HESS, P.E., MOSES, H. and W.R. ROBINSON, 1973: "METROMEX urban/rural wind-aloft measurement, double theodolite pilot balloon runs, August 1971 - St. Louis, Missouri", ANL-8050, Argonne Nat. Lab., Argonne, Ill.

ACKERMAN, B. and H. APPLEMAN, 1974: "Boundary layer program," Interim Report of METROMEX Studies, NSF G1-38317, Ill. State Water Survey, Urbana, 121-143.

ACKERMAN, T.P., 1977: "A model of the effect of aerosols on urban climates with particular applications to the Los Angeles basin", J. Atmos. Sci., 34, 531-547.

ACKERMAN, T.P., LIOU, K-N. and C.B. LEOVY, 1976: "Infrared radiative transfer in polluted atmospheres", J. Appl. Meteorol., 15, 28-35.

AITKEN, A.P., 1973: "Hydrologic investigation and design in urban areas - a review", Austral. Water Resources Council Tech. Paper, No. 5, Austral. Govt. Publ. Service, Canberra, 79 pp.

AKERMAN, J., 1974: "Some climatologic aspects on road and road-projection", Uppsala Univ. Naturgeografiska Instit., Report No. 34, 211-229, (in Swedish).

AKINS, R.E.,PETERKA, J.A. and J.E. CERMAK, 1975: "Pressure distributions on buildings in atmospheric shear flows", Proc. 2nd US Nat. Conf. Wind Engineer. Res., WERC/NSF, Ft. Collins, Colo., III-2-1 to III-2-3.

ALBERT, R.E., MOSES, H. and W.R. ROBINSON, 1973: "Some measurements of nocturnal wind flow over St. Louis: METROMEX 1971", Annual Report Radiolog & Envir. Res. Div., ANL - 7960, Pt. IV, Argonne Nat. Lab., Argonne, Ill., 1-19.

ALKEZWEENY, A.J., 1975: "Evolution of the St. Louis aerosol distribution", 1974 Annual Report US Atmomic Energy Commiss., Div. of Biomedic and Environ. Res., Pt. 3, Atmos. Sci. Rpt. BNWL - 1950PT3, Battelle Pacific Northwest Labs., Richland, Wash., 65-69.

ALKEZWEENY, A.J., DANA, M.T., HALES, J.M., TANNER, T.M., THOMAS, C.W., THORP, J.M., WOGMAN, N.A. and J.A. YOUNG, 1974: "Activities of the Battelle-Northwest Laboratory in METROMEX", Bull. Amer. Meteorol. Soc., 55, 110-112.

ANGELL, J.K. and A.B. BERNSTEIN, 1975: "Flow across an urban area determined from double-theodolite pilot balloon observations", J. Appl. Meteorol., 14, 1072-1079.

ANGELL, J.K., HOECKER, W.H., DICKSON and D.H. PACK, 1973: "Urban influence on a strong daytime air flow as determined from tetroon flights", J. Appl. Meteorol., 12, 924-936.

ANGOURIDAKIS, V., 1975: "On the distribution of precipitation in the major area of Thessaloniki", Univ. Meteorol. Instit., Meteorologika No. 49, 45-69.

ANGOURIDAKIS, V. and P. MACHAIRAS, 1973: "Precipitation in Thessaloniki, Pt. 1", Univ. Meteorol. Instit., Report No. 32, Thessaloniki, Greece, 347-378.

APSALYAMOVA, Z.G., GERBURT-GEYBOVICH, A.A. and O.B. ZVORYKINA, 1973: "Issledovaniye mikroklimata novykh rayonov zhiloy zastroyki g. Moskvy", Leningrad, Tsentral'haya Vysotnaya Gidrometeorol. Observ., Trudy No. 2, 105-109.

ARAKAWA, H. and K. TSUTSUMI, 1975: "Strong gusts in the lowest 250m layer over the city of Tokyo", Boundary-Layer Meteorol., 8, 359-363.

ARENS, E., 1975: "Outdoor comfort of pedestrians in cities", paper presented at SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

ARMSTRONG, J.J., 1974: "Temperature differences between two ground-level sites and a roof site in Southampton", Meteorol. Mag., 103, 360-368.

ARNFIELD, J.A., 1976: "Numerical modelling of urban surface radiative parameters", Papers in Climatol., (Cam Allen Memorial Volume), Davies, J.A. ed., McMaster Univ., Hamilton, 1-28.

ARSENI-PAPADIMITRIOU, A., 1973: "On the annual variation of air temperature in Athens", Univ. Meteorol. Instit. Report No. 31, Thessaloniki, Greece, 325-345.

ASSAF, G. and Y. TZUR, 1974: "Measurement of the capacity of urban air for pollution using natural radioactivity", Israel J. Earth Sci., 23, 139-144.

ATKINSON, B.W., 1975: "The mechanical effect of an urban area on convective precipitation", Occas. Paper No. 3, Dept. Geog., Queen Mary College, Univ. London, 27 pp.

ATWATER, M.A., 1974: "Thermal changes induced by pollutants for different climatic regions", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 147-150.

ATWATER, M.A., 1975: "Thermal changes induced by urbanization and pollutants", J. Appl. Meteorol. 14, 1061-1071.

ATWATER, M.A. and J.P. PANDOLFO, 1975: "Tundra environmental changes induced by urbanization", in "Climate of the Arctic", Geophys. Instit., Univ. Alaska, Fairbanks, Alaska, 312-315.

AUER, A.H. Jr., 1974: "Cumulus congestus growth downwind of St. Louis, Missouri: Case study", J. Weath. Modif. 6, 229-237.

AUER, A.H. Jr., 1975a: "Calculations of divergence from the wind field over an urban area", Proc., 2nd U.S. Nat. Conf. Wind Engineer. Res., WERC/NSF, Ft. Collins, Colo., I-20-1 to I-20-3.

AUER, A.H. Jr., 1975b: "The production of cloud and Aitken nuclei by the St. Louis Metropolitan area (Project METROMEX)," J. Recherches Atmosphériques 9, 11-22.

AUER, A.H. Jr., 1976: "Observations of an industrial cumulus," J. Appl. Meteorol., 15, 406-413.

AUER, A.H. Jr., and R.A. DIRKS, 1974: "Contributions to an urban meteorological study: METROMEX," Bull. Amer. Meteorol. Soc., 55, 106-110.

BACH, W., 1973: "Solar radiation and atmospheric pollution", Archiv. Met. Geophys. Biokl., Ser. B, 21, 67-75.

BACH, W. and A. DANIELS, 1973: "Aerometric studies in Greater Cincinnati using an integrating nephelometer", Tellus, 25, 499-507.

BALKE, K.-D., 1974: "Die Kölner Temperaturanomalie," Die Umschau, 74, 315-316.

BALL, T., LaDOCHY, S., CHESTER, K., and T. WELCH, 1973: "The structure of the urban heat island: investigation of the heat storage capacity of the Winnipeg urban area", Manitoba Env. Res. Counc. Publ. Project No. 33, 15 pp.

BARNUM, D.C. and G.V. RAO, 1974: "The interaction of the urban heat island with the planetary boundary layer", Preprint 5th Conf. on Weather Forecasting and Analysis, Amer. Meteorol. Soc., 176-179.

BARNUM, D.C. and G.V. RAO, 1975: "Role of advection and penetrative convection in affecting the mixing-height variations over an idealized metropolitan area", Boundary-Layer Meteorol., 8, 497-514.

BENARIE, M.M., 1975: "Calculation of the mean yearly mixing height over urban areas, from air pollution data", Sci. Total Environ., 3, 259-265.

BENNETT, R.C. and R. LIST, 1974: "Urban boundary layer structures", Preprint 8th Annual Congress Canadian Meteorological Soc., Toronto.

BENSON, C.S. and S.A. BOWLING, 1975: "The sub-arctic urban heat island as studied at Fairbanks, Alaska", in "Climate of the Arctic" (Weller, G. and S.A. Bowling, eds.), Geophys. Instit., Univ. Alaska, Fairbanks, Alaska, 309-311.

BERAN, D.W. and F.F. HALL Jr., 1974: "Remote sensing for air pollution meteorology", Bull. Amer. Meteorol. Soc., 55, 1097-1105.

BERGQVIST, E., 1974: "Some climatic differences within the Uppsala area", Uppsala Univ. Naturgeografiska Instit., Report No. 34, p. 237.

BERGSTROM, R.W. Jr., 1973a: "Comments on the estimation of aerosol absorption coefficients in the atmosphere, Beitr. Physik Atmos. 46, 198-202.

BERGSTROM, R.W. Jr., 1973b: "Extinction and absorption coefficients of the atmospheric aerosol as a function of particle size", Beitr. Physik Atmos., 46, 223-234.

BERGSTROM, R.W. Jr. (ed.), 1976: "Modeling the urban boundary layer", NASA Tech. Memo. NASA TM X-73,099, Ames Research Center, Moffett Fd., Calif., 19 pp.

BERGSTROM, R.W. Jr., and R. VISKANTA, 1973a: "Modeling of the effects of gaseous and particulate pollutants in the urban atmosphere, Part I: Thermal Structure", J. Appl. Meteorol., 12, 901-912.

BERGSTROM, R.W. Jr. and R. VISKANTA, 1973b: "Modeling of the effects of gaseous and particulate pollutants in the urban atmosphere, Part II: Pollutant dispersion", J. Appl. Meteorl., 12, 913-918.

BERGSTROM, R.W. Jr. and R. VISKANTA, 1973c: "Prediction of the solar radiant flux heating rates in a polluted atmosphere," Tellus, 25, 486-498.

BERGSTROM, R.W. Jr. and R. VISKANTA, 1974: "Spherical harmonics approximation for radiative transfer in polluted atmospheres", Progress in Astronautics and Aeronautics, 35, 23-40.

BERLYAND, M. Ye., BUDYKO,M.I. and K. Ya KONDRAT'YEV, 1973: "Urban climate and the problems of variation of the global climate", Meteorol. i Gidrol., No. 1, 3-14 - transl. in Meteorol. and Hydrol. same vol. and page nos.

BERLYAND, M.E. and K. Ya KONDRAT'YEV, 1972: "Cities and the global climate", Transl. by A. Nurklik from Gidrometeoizdat, L., 1972, in Meteorol. Transl. No. 23, Atmos. Environ. Service Canada, 1973, 25-59.

BERLYAND, M. Ye, KONDRAT'YEV, K. Ya., VASIL'YEV, O.B., VASIL'CHENKO, I.V., ZHVALEV, V.F., ZRAZHEVSKIY, I.M. and L.S. IVLEV, 1974: "Combined investigations of peculiarities of the meteorological regime of a big city in the example of Zaporozh'ye (CAENEX-72)", Meteorologiya i Gidrologiya, No. 1, 14-23 - transl. in Meteorol. and Hydrol. same vol. and page nos.

BERNATZKY, A., 1975: "Gardens for stepped terrace housing", Urban Ecology, 1, 49-62.

BERRY, B.J.L. (ed.), 1974: "Land use, urban form and environmental quality", Research Paper No. 155, Dept. Geog., Univ. Chicago, 440 pp.

BLACKBURN, T., 1975: "Washington's 'free' 300-station micro weather network", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ. Syracuse, N.Y.

BLANCHARD, D., 1975: "Final NSF Report on Second Inadvertent Weather Modification Workshop", ASRC-SUNY Public. No. 366, State Univ. N.Y., Albany, 82 pp.

BLANCHARD, G.W., FREESTON, D.H. and R. FREASEY, 1975: "Simulation of a strong-wind urban boundary layer in a wind tunnel." Proc. 5th Austral. Conf. Hydraul. and Fluid Mech., 190-199.

BOATMAN, J.F. and A.H. AUER, 1974: "Inadvertent thunderstorm modification by an urban area", Proc. 4th Conf. Weath. Modif. Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 366-373.

BOLIN, B., 1975: "Energy and Climate", Secretariat for Future Studies, Stockholm, Sweden, 55 p.

BORNGEN, M. and O. DOBIERZIN, 1976: "Beitrag zur Kenntnis des anthropogen Effekts auf die mittlere Lufttemperatur dargestellt anhand eines Vergleichs zwishen den Stationen Leipzig und Schwerin", Zeit. Meteorol., 26, 146-151.

BORNSTEIN, R.D., 1973: "Conference on the urban boundary layer at California State University, San Jose", Bull. Amer. Meteorol. Soc., 54, 549-550.

BORNSTEIN, R.D., 1975: "The two-dimensional URBMET urban boundary layer model", J. Appl. Meteorol., 14, 1459-1477.

BORNSTEIN, R.D., LORENZEN, A. and D. JOHNSON, 1972: "Recent observations of urban effects on winds and temperatures in and around New York City." Preprints Conf. Urban Environ. Second Conf. Biometeorol., Amer. Meteorol. Soc., 28-33.

BORNSTEIN, R.D., MORGAN, T., TAM, Y.-T., LOOSE, T., LEAP, K., SIGAFOOSE, J. and C. BERKOWITZ, 1976: "New York University New York City urban air pollution project of 1964-1969: The data," Final Report, Vol. 1, Contract DU-74-8491, San Jose State Univ., San Jose.

BORNSTEIN, R.D. and A.D. ROBOCK, 1976: "Effects of variable and unequal time steps for advective and diffusive processes in simulations of the urban boundary layer", Month. Weath. Rev., 104, 260-267.

BOURQUE, D.A., 1974: "The use of condensation plumes in the determination of horizontal urban wind fields", Preprint, 2nd Canadian Conf. Remote Sensing, Guelph.

BOURQUE, D.A., 1976: "The determination of horizontal urban wind fields by condensation plumes", Can. Meteorol. Res. Reports, Can. Atmos. Environ. Service, Environ. Canada, Downsview.

BOWLING, S.A., BENSON, C.S. and G.E. SHAW, 1976: "City climates and air pollution", Annual Report 1975-76, Geophys. Instit., Univ. Alaska, Fairbanks, 110-111.

BRAHAM, R.R. Jr., 1972: "University of Chicago contribution to Project METROMEX - 1", Final Tech. Report, NSF Grant GA 28190X1, Univ. Chicago, Chicago, Ill., NTIS No. PB-218 678, 101 pp.

BRAHAM, R.R. Jr., 1974a: "Cloud physics of urban weather modification - a preliminary report", Bull. Amer. Meteorol. Soc., 55, 100-106.

BRAHAM, R.R. Jr., (compiler), 1974b: "1974 Operational Report for METROMEX", Univ. Chicago, Chicago.

BRAHAM, R.R. Jr., 1974c: "Information content of CCN spectra vs measurements at a single supersaturation", Preprints Conf. Cloud Phys., Tucson, Amer. Meteorol. Soc., Boston, 9-12.

BRAHAM, R.R. Jr., 1975: "Overview of urban climate", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

BRAHAM, R.R. Jr., 1976a: "CCN spectra in C-k space", J. Atmos. Sci., 33, 343-345.

BRAHAM, R.R. Jr., 1976b: "Modification of clouds and weather by a large metropolitan area", Proc. 2nd WMO Sci. Conf. Weath. Modif., Boulder, WMO Report 443, World Meteorol. Organiz., Geneva, 435-444.

BRAHAM, R.R. Jr., and M. DUNGEY, 1976: "Effects of a large city upon convective clouds and coalescence rain", Preprints Int. Conf. Cloud Phys., Boulder, Amer. Meteorol. Soc., Boston, 275-278.

BRAHAM, R.R. Jr., DUNGEY, M. MORRIS, T.R., CHANGNON, S.A. Jr., and F.A. HUFF, 1975: "A summary of Project METROMEX radar findings", Preprints 16th Radar Meteorol. Conf., Houston, Amer. Meteorol. Soc., Boston, 404-409.

BRAHAM, R.R., DYTCH, H. and R.G. KNOLLENBERG, 1973: "Aerosol measurements over St. Louis", Amer. Geophys. Union Meeting, Washington, D.C.

BRAHAM, R.R. and P. SPYERS-DURAN, 1974a: "Ice nucleus measurements in an urban atmosphere", J. Appl. Meteorol., 13, 940-945.

BRAHAM, R.R. Jr. and P. SPYERS-DURAN, 1974b: "Ice nucleus measurements at St. Louis", Preprints, 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 384-385.

BRAZEL, A.J. and R. OSBORNE, 1976: "Observations of atmospheric thermal radiation at Windsor, Ontario, Canada", Archiv. Meteorol. Geophys. Bioklima., Ser. B, 24, 189-200.

BREEDING, R.J., HAAGENSON, P.L., ANDERSON, J.A., LODGE, J.P. Jr., and J.F. STAMPFER, Jr., 1975: "The urban plume as seen at 80 and 120 km by five different sensors:, J. Appl. Meteorl., 14, 204-216.

BROOK, R.R., 1974a: "A study of self-similarity in turbulence measured at an urban site", J. Appl. Meteorol., 13, 767-770.

BROOK, R.R., 1974b: "A study of wind structure in an urban environment", Meteorol. Study No. 27, Australian Govt. Publ. Service, Canberra, 232 pp.

BROOK, R.R., 1975: "A note on vertical coherence of wind measured in an urban boundary layer", Boundary-Layer Meteorol. 9, 11-20.

CARRERA, N.J., 1975: "Urban influences on cloud microstructure downwind from St. Louis, Missouri: Upper level observations", J. de Recherches Atmosphériques, 9, 157-165.

CATANEO, R., 1973a: "Aircraft measurements and observations", Summary Report of METROMEX Studies, 1971-72, Rept. of Investig. 74, Ill. State Water Survey, Urbana, 153-162.

CATENEO, R., 1973b: "Surface measurements of condensation nuclei and raindrop distribution", Summary Report of METROMEX Studies, 1971-72, Rept. of Investig. 74, Ill. State Water Survey, Urbana, 84-88.

CATANEO, R., 1974: "Operational aspects of Project METROMEX - an inadvertent weather modification study", Preprints, 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 379-381.

CECH, I., WEISBERG, R., HACKER, C. and R. LANE, 1976: "Relative contribution of land uses to the urban heat problem in the coastal subtropics", Internat. J. Biometeorol., 20, 9-18.

CERMAK, J.E., 1975: "Applications of fluid mechanics to wind engineering - A Freeman Scholar Lecture", J. Fluids Engineer., 97, 9-38.

CERMAK, J.E., LOMBARDI, D.J. and R.S. THOMPSON, 1974: "Application of physical modeling to the investigation of air pollution problems in urban areas", APCA #74-160, Denver, Colo.

CHANDLER, T.J., 1970: "Selected bibliography on urban climate", WMO No. 276, TP 155, World Meteorol. Organiz., Geneva, 383 pp.

CHANDLER, T.J., 1976a: "Urban climates and urban design", Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 176-202.

CHANDLER, T.J., 1976b: "Urban climatology and its relevance to urban design", WMO Tech. Note No. 149, WMO No. 438, World Meteorol. Organiz., Geneva, 62 pp.

CHANDLER, T.J., 1976c: "Urban climates and the natural environment", Internat. J. Biometeorol., 20, 128-138.

CHANGNON, S.A. Jr., 1973: "Inadvertent weather and precipitation modification by urbanization", J. Irrig. Drain. Div. A.S.C.E., 99 IRI, 27-41.

CHANGNON, S.A. Jr., 1974a: "Increases in modulated temperatures - an indication of inadvertent climate modification", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 155-158.

CHANGNON, S.A. Jr., 1974b: "A review of inadvertent mesoscale weather and climate modification and assessment of research needs", Preprints, 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 347-352.

CHANGNON, S.A. Jr., 1975: "Operations of mesoscale networks, illustrated by METROMEX", Bull. Amer. Meteorol. Soc., 56, 971-977.

CHANGNON, S.A. Jr., 1976a: Discussion of "A comparison of urban climatic modifications in three cities", Atmos. Environ., 10, 494.

CHANGNON, S.A. Jr., 1976b: "Effects of urban areas and echo merging on radar echo behavior", J. Appl. Meteorol., 15, 561-570.

CHANGNON, S.A. Jr., and F.A. HUFF, 1973: "Enhancement of severe weather by the St. Louis urban-industrial complex", Preprint 8th Conf. on Severe Local Storms, Denver, Amer. Meteorol. Soc., 122-129.

CHANGNON, S.A. Jr. and R.G. SEMONIN (eds.), 1975): "Studies of selected precipitation cases from METROMEX" Report of Investig. 81, Illinois State Water Survey, State of Illinois, Dept. Registration and Education, Urbana, 329 pp. [incl. papers by HUFF, F.A. and S.A. CHANGNON Jr., 11-67; SEMONIN, R.G., 68-89; SCHICKEDANZ, P.T. and D.F. GATZ, 90-127; CHANGNON, S.A. Jr. and F.A. HUFF, 128-161; CATANEO, R.C. and D.M.A. JONES, 162-174; CATANEO, R.C., 175-190; VOGEL, J.L., 191-231; MORGAN, G.M. Jr., ACHTEMEIER, G.L. and H.T. OCHS III, 232-267; GATZ, D.F. and P.T. SCHICKEDANZ, 268-321.]

CHANGNON, S.A. Jr., SEMONIN, R.G. and F.A. HUFF, 1976: "A hypothesis for urban rainfall anomalies", J. Appl. Meteorol., 15, 544-560.

CHARTON, F.L. and J.R. HARMAN, 1973: "An additional comment on the La Porte precipitation anomaly", Bull. Amer. Meteorol. Soc., 54, 26.

CLARKE, J.F. and J.T. PETERSON, 1973: "An empirical model using eigenvectors to calculate the temporal and spatial variations of the St. Louis heat island", J. Appl. Meteorol., 12, 195-210.

CLARKE, J.F. and J.L. McELROY, 1974: "Effects of ambient meteorology and urban meteorological features on the vertical temperature structure over cities", 67th Annual Meeting Air Poll. Control. Assoc., Denver, Colo.

COLE, R.J., 1976a: "The longwave radiation incident upon the external surface of buildings", Build. Services Engineer, 44, 195-206.

COLE, R.J., 1976b: "The longwave radiative environment around buildings", Build. Environ., 11, 3-13.

COLLINS, M.P., BIRKEMOE, P.C., MILLS, R.H., ROBINSKY, E.I., SCHWAIGHOFER, J., TIMUSK, J. and S.M. UZUMERI, 1975: "Instrumentation of the CN Tower", Proc. 2nd US Nat. Conf. Wind Engineer. Res., WERC/NSF, Ft. Collins, Colo., II-18-1.

CONRADS, L.A., 1976: "Observations of meteorological urban effects: The heat island of Utrecht", Univ. Netherlands, Utrecht.

COOK, N.J., 1973: "On simulating the lower third of the urban adiabatic boundary layer in a wind tunnel", Atmos. Environ. 7, 691-705.

COOK, N.J., 1974: "On applying a general atmospheric simulation method to a particular urban site for ad hoc wind loading or wind environment studies", Atmos. Environ. 8, 85-87.

COUNIHAN, J., 1973: "Simulation of an adiabatic urban boundary layer in a wind tunnel", Atmos. Environ., 7, 673-689.

COUNIHAN, J., 1975: "Adiabatic atmospheric boundary layers: a review and analysis of data from the period 1880-1972", Atmos. Environ., 9, 871-905.

CRANE, F. and H.A. PANOFSKY, 1976: "A dispersion model for Los Angeles", Preprints 3rd Symp. Atmos. Turb., Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 122-123.

DABBERDT, W.F. and P.A. DAVIS, 1974a: "Determination of energetic characteristics of urban-rural surfaces in the Greater St. Louis area", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 133-141.

DABBERDT, W.F. and P.A. DAVIS, 1974b: "Determination of energetic characteristics of urban-rural surfaces in the Greater St. Louis Area", Report No. EPA-650/ 4-74-007, Stanford Res. Instit., Menlo Pk., Calif., 77 pp.

DABBERDT, W.F., LUDWIG, F.L. and W.B. JOHNSON Jr., 1973: "Validation and applications of an urban diffusion model for vehicular pollutants", Atmos. Environ., 7, 603-618.

DIAGO, M. and T. NAGAO, 1972: "Urban Climatology", Asakura-Shoten, Tokyo, 214 pp. (in Japanese).

DANIEL, C.E.J. and K. KRISHNAMURTHY, 1973: "Urban temperature fields at Poona and Bombay", Indian J. Meteorol. Geophys., 24, 407-412.

DANNEVIK, W.P., FRISELLA, S., HWANG, H.J. and R.B. HUSAR, 1974: "Analysis and characterization of heat island-induced urban circulation during the 1973 EPA aerosol characterization study, St. Louis, Missouri", Preprint Fifth Conference on Weather Forecasting and Analysis, Amer. Meteorol. Soc., Boston.

DAW, F.A. and K.J. O'LOUGHLIN, 1972: "Canberra - A.C.T. - Dispersion climatology and meteorological effects on the distribution of air pollution", Proc. Int. Clean Air Conf., Melbourne, Australia, 39-46.

DE FREITAS, C.R., 1975: "Estimation of the disruptive impact of snowfalls in urban areas", J. Appl. Meteorol., 14, 1166-1173.

DeMARRAIS, G.A., 1975: "Nocturnal heat island intensities and relevance to forecasts of mixing heights", Mo. Weath. Rev., 103, 235-245.

DETTWILLER, J.W. and S.A. CHANGNON, Jr., 1976: Possible urban effects on maximum daily rainfall at Paris, St. Louis and Chicago", J. Appl. Meteorol., 15, 517-519.

DETWILER, A., 1974: "Urban influence on cumulus formation", Bull. Amer. Meteorol. Soc., 55, 1240-1241.

DIETERLE, D., 1976: "Simulation of the urban surface energy balance, including the effects of anthropogenic heat production", Unpubl. M.Sc. Thesis, San Jose, Calif.

DIRKS, R.A., 1974a: "Urban atmosphere: Warm dry envelope over St. Louis", J. Geophys. Res., 79, 3473-3475.

DIRKS, R.A., 1974b: "Urban modification of heat and moisture fields", Preprints, 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 362-365.

DIRKS, R.A. and K.K. WONG, 1975: "The urban wind field - a thermal perturbation", paper AMS Conf. Regional and Mesoscale Model. Anal. and Predict., Las Vegas, May.

DOVGYALLO, E.N., 1974: "Horizontal transmission in urban and industrial centres", in "Actinometry, Atmospheric Optics and Ozonometry", (G.P. Guschin, ed.), Israel Progr. Sci. Transl. 141-147.

DUCHÊNE-MARULLAZ, P., 1975a: "Turbulence atmosphérique au voisinage d'une ville", Report EN. CLI 75-2, Centre Scientif. Tech. Bâtiment, Nantes.

DUCHÊNE-MARULLAZ, P., 1975b: "Vent et température au voisinage d'une ville: comparaison avec la station meteorologique de l'aéroport", Report EN, CLI 75-4, Centre Scientif. Tech. Bâtiment, Nantes.

DUCHÊNE-MARULLAZ, P., 1975c: "Full-scale measurements of atmospheric turbulence in a suburban area", preprint Fourth Internat. Conf. Wind Effects on Build. and Struct., London.

DUCHÊNE-MARULLAZ, P., 1976: "Structure du vent en zone suburbaine rugosité et corrélation latérale", Report EN, CLI 76-2, Centre Scientif. Tech. Batiment, Nantes.

DUNGEY, M. and T.R. MORRIS, 1972: "Radar studies of urban precipitation anomaly", in Final Tech. Report, NSF Grant GA 28190X1, Univ. Chicago, Chicago, Ill. NTIS No. PB-218 678, 25-33.

DUNGEY, M., MORRIS, T.R. and R.R. BRAHAM Jr., 1974: "Radar data analyses in METROMEX, 1971-72-73", Preprints 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 358-361.

DYTCH, H.E., 1972: "METROMEX temperature and aerosol data reduction: analysis of the urban anomaly", in Final Tech. Report. NSF Grant GA 28190X1, Univ. Chicago, Chicago, Ill. NTIS No. PB-218 678, 73-90.

DYTCH, H.E., 1974a: "Observations of natural CCN and large aerosol over St. Louis," Preprints Conf. Cloud Phys., Tucson, Amer. Meteorol. Soc., Boston, 5-8.

DYTCH, H.E., 1974b: "An investigation of urban influence upon cloud microstructure several thousand feet above cloud base", Preprints 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 386-389.

DYTCH, H.E., 1975: "Urban influences on cloud microstructure downwind from St. Louis, Missouri: Lower level observations", J. de Recherches Atmosphériques, 9, 145-156.

EAGLEMAN, J.R., 1974: "A comparison of urban climatic modifications in three cities", Atmos. Environ., 8, 1131-1142.

EICHENLAUB, V.L. and C.M. BACON, 1974: "Convective precipitation in the Detroit urban area", Profess. Geogr., 26, 140-146.

EL-AGRAA, O.M.A., 1974: "Environmentally oriented planning for human settlement - Africa", in "Environment and Development", SCOPE Misc. Public., Indiannapolis, 213-226.

ELLEFSEN, R.A., TAKIZAWA, B. and R.D. BORNSTEIN, 1976: "Use of computer processed satellite data in numerical boundary layer models for land-use planning", Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 261-279.

FERRAR, T.A., (ed.), 1976: "Urban costs of climate modification", John Wiley and Sons, N.Y., 284 pp.

FINKELSTEIN, P.L., 1974: "Study of urban fumigation", unpubl. Ph.D. Thesis, Drexel Univ., Philadelphia, 105 pp.

FITZGERALD, J.W. and P.A. SPYERS-DURAN, 1973: "Changes in cloud nucleus concentration and cloud droplet size distribution associated with pollution from St. Louis", J. Appl. Meteorol., 12, 511-516.

FOGELBERG, P., NIKIFOROW, M., SÖDERMAN, G. and L. TORNBERG, 1973: "Observations on the temperature climate of Helsinki in winter", Terra, 85, 234-239.

FONTAN, J. et al., 1976: "Surveillance de la stabilité verticale dans un site urbain", Pollution Atmosphérique, 18, 231-240.

FRENZEN, P., 1972: "Instrumentation for atmospheric boundary layer studies; The WHAT system", Argonne National Lab. Radiological Physics Div., Annual Report, ANL 7960, Pt. IV, 84-87.

FRISKEN, W.R., 1973: "The Atmospheric environment of cities", in "The atmospheric environment", Resources for the Future Inc., 9-48.

and

Climat. Studies No. 25, Atmos. Environ. Service, Canada, 30 pp.

FRITTS, H.C. and W.C. ASHBY, 1973: "Reply" to Charton and Harmon, Bull. Amer. Meteorol. Soc., 54, 26-27.

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 Meteorol., 10, 113-120.

FUKUOKA, Y. and K. TANAKA, 1973: "Air pollution and micro-meteorology in and around a tunnel", Geog. Review of Japan, 46, 550-554.

GAGE, K.S. and W.H. JASPERSON, 1974: "Prototype balloon-tracking system yields accurate high-resolution winds in Minneapolis field test", Bull. Amer. Meteorol. Soc., 55, 1107-1114.

GAGE, K.S. and W.H. JASPERSON, 1976: "Diffusion coefficients estimated from turbulence data measured by the METRAC positioning system in Minneapolis field test", Preprints 3rd Symp. Atmos. Turb., Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 114-121.

GARSTANG, M., TYSON, P.D. and G.D. EMMITT, 1975: "The structure of heat islands", Rev. Geophys. Space Phys., 13, 139-165.

GARTSHORE, I.S., 1973: "A relationship between roughness geometry and velocity profile shape for turbulent boundary layers", Report, LTA-LA-140, Low Speed Aerodynamics, Nat. Aero. Estab., Nat. Res. Council Canada, 27 pp.

GATZ, D.F., 1974: "METROMEX: air and rain chemistry analyses", Bull. Amer. Meteorol. Soc., 55, 92-93.

GEBURT-GEBOVICH, A.A. and P.M. IL'IN, 1974: "Klimat-gorodchelovek", Akad. Nauk SSSR, Moscow, Ivestiya, Ser. Geog., No. 4, 48-54.

GEIGER, B., 1974: "Energetische Belastung des Stadtklimas," Preprints CIB/WMO Symp. Climatol. of Build., Zurich, Schweizer Bau Dokumentation, Zurich, 41-54.

GIFFORD, F.A., 1972: "Transport and dispersion in urban environments", in Dispersion and Forecasting of Air Pollution", WMO Tech. Note No. 121, WMO No. 319, Geneva, 27-42.

GIVONI, B., 1973: "Urban and building biometeorological research: an overview", Int. J. Biometeorol., Suppl. 16, Vol. 5, Pt. II, 85-87.

GLAZIER, J., MONTEITH, J.L. and M.H. UNSWORTH, 1976: "Effects of aerosol on the local heat budget of the lower atmosphere", Quart. J. Royal Meteorol. Soc., 102, 95-102.

GOLDMAN, J.L., 1977: "Urbanization and climatic change", in "The Urban Costs of Climate Modification", T.A. Ferrar (ed.), John Wiley and Sons, New York, 43-101.

GOLDREICH, Y., 1974a: "Empirical computation of weather influence on the heat island intensity", Proc. 5th Sci. Conf. Israel Ecolog. Soc., Tel Aviv, A69-A77.

GOLDREICH, Y., 1974b: "Observations on the urban humidity island in Johannesburg", Israel J. Earth Sci., 23, 39-46.

GOLDREICH, Y. and A. MANES, 1975: "Urban effects on precipitation patterns at the Greater Tel-Aviv area", in "Urban effects on local climate at the Greater Tel-Aviv area", Bar-Ilan Univ. and Israel Meteorol. Service, Bet-Dagan.

GRIFFITHS, J.F., 1976: "Climate and the Environment", Elek Books Ltd., London, 125-131.

GRØNSKEI, K.E., 1974: "Requirements of air quality models for land use planning". In Proc. Air Pollution Expert Panel Meeting, NATO Comm. on the Challenges of Modern Soc., NATO/CCMS Air Poll. Publ. No. 35, Ch. 11, 29 pp.

GRØNSKEI, K.E., JORANGER, E. and F. GRAM, 1973: "Assessment of air quality in Oslo, Norway", Appendix D to NATO/CCMS Air Poll. Doc No. 6, Norweg. Instit. Air Research, Kjeller, Norway, 50-54.

GROSH, R.C. and R.G. SEMONIN, 1973: "Moisture budgets and wind fields of thunderstorms passing over an urban area in the Midwest", Preprints 8th Conf. on Severe Local Storms, Denver, Amer. Meteorol. Soc., 130-137.

GROSH, R.C. and R.G. SEMONIN, 1974: "Growth rates of urban radar echoes observed during METROMEX", Preprint 8th Annual Congress Canadian Meteorol. Soc., Toronto, 9 p.

GUGIUMAN, I. and M. COTRĂU, 1975: "Elemente de Climatologie Urbana cu exemple din România", Editura Academiei Repub. Social. România, Bucharest.

GUTMAN, D.P., 1974: "Heat rejection and roughness effects on the planetary boundary layer above cities", unpubl. Ph.D. Thesis, Cornell Univ., Ithaca, N.Y., 223 pp.

GUTMAN, D.P. and K.E. TORRANCE, 1975: "Response of the urban boundary layer to heat addition and surface roughness", Boundary-Layer Meteorol., 9, 217-233.

HAAGENSON, P.L. and A.L. MORRIS, 1974: "Forecasting the behavior of the St. Louis, Missouri pollutant plume", J. Appl. Meteorol., 13, 901-909.

HÄCKEL, H., 1975: "Modellrechnungen zum nachtlichen Strahlen haushalt von Pflanzen", Meteorol. Rundschau, 28, 148-154.

HÄFELE, W., 1973: "Energy systems", Proc. IIASA Planning Conf. Energy Systems, Internat. Instit. Appl. Systems Analysis, Schloss-Laxenburg, Austria, 9-78.

HAGE, K.D., 1975: "Urban-rural humidity differences", J. Appl. Meteorol., 14, 1277-1283.

HALPERN, P. and K.L. COULSON, 1974: "Effect of particulate pollutants on solar energy transfer through the lower troposphere", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 142-146.

HANNELL, F.G., 1976: "Some features of the heat island in an equatorial city", Geograf. Annaler, 58, Ser. A. 1-2, 95-109.

HARDMAN, C.E., HELLIWELL, N.C. and J.S. HOPKINS, 1973: "Extreme wind speeds over the United Kingdom for periods ending 1971", Meteorol. Office Climatol. Mem. No. 50A, Meteorol. Office, Bracknell, Berks.

HARLFINGER, O., 1976: "Die bioklimatische Bedeutung des "Höllentälers" für Freiburg", Meteorol. Rundschau, 29, 15-18.

HARNACK, R.P. and H.E. LANDSBERG, 1975: "Selected cases of convective precipitation caused by the metropolitan area of Washington, D.C.", J. Appl. Meteorol., 14, 1050-1060.

HAUGEN, D.A., KAIMAL, J.C., READINGS, C.J. and R. RAYMENT, 1975: "A comparison of balloon-borne and tower-mounted instrumentation for probing the atmospheric boundary layer", J. Appl. Meteorol., 14, 540-545.

HAY, D.R. and V.E. SELLS, 1974: "Thermal plumes in an urban environment", Preprint 8th Annual Congress, Canadian Meteorol. Soc., Toronto.

HERRINGTON, L.P. and G.M. HEISLER, 1976: "Conference summary", Bull. Amer. Meteorol. Soc., 57, 696-699.

HERRMANN, R., 1973: "Untersuchungen über die zeitliche und räumliche Anderung des Temperaturfeldes im Stadtgebiet von Giessen", Die Erde, 104, 226-246.

HIRT, M.S. and R.W. SHAW, 1973: "The passage of a lake-breeze front at Toronto - a comparison between the city and the suburbs", Atmos. Environ., 7, 63-73.

HOLMER, B., 1974: "Fields of wind direction around buildings - aspects of interpretation and application", Uppsala Univ. Naturgeografiska Inst., Report No. 34, 179-192, (in Swedish).

HOLZWORTH, G.C., 1967: "Mixing depths, wind speeds and air pollution potential for selected locations in the United States", J. Appl. Meteorol., 6, 1039-1044.

HOSOKAWA, K., 1974: "Horizontal profiles of air temperature across small towns in Southern Miyagi Prefecture", Science Reports, Tohoku Univ., 7th Ser., Geog., 24, 25-31.

HOYDYSH, W.G., OGAWA, Y., PIVA, R. and P. ORLANDI, 1975: "A combined experimental and numerical study of flow in street canyons", Proc. 2nd U.S. Nat. Conf. Wind Engineer. Res., WERC/NSF, Ft. Collins, Colo., I-17-1 to I-17-3.

HUCKABY, J.L. and L. ROUCH, 1975: "The microclimatic impact of reflective glass buildings in an urban environment", paper presented to SUNY/USFS/AMS Conf. Metro Phys. Environ. Syracuse, N.Y.

HUFF, F.A., (ed.), 1973: "Summary report of METROMEX studies, 1971-1972", Report of Investig. No. 74, Illinois State Water Survey, Urbana.

HUFF, F.A., 1975a: "Urban effects on the distribution of heavy convective rainfall", Water Resources Res., 11, 889-896.

HUFF, F.A., 1975b: "Mesoscale features of urban rainfall enhancement", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

HUFF, F.A. and S.A. CHANGNON Jr., 1973: "Precipitation modification by major urban areas", Bull. Amer. Meteorol. Soc., 54, 1220-1232.

HUFF, F.A. and P.T. SCHICKEDANZ, 1974: "METROMEX: rainfall analyses", Bull. Amer. Meteorol. Soc., 55, 90-92.

HUFF, F.A. and E.E. SCHLESSMAN, 1974: "1973 analyses of monthly, seasonal and storm rainfall with summary of 1971-73 findings," Interim Report of METROMEX Studies, NSF GI-38317, Ill. State Water Survey, Urbana, 17-29.

HUFTY, A., 1973: "Types de temps synoptiques en Belgique et climats locaux à Liège", Sociéte Belge d'Etudes Géog., Ghent, Memoir No. 23, 80 p.

IHD Working Group, 1973: "Man's Influence on the Hydrological Cycle", FAO Irrig. Drain. Paper No. 17, Food and Agriculture Organization of the United Nations, Rome.

ISYUMOV, N. and A.G. DAVENPORT, 1975: "Comparison of full-scale and wind tunnel wind speed measurements in the Commerce Court Plaza", J. Indus. Aerodynamics, 1, 201-212.

IVÁNYI, Zs., 1976: "Anthropogenic modification of the temperature profile in the planetary boundary layer", Időjárás, 80, 342-349.

JAUREGUI, E., 1973: "Urban climate of Mexico City", Erdkunde, 27, 298-307.

JAYAWEERA, K.O.L.F., 1973: Comments on "Potential relief from extreme urban air pollution", J. Appl. Meteorol., 12, 887.

JENNER, C., 1975: "Modeling the effect of land use on the urban temperature field", unpubl. Ph.D. Thesis, Univ. Maryland, College Park.

JOHNSON, D.B., 1976: "Ultragiant urban aerosol particles", Science, 194, 941-942.

JOHNSON, D.S. and R.D. BORNSTEIN, 1974: "Urban-rural wind velocity differences and their effects on computed pollution concentrations in New York City", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 267-272.

JOHNSON, F.L., BELL, D.T. and S.K. SIPP, 1975: "A comparison of urban and forest microclimates in the mid-Western United States", Agric. Meteorol., 14, 335-345.

JOHNSON, W.B. Jr., ALLEN, R.J. and W.E. EVANS, 1973: "Lidar studies of stack plumes in rural and urban environments", Final Report Contract No. EPA-CPA 70-49, Stanford Res. Instit., Menlo Park, Calif., 65 p.

JONES, D. and P. SCHICKEDANZ, 1974: in "Interim report of METROMEX studies", F. Huff (ed.), Illinois State Water Survey, Urbana, Ill., 98-120.

JOYNER, S. and R. REITER, 1975: "Microclimatic aspects of developmental suitability of the metropolitan landscape", paper presented to SUNY/USFS/AMS. Conf. Metro. Phys. Environ., Syracuse, N.Y.

KALMA, J.D., 1974: "An advective boundary-layer model applied to Sydney, Australia", Boundary-Layer Meteorol., 6, 351-361.

KALMA, J.D., ASTON, A.R. and R.J. MILLINGTON, 1972: "Energy use in the Sydney area", Ch. 8 in "The city as a life system?", Proc. Ecol. Soc. (Austr.), 7, 125-142.

KALMA, J.D. and G.E. BYRNE, 1976: "Energy use and the urban environment; some implications for planning", Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 237-258.

KALMA, J.D., JOHNSON, M. and K. NEWCOMBE, 1976: "Energy use and the atmospheric environment in Hong Kong: three case studies", Urban Ecol., 2.

KARALIS, J.D., 1976: "The turbidity parameters in Athens", Achiv. Meteorol. Geophys. Bioklima., Ser. B, 24, 25-34.

KARL, T.R., 1976: "Summertime surface wind fields in St. Louis", Preprints 3rd Symp. Atmos. Turb. Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 107-113.

KAWAMURA, T., 1977: "Climatic modification by human activities", in "The Climate of Japan", Fukui, E. (ed.), Kodansha Ltd./Elsevier Publ. Co., Tokyo/Amsterdam, 209-224.

KAWAMURA, S. and E. KIMOTO, 1975: "Diagram for wind effect due to tall buildings on the neighboring district", Proc. 2nd US Nat. Conf. Wind Engineering Res., WERC/NSF, Ft. Collins, Colo. I-16-1 to I-16-5.

KHALILI, A., 1975: "Precipitation climatology of Tehran area", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

KHEMANI, L.T. and BH. V. RAMANA MURTY, 1973: "Rainfall variations in an urban industrial region", J. Appl. Meteorol., 12, 187-194.

KONDRAT'YEV K.Ya., 1973: "The Complete Atmospheric Energetics Experiment", GARP Public Series, No. 12, World Meteorol. Organiz., Int. Coun. Sci. Unions, Geneva, 43 p.

KONDRAT'YEV, K. Ya. and L.P. Orlenko (eds.) 1972: "The Complete Atmospheric Energetics Experiment (material of the CAENEX-70 expedition)", Proc. Main Geophys. Obser., Voyeykov, No. 276.

KONDRAT'YEV, K.Ya, MALEVSKY-MALEVICH, S.P., ORLENKO, L.R., TER-MARKARYANZ, N.E., VASSILYEV, O.B. and V.F. ZHVALEV, 1973: "Some results of investigations under the programme of the Complete Atmospheric Energetics Experiment (1970-1972)", WMO Bulletin, 22, 7-13.

KOPEC, R.J., 1973: "Daily spatial and secular variations of atmospheric humidity in a small city", J. Appl. Meteorol., 12, 639-648.

KOSSOWSKA, U., 1973a: "Osobliwości klimatu wielkomiejskiego na przykladzie Warszawy", Uniwersytet Instytut Geografi, Prace i studia: Klimatologia No. 7, 141-185.

KOSSOWSKA, U., 1973b: "Przebieg roczny temperatury powietrza w Warszawie w róznych okresach obserwacyjnych", Uniwersytet Instytut Geografi, Prace i Studia: Klimatologia No. 7, Warsaw, 87-96.

KUTZBACH, J.E., 1974: "Possible impact of Man's energy generation on climate", Preprint Int. Study Conf. on Phys. Basis of Climate Modelling, ICSU and WMO, Stockholm, 8 p.

LAL, M., 1975: "Boundary layer model for thermal effects of pollutants in the atmosphere", Archiv Meteorol. Geophys. Bioklima., Ser. B., 23, 59-68.

LAL, M., 1976: "Radiative effects of pollutants in the atmospheric boundary layer", Preprints 3rd Symp. Atmos. Turb., Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 543-546.

LANDSBERG, H.E., 1973a: "The Meteorologically Utopian City", Bull. Amer. Met. Soc. 54, 86-89.

LANDSBERG, H.E., 1973b: "Climate of the urban biosphere", Int. J. Biometeorol., Supplement 16, Vol. 5, Pt. II, 71-83.

LANDSBERG, H.E., 1973c: "Stadtplanung", Promet. Meteorologische Fortbildung, 4, 7-10.

LANDSBERG, H.E., 1974a: "The urban area as a target for meteorological research", Bonner Meteorol. Abhandlungen, No. 17, Bonn, 475-480.

LANDSBERG, H.E., 1974b: "Inadvertent atmospheric modification through urbanization", In "Weather and Climate Modification", W.N. Hess (ed.) John Wiley and Sons, New York, 726-763.

LANDSBERG, H.E., 1974c: "Man-made climatic changes", Proc. Symp. Phys. Dynam. Climatol., Leningrad, WMO No. 347, World Meteorol. Organiz., Geneva, 262-303.

LANDSBERG, H.E., 1975a: "Discussion of "A comparative study of turbidity in an urban and rural environment at Toronto" by S. Yamashita, Atmos. Environment, 9, 271.

LANDSBERG, H.E., 1975b: "Atmospheric changes in a growing community (the Columbia, Maryland experience)", Tech. Note BN 823, Instit. Fluid Dynamics Appl. Math., Univ. Maryland, College Pk., Md.

LANDSBERG, H.E., 1975c: "Micrometeorological wind effects in urban areas", Proc. 2nd US Nat. Conf. Wind Engineer. Res., WERC/NSF, Ft. Collins, Colo., VI-4-1.

LANDSBERG, H.E., 1976a: "Climate and land-use", Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 1-7.

LANDSBERG, H.E., 1976b: "Weather, climate and human settlements", WMO Spec. Environ. Report, No. 4, World Meteorol. Organiz., Geneva.

LANDSBERG, H. and L. MACHTA, 1974: "Anthropogenic pollution of the atmosphere: whereto?", Ambio, 3, 146-150.

LA PENTA, K.D., 1973: "An empirical method of forecasting the diurnal variation in the mixing depth at St. Louis", M.S. Thesis, St. Louis Univ., St. Louis, Mo.

LARSON, R.P. and A.H. AUER, Jr., 1976: "Urban induced influences on convective cloud activity", J. Rech. Atmosphériques, 10, 143-156.

LAWRENCE, E.N., 1973: "Weekly weather cycles", Bull. Amer. Meteorol. Soc., 54, 1034.

LEE, D.O., 1975: "Rural atmospheric stability and the intensity of London's heat island", Weather, 30, 102-109.

LEE, R.L., BERGSTROM, R.W. and R.D. BORNSTEIN, 1976: "Workshop summary: Workshop on modeling the urban boundary layer, Las Vegas, Nevada, 5 May 1975", Bull. Amer. Meteorol. Soc., 57, 313-314.

LEE, R.L. and D.B. OLFE, 1974: "Numerical calculations of temperature profiles over an urban heat island", Boundary-Layer Meteorol., 7, 39-52.

LESLIE, L.M. and B.R. MORTON, 1973: "Convective stagnation under an inversion - a numerical experiment", Proc. 1st Australian Conf. Heat and Mass Transfer, Melbourne, 49-56.

LETTAU, H.H. and K. LETTAU, 1969: "Shortwave radiation climatonomy", Tellus, 21, 208-222.

LEWIS, J.E. Jr., OUTCALT, S.I. and R.W. PEASE, 1976a: "Urban surface thermal response associated with land-use," Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 229-236.

LEWIS, J.E., OUTCALT, S.I. and R.W. PEASE, 1976b: "Urban surface thermal response associated with land use", Climatol. Bull. (McGill), 19, 23-29.

LINACRE, E. and C. EDGAR, 1972: "Climatology of Sydney in relation to air pollution", Proc. Int. Clean Air Conf., Melbourne, Australia, 23-30.

LINDQVIST, S., 1974: "Methods in mesoclimatological studies", Uppsala Univ. Naturgeografiska Inst. Report No. 34, 167-178, (in Swedish).

LILJEQUIST, G.H., 1974: "Climatology and community planning", Uppsala Univ. Naturgeografiska Inst., Report No. 34, 161-165 (in Swedish).

LIST, R. and H. MELLING, 1974: "Plume convection over an urban area as observed by acoustic echo sounding", Atmosphere, 12, 144-153.

LOOSE, T. and R.D. BORNSTEIN, 1976: "Observations of mesoscale effects on frontal movement through an urban area", Final Report, Vol. 4, Contract GA041886, San Jose State Univ., San Jose.

LORENZ, D., 1973: Meteorologische Probleme bei der Stadtplanung", FBW - Blätter, Folge 5, Baupraxis, 9, 57-62.

LOWRY, W.P. (compiler), 1973: "1972 Operational Report for METROMEX," Illinois State Water Survey, Urbana, Ill.

LOWRY, W.P.,1974: "Project METROMEX: its history, status and future", Bull. Amer. Meteorol. Soc., 55, 87-88.

LOWRY, W.P., 1975: "North American research concerning the effects of urbanization on local and regional weather and climate", preprint Bilateral Seminar on Geog. Charact. of Urban Devel., Budapest, May 26 - June 6, 28 p.

LOWRY, W.P., 1977: "Empirical estimation of urban effects on climate: A problem analysis", J. Appl. Meteorol., 16, 129-135.

LUDWIG, F.L. and W.F. DABBERDT, 1973: "Effects of urbanization on turbulent diffusion and mixing depth", Internat. J. Biometeorol., 17, 1-11.

LUDWIG, F.L. and W.F. DABBERDT, 1976: "Comparison of two practical atmospheric stability classification schemes in an urban application", J. Appl. Meteorol., 15, 1172-1176.

LUNDE, B.K., 1977: "Seasonal and wavelength dependence of urban/rural radiance in Iowa", J. Appl. Meteorol., 16, 103-105.

LYONS, T.J., 1974a: "A climatic survey of the Adelaide region", unpublished Ph.D. Thesis, Flinders Univ. of S. Austr.

LYONS, T.J., 1974b: "Adelaide's urban climate", Flinders Instit. Atmos. Marine Sci., Research Report No. 12, 10 p.

LYONS, T.J. and D.R. CUTTEN, 1974: "Atmospheric pollutant and temperature traverses in an urban area", Atmos. Environ., 9, 731-737.

LYONS, T.J. and B.W. FORGAN, 1973: "Atmospheric attenuation of solar radiation at Adelaide", Flinders Instit. Atmos. Marine Sci., Res. Report No. 9, 14 p.

LYONS, T.J. and B.W. FORGAN, 1975: "Atmospheric attenuation of solar radiation at Adelaide", Quart. J. Royal Meteorol. Soc., 101, 1013-1017.

LYONS, W.A., 1974: "Inadvertent weather modification by Chicago-Northern Indiana pollution sources observed by ERTS-1", Month. Weath. Rev., 102, 503-508.

LYONS, W.A. and H.S. COLE, 1976: "Photochemical oxidant transport: Mesoscale breeze and synoptic-scale aspects", J. Appl. Meteorol., 15, 733-743.

MacCRACKEN, M.C. and R.D. BORNSTEIN, 1975: "On the treatment of advection in flux formulations for variable grid models, with application to two models of the atmosphere", UCRL Preprint 76692, submitted to J. of Comp. Phys.

MACHALEK, A., 1974: "Das vertikale Temperaturprofil über der Stadt Wien", Wetter und Leben, 26, 87-93.

MALISSA, H., JUTTE, W. and ALIDAD, I., 1975: "Untersuchung der Vertikalverteilung von Stickstoffdioxid über einer verkehrsreichen Strasse", Archiv Meteorol. Geophys. Biokl., Ser. B, 23, 127-136.

MANES, A., GOLDREICH, Y., RINDSBERGER, M. and D. GUETTA, 1975: "Inadvertent modification of the solar radiation climate at Bet-Dagan", in "Urban effects on local climate at the Greater Tel-Aviv area", Bar-Ilan Univ., and Israel Meteorol. Service, Bet-Dagan.

MANI, A., HUDDAR, B.B., JOSEPH, C.P., CHACKO, O. and A.K. DE, 1974: "Studies of dust and aerosols and their effect on atmospheric electricity and turbidity parameters", paper to IAMAP/IAPSO Conf., Melbourne.

MAROTZ, G.A. and J.C. COINER, 1973: "Acquisition and characterization of surface material data for urban climatological studies", J. Appl. Meteorol., 12, 919-923.

MARTIN, F.P. and G.L. POWELL, 1975: "The urban heat island in Akron, Ohio", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

MARTIN, F.P. and P.M. EVANS, 1975: "Heat island effect of a large shopping mall in Akron, Ohio", Weatherwise, 28, 254-255.

MAYER, H. and G. GIETL, 1976: "Bioklimatische Unterschiede zwischen einer Stadt-und einer Waldatmosphäre, Internat. J. Biometeorol., 20, 325-332.

McBOYLE, G.R., 1973: "The application of climatological knowledge - particularly in future urban forms", in "Applied Geography and the Human Environment" (Preston, R.E., ed.), University of Waterloo, Dept. Geog. Pub. Ser. Nov. 2, 273-276.

McELROY, J.L., 1973: "A numerical study of the nocturnal heat island over a medium-sized mid-latitude city (Columbus, Ohio)", Boundary-Layer Meteorol., 3, 442-453.

McELROY, J.L., CLARKE, J.F. and J.M. GODOWITCH, 1973: "Urban boundary layer structure during sunrise-sunset transitional periods", 1973 Fall Ann. Gen. Meeting Amer. Geophys. Union, San Francisco, Calif.

MILLER, D.R., 1975: "Structure of the microclimate at a woodland-parking lot interface", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

MILLER, E.L., 1974: "Multiple site acoustic sounding in METROMEX", Bull. Amer. Meteorol. Soc., 55, 114-115.

MILLER, E.L., 1975: "Use of an acoustic-sounder array to study urban atmospheric structure", Radiol. and Environ. Res. Div. Annual Report, Argonne Nat. Lab., Argonne, Ill.

MILLWARD, G.E. and R.H. MOTTE, 1976: "Observations of the Plymouth temperature field", Weather, 31, 255.

MILTON, D. and A.J.W. CATCHPOLE, 1976: "Atmospheric particulate matter content and bright sunshine", Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 218-227.

MISKOLCI, F., 1975: "A hosszúhallámú sugárzásáram módosulása városi környezetben", Időjárás, 79, 207-213.

MORGAN, D.L. and R.L. BASKETT, 1974: "Comfort of man in the city: an energy balance model of man-environment coupling", Int. J. Biometeorol., 18, 184-198.

MOSES, H., 1974: "Argonne urban-rural airflow program", Bull. Amer. Meteorol. Soc., 55, 112-114.

MOSES, H. and D.N. EGGENBERGER, 1973: "The use of pyrheliometers for continuous measurements of an effective air pollution mixing depth", Solar Energy, 15, 143-154.

MOSES, H. and P.E. HESS, 1972: "Comparison of the surface and geostrophic winds", Argonne National Lab., Radiol. Physics Div., Annual Report ANL 7960, Pt. IV, Jan.-Dec. 1972, 20-38.

MUKHERJEE, A.K. and C.E.J. DANIEL, 1976: "Temperature distribution over Bombay during a cold night", Indian J. Meteorol. Hydrol. Geophys., 27, 37-41.

MUNN, R.E., 1973: "Urban meteorology: some selected topics", Bull. Amer. Meteorol. Soc., 54, 90-93.

MUNN, R.E., 1974: "Study of regional particulate pollution in the Detroit-Windsor, Sarnia-Port Huron area", in "Turbulent diffusion in environmental pollution" (F.N. Frenkiel and R.E. Munn, eds.), Advances in Geophys., 18B, Academic Press, 111-126.

NAPPO, C.J., Jr., 1975: "Parameterization of surface moisture and evaporation rate in a planetary boundary layer model", J. Appl. Meteorol., 14, 289-296.

NEAÇSA, O., 1973: "Contributii la studiel climei orasului Bucuresti" in "Studii de Climatologie", Instit. de Meteorol. si Hidrol., Bucharest, Vol. 1, 5-54.

NEMETH, E., 1974: "Nyári és hőségnapok Budapesten", Időjárás, 78, 295-299.

NEWBERRY, C.W., EATON, K.J. and J.R. MAYNE, 1973: "Wind loading on tall buildings - further results from Royex House", Indus. Aerodyn. Abstracts, 4, 18 p.

NEWBERRY, C.W. and K.J. EATON, 1974: "Wind loading handbook", Build. Res. Estab. Report, Dept. Environ., H.M.S.O., London, 74 p.

NICHOLAS, F.W., 1974: "Parameterization of the urban fabric: A study of surface roughness with application to Baltimore, Maryland", unpubl. Ph.D. Thesis, Univ. Maryland, College Park.

NICHOLAS, F.W., 1976: "Measuring and interpreting the urban heat island: a student field project", J. Geog., 75, 409-418.

NICHOLSON, S.E., 1975: "A pollution model for street-level air", Atmos. Environ., 9, 19-31.

NICKERSON, E.C. and V.E. SMILEY, 1975: "Surface layer and energy budget parameterizations for mesoscale models", J. Appl. Meteorol., 14, 297-300.

NICOL, K.S., 1976: "Anthropogenic heat and its relation to building and urban climate in Inuvik, N.W.T.", unpubl. M.Sc. Thesis, Univ. B.C., Vancouver.

NISHIZAWA, T., 1973: "Urban climate, with special reference to heat island", Kagaku, 43, 487-494.

NKEMDIRIM, L.C., 1976: "Dynamics of an urban temperature field - A case study", J. Appl. Meteorol., 15, 818-828.

NKEMDIRIM, L.C., LUNN, G.R. and R.D. ROWE, 1975: "Pollutant concentration and stratification in urban heat island", Water, Air and Soil Poll., 4, 99-112.

NORTH, E.M., PETERSON, A.M. and H.D. PARRY, 1973: "RASS, a remote sensing system for measuring low-level temperature profiles", Bull. Amer. Meteorol. Soc., 54, 912-919.

NORWINE, J.R., 1973: "Heat island properties of an enclosed multi-level suburban shopping centre", Bull. Amer. Meteor. Soc., 54, 637-641.

NORWINE, J., 1975: "Urban climates and human ecology", J. Geog., 74, 71-78.

NOZAKI, K.Y., 1973: "Heating of a large building complex in relation to weather factors", Tech. Note BN 777, Instit. Fluid Dynamics Appl. Math., College Pk., Maryland.

NUBLER, W., 1975: "Lokalklimatische Untersuchungen als Beitrag zur ökologischwertenden Differenzierung des Stadtgebiets von Freiburg", Sonderdruck aus Daten und Dokumente zum Umweltschutz, 14, 83-94.

NUNEZ, M., 1975: "The energy balance of an urban canyon", unpubl. Ph.D. Thesis, Univ. British Columbia, Vancouver.

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 Meteorol., 10, 121-135.

NUNEZ, M. and T.R. OKE, 1977: "The energy balance of an urban canyon", J. Appl. Meteorol., 16, 11-19.

OCHS, H.T. III, 1974: "Cloud modelling in METROMEX", Preprints, 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 396-400.

OCHS, H.T. III, 1975: "Modeling of cumulus initiation in METROMEX", J. Appl. Meteorol., 14, 873-882.

OKE, T.R., 1973: "City size and the urban heat island", Atmos. Environ., 7, 769-779.

OKE, T.R., 1974: "Review of urban climatology, 1968-1973", WMO Tech. Note No. 134, WMO No. 383, World Meteorol. Organiz., Geneva, 132 p.

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

OKE, T.R., 1976b: "Inadvertent modification of the city atmosphere and the prospects for planned urban climates", Proc. WMO Symp. Meteorol. as Related to Urban and Regional Land-Use Planning, Asheville, WMO No. 444, World Meteorol. Organiz., Geneva, 150-175.

OKE, T.R., 1977a: "The urban atmosphere as an environment for air pollution dispersion", Preprint WMO Meeting on Educ. and Train. in Meteorol. Aspects of Atmos. Poll. and Related Environ. Problems, Research Triangle Pk.

OKE, T.R., 1977b: "The climate of urban areas", in "Yearbook of Science and the Future", Encyclopaedia Britannica, Chicago, 116-132.

OKE, T.R. and R.F. FUGGLE, 1972: "Comparison of urban/rural counter and net radiation at night", Boundary-Layer Meteorol., 2, 290-308.

OKE, T.R. and G.B. MAXWELL, 1975: "Urban heat island dynamics in Montréal and Vancouver", Atmos. Environ., 9, 191-200.

OLIVER, H.R., 1974: "Wind-speed modification by a very rough surface", Meteorol. Mag., 103, 141-145.

OLSSON, L.E., PERSSON, C., HAGARD, A., OTTERSTEIN, H., GRANAT, L. and C. TRÅGARDH, 1974: "Measurements of meteorological parameters and air pollution spread over Stockholm, Sweden, by means of remote sensing and airborne instrumentation", WMO Special Environ. Report, No. 3, World Meteorol. Organiz., 545-556.

OUJEZDSKY, T.W., 1973: "Diurnal and seasonal change of the urban heat island in Austin, Texas", Atmos. Sciences Group, Report No. 34, Univ. of Texas, 52 p.

PADMANABHAMURTY, B. and R.E. MUNN, 1973: "A case study of mixing-height variations in the Toronto area", Atmosphere, 11, 21-25.

PADMANABHAMURTY, B. and M.S. HIRT, 1974: "The Toronto heat island and pollution distribution", Water, Air, Soil Poll., 3, 81-89.

PAGE, J.K., 1972: "The problem of forecasting the properties of the built environment from the climatological properties of the green-field site", in "Weather Forecasting for Agriculture and Industry", Taylor, J.A. (ed.), David and Charles, Newton Abbot, 195-208.

PAGE, J.K., 1976: "A report on building climatology and its application to meet the problems of housing and building for human settlements", WMO Tech. Note No. 150, World Meteorol. Organiz., Geneva.

PAL, S.R., HOUSTON, J.D. and A.I. CARSWELL, 1974: "Lidar back-scattering from cirrus clouds and inversion layers", Preprint 8th Annual Congress, Canadian Meteorological Society, Toronto.

PANOFSKY, H.A., 1975: "A model for vertical diffusion coefficients in a growing urban boundary layer", Bound.-Layer Meteorol., 9, 235-244.

PAPADAKIS, C.N. and H.C. PREUL, 1973: "Testing of methods for determination of urban run-off", Amer. Soc. Civil Engin., N.Y., Hydraulics Div. J., 99, 1319-1335.

PEASE, R.W., LEWIS, J.E. and S.I. OUTCALT, 1976: "Urban terrain climatology and remote sensing", Annals Assoc. Amer. Geog., 66, 557-569.

PEAT, D., 1976: "Blunting the teeth of the gale", Science Dimension, 8, 22-25.

PENDERGAST, M.M., 1975: "Study of the effects of the urban mesoclimate on local and regional pollution potential in southeast Texas", Ph.D. Thesis, Texas A & M Univ., 208 p.

PENWARDEN, A.D., 1973: "Acceptable wind speeds in towns", Building Science, 8, 259-267.

PENWARDEN, A.D. and A.F.E. WISE, 1975: "Wind environment around buildings", Build. Res. Estab. Report, Dept. Environ., HMSO, London, 52 p.

PESCHIER, J. Jr., 1973: "Wind and temperature profiles in an urban area", Atmos. Sci. Group, Report No. 33, Univ. of Texas, 32 p.

PETERSON, J.T. and E.C. FLOWERS, 1973: "Effects of air pollution on solar radiation", Bull. Amer. Meteorol. Soc., 54, 910.

PETERSON, J.T. and E.C. FLOWERS, 1974: "Urban-rural solar radiation and aerosol measurements in St. Louis and Los Angeles", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 129-132.

PIVA, R. and P. ORLANDI, 1974: "Numerical solutions for atmospheric boundary layer flows over street canyons", Proc. Fourth Int. Conf. Numerical Methods in Fluid Dynamics, Springer-Verlag.

POGOSYAN, Kh. P., 1974: "Vliyaniye krupnykh gorodov na ikh meteorologicheskiy rezhim", Meteorol. i Gidrol., Moscow, No. 10, 3-8. (Engl. transl. in corresp. issue of Meteorol. and Hydrol., Wash., D.C.

POGOSYAN, Kh. P. and A.A. BACHURINA, 1975: "O nekotorykh osobennostyakh meteorologicheskogo rezhima krupnykh gorodov", Geograf. Obshchestvo SSR, Leningrad, Izvestiya, 107, 245-248.

PRADHAN, S.K., DAYAKISHAN, and N.S. MANRAL, 1976: "Effects of urbanization and industrial development on air temperatures at Bombay Airport", Indian J. Meteorol., Hydrol. and Geophys., 27, 187-190.

Principal Investigators of Project METROMEX, 1976: "METROMEX update", Bull. Amer. Meteorol. Soc., 57, 304-308.

PRITCHARD, W. and K. CHOPRA, 1975: "Air pollution and urban climatology at Norfolk, Virginia", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

PROBÁLD, F., 1975: "A városklimatológia időszerű feladatai", Időjárás, 79, 69-76.

PUESCHEL, R.F. and P.M. KUHN, 1975: "Infrared absorption of tropospheric aerosols: Urban and rural aerosols of Phoenix, Arizona", J. Geophys. Res., 80, 2960-2962.

RASTORGUEVA, G.P., 1973: "Seasonal variation of air temperature in cities", Trudy, Glavnaia Geofiz. Observ., No. 293, 209-214.

RAUNER, Yu L. and M.M. CHERNAVSKAYA, 1972: "Teplovoy balans goroda i vliyaniye gorodskogo ozdeneniya na temperaturnyy rezhim", Akad. Nauk SSR, Moscow, Isvestiya Ser. Geograf., No. 5, 46-53.

RIVOLIER, J., 1974: Une approche en matière de biométéorologie urbaine", La Metéorologie, Ser. 5, 29, 9-13.

RODIN, E.Y., 1973: "Orbital pollution control", Proc. Meeting Soc. Engineer. Sci., "Pollution: engineering and scientific solutions", Plenum Press, N.Y., 38-53.

ROUSE, W.R., NOAD, D. and J. McCUTCHEON, 1973: "Radiation, temperature and atmospheric emissivities in a polluted urban atmosphere at Hamilton, Ontario", J. Appl. Meteorol., 12, 798-807.

ROWNTREE, R. and H. PLUMLEY, 1975: "Weather and human behavior in the urban environment", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

RUSSELL, P.B., UTHE, E.E., LUDWIG, F.L. and N.A. SHAW, 1974: "Comparison of atmospheric structure as observed with monostatic acoustic sounder and lidar techniques", J. Geophys. Res., 79, 5555-5566.

RUSSELL, P.B. and E.E. UTHE, 1975: "Development of acoustic sounder network for air pollution and land use applications: progress report II", paper presented at 3rd Workshop in Atmos. Acoustics, Toronto, June, 45 p.

SANDERSON, M., 1974: "A preliminary radiation climatology of Windsor, Ontario", Climatol. Bull. (McGill), No. 16, 1-12.

SANDERSON, M., KUMANAN, I., TANGUAY, J. and W. SCHERTZER, 1973: "Three aspects of the urban climate of Detroit-Windsor", J. Appl. Meteorol., 12, 629-638.

SANTOMAURO, L., 1976: "About a diffusion model for a weak atmospheric circulation on urban area - Milan, Italy", Proc. Seminar Air Poll. Modelling, Venice, IBM Italy Scien. Center, Venice, 10.1-10.59.

SASAKI, Y., 1973: "Distribution of the air temperature and the phase of its diurnal variation in the urban area of Sendai", Japanese Progress in Climatology, 1973, 38-40.

SAVAGE, R.C., 1973: "Comments on remote sensing of urban 'heat island' from an environmental satellite", Bull. Amer. Meteorol. Soc., 54, 222.

SAVDIE, I., 1975: "Effect of urban expansion on fuel consumption for space heating", unpubl. manuscript, Project Report No. 17, Applic. and Consult. Div., Atmos. Environ. Service, Downsview, Ont., 6 p.

SAWYER, J.S., 1974: "Can Man's waste heat affect the regional climate", paper to IAMAP/IAPSO Conf., Melbourne.

SAX, R.I., CHANGNON, S.A., GRANT, L.O., HITSCHFELD, W.J., HOBBS, P.V., KAHAN, A.M. and J. SIMPSON, 1975: "Weather modification: Where are we now and where should we be going? An editorial overview", J. Appl. Meteorol., 14, 652-672.

SCHICKEDANZ, P.T., 1974: "Inadvertent rain modification as indicated by surface raincells", J. Appl. Meteorol., 13, 891-900.

SCHMID, J.A., 1974: "The environmental impact of urbanization", In "Perspectives on Environment", M. Mikesell and G.R. Manners, eds., Assoc. Amer. Geog., Washington, D.C., 213-251.

SCHRIVER, W.R., 1976: "Ground-level winds around tall buildings", Can. Build. Digest, No. 174, Div. Build. Res., Nat. Res. Council Canada, Ottawa.

SCHUEPP, W., 1974: "Meteorologische Aspekte der Energiebilanz von Ballungszentren", CIB/WMO Symp. Climatol. of Build., Zurich, Schweizer Bau Dokumentation, Zurich, 61-69.

SCHWERDTFEGER, P., 1972: "Meteorological measurements relevant in planning urban environments", Flinders Univ. Instit. Atmos. Marine Sci., Research Report No. 3, 19 p.

SCHWERDTFEGER, P., 1976: "Climate", in "Natural History of the Adelaide Region", Royal Soc. South Austr., Adelaide, 75-86.

SCHWERDTFEGER, P. and T.J. LYONS, 1976: "Wind field studies in an urban environment", Urban Ecology, 2, 93-107.

SEKIGUTI, T., 1973: "Basin and city climate complex", Japanese Progress in Climatology, 1973, 3-14.

SEKIGUTI, T., 1975: "Thermal situations of urban areas, horizontally and vertically", Japanese Progress in Climatology, Lab. Climatol., Tokyo Univ. Educ., Otsuka, Tokyo, 85-88.

SEKIGUTI, T. and K. KAWAKAMI, 1975: "Heat island formation at concentrated new residence towns", Japanese Progress in Climatology, Lab. Climatol., Tokyo Univ. Educ., Otsuka, Tokyo, 82-83.

SEKIGUTI, T. and K. TAKANO, 1975: "Mathematical simulation of heat island model", Japanese Progress in Climatology, Lab. Climatol., Tokyo Univ. Educ., Otsuka, Tokyo, 80-81.

SEKIGUTI, T. and H. TAMIYA, 1975: "Precipitation climatology of Japanese city area", Japanese Progress in Climatology, Lab. Climatol., Tokyo Univ. Educ., Otsuka, Tokyo, 84.

SEKIHARA, K., 1973: "Some aspects of radiation climate of Tokyo as observed by the elevan year measurement of spectral global radiation from 1961 to 1971", J. Meteorol. Soc. Japan, 51, 119-132.

SEMONIN, R.G., 1975: "Temporal and spatial variability of rainfall pH", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

SEMONIN, R.G. and S.A. CHANGNON, Jr., 1974a: "METROMEX: Summary of 1971-72 results", Bull. Amer. Meteorol. Soc., 55, 95-100.

SEMONIN, R.G. and S.A. CHANGNON, Jr., 1974b: "METROMEX: Lessons for precipitation enhancement in the Midwest", Preprints, 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 353-357.

SETHURAMAN, S., 1973: "Stratified shear flows over a simulated three-dimensional urban heat island", unpubl. Ph.D. Thesis, Colorado State Univ., Ft. Collins.

SETHURAMAN, S., 1976: "Air mass modification due to change in surface characteristics", Month. Weath. Review, 104, 1040-1043.

SETHURAMAN, S. and J.E. CERMAK, 1974a: "Physical modeling of flow and diffusion over an urban heat island", in "Turbulent diffusion and environmental pollution", (F.N. Frenkiel and R.E. Munn, eds.), Advances in Geophys., 18B, Academic Press, 223-240.

SETHURAMAN, S. and J.E. CERMAK, 1974b: "Mean temperature distributions over a physically modelled three-dimensional heat island for different stability conditions", Preprints, Symp. Atmos. Diffusion and Air Pollution, Santa Barbara, Amer. Meteorol. Soc., Boston, 381-386.

SETHURAMAN, S. and J.E. CERMAK, 1975: "Mean temperature and mean concentration distributions over a physically modelled three-dimensional heat island for different stability conditions", Boundary-Layer Meteorol., 9, 427-440.

SHÁRÁN, V. Kr., 1973: "On simulating the lower portion of the natural boundary layer", Atmos. Environ., 7, 225-226, and discussion.

SHARMA, V. and L.O. MYRUP, 1975: "Diffusion from a line source in an urban atmosphere", Atmos. Environ., 9, 907-922.

SHEA, D.M. and A.H. AUER, Jr., 1976: "Observations of the regional influence on thermodynamic properties and aerosol patterns in the plume downwind of St. Louis", Preprints, 3rd Symp. Atmos. Turb., Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 348-353.

SHITARA, H., 1976: "Climatology", Geogr. in Japan, S. Kinchi (ed.), University of Tokyo Press, Tokyo, 65-84.

SHITARA, H., HOSOKAWA, K., ISHIKAWA, I., KIKUCHI, R., MAKITA, H., and Y. SASAKI, 1973: "On the micro-scale distribution of the nocturnal cooling in a small basin", Japanese Progress in Climatology, 1973, 15-37.

SHKLYAREVICH, O.B., 1974: "Peculiarities of vertical wind distribution and temperature under city conditions", Meteorol. i Gidrol., No. 7, 42-46 - transl. in Meteorol. and Hydrol., same vol. no.

SIEVERING, H., 1975: "Visibility, mass concentration and power use in urban environments", Atmos. Environ., 9, 755-757.

SIKORSKA, M., 1973: "Próba porównania warunków klimatyczn ch Warszawy i okolic podniejskich metoda kompleksowa", Uniwersytet Instytut Geografi, Prace i Studia: Klimatologia No. 7, 97-108.

SIMUI, E., 1975: "Recent developments in wind engineering and their proposed use in codes and standards", Proc. 2nd US Nat. Conf. Wind Engineer. Res., WERC/NSF, Fort Collins, Colo. II-23-1 to II-23-1.

SISTERSON, D.L., 1975: "Studies on the urban moisture budget", Report No. AS114, Dept. Atmos. Sci., Univ. Wyoming, Laramie.

SISTERSON, D.L. and R.A. DIRKS, 1975a: "Structure of the urban moisture field", Radiol. and Environ. Res. Div. Annual Report, Argonne Nat. Lab., Argonne, Ill., 34-36.

SISTERSON, D. and R.A. DIRKS, 1975b: "The urban moisture climate", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

SMITH, C.V., 1972: "Some environmental problems of livestock housing", WMO Tech. Note No. 122, WMO No. 325, Geneva, 71 p.

SMITH, K., 1975: "Principles of Applied Climatology", McGraw-Hill Book Co., London, 48-61.

SNYDER, W.H. and R.E. LAWSON, Jr., 1976: "Determination of a necessary height for a stack close to a building - a wind tunnel study", Atmos. Environ., 10, 683-691.

SORBJAN, Z., 1976: "Parameterization of dynamical structure of boundary layer in urban areas", WMO Symp. Interpret. Broad-Scale NWP Products for Local Forecast Purposes, WMO No. 450, World Meteorol. Organiz., Geneva, 27-31.

SPANGLER, T.C. and R.A. DIRKS, 1974: "Meso-scale variations of the urban mixing height", Boundary-Layer Meteorol., 6, 423-441.

SPAR, J. and J.A. MAYER, 1973: "Temperature trends in New York City: a postscript", Weatherwise, 26, 128-130.

SPRIGG, W.A., 1974: "Estimation of sulphur dioxide and soiling index from observed solar radiant flux density attenuation," WMO No. 368, Spec. Environ. Rep. No. 3, 481-489.

SPYERS-DURAN, P. 1972a: "Observations of the cloud nucleus concentration around the St. Louis urban complex", in Final Tech. Report, NSF Grant GA 28190X1, Univ. Chicago, Chicago, Ill., NTIS No. PB-218 678, 25-52.

SPYERS-DURAN, P. 1972b: "Upwind and downwind cloud-base microstructure", in Final Tech. Report, NSF Grant GA 28180X1, Univ. Chicago, Chicago, Ill., NTIS No. PB-218-678, 53-71.

SPYERS-DURAN, P., 1974: "Cloud condensation nuclei measurements and estimates of production rates for the St. Louis urban complex", Preprints 4th Conf. Weath. Modif., Ft. Lauderdale, Amer. Meteorol. Soc., Boston, 390-395.

STAMPFER, J.F., Jr. and J.A. ANDERSON, 1975: "Locating the St. Louis urban plume at 80 and 120 km and some of its characteristics", Atmos. Environ., 9, 301-313.

STARK, T.F. and D.R. MILLER, 1975: "The effect of vegetation in urban areas on human energy balance and comfort", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

STEELE, W.G. Jr., 1975: "Analytical solutions for atmospheric temperature profiles", unpubl. Ph.D. Thesis, North Carolina State Univ., Raleigh, 75 p.

STOCK, P., 1975: "Interpretation von Thermal Bilden der Stadtregion Dortmund", Zeit. Photogramm. Fernerkund., 4, 144-151.

SUMMERS, P.W., 1964: "An urban ventilation model applied to Montréal", unpublished Ph.D. Thesis, McGill Univ., Montréal.

SUMMERS, P.W., 1974: "Use and abuse of the urban mixing depth concept", Preprint 8th Annual Congress. Canadian Meteorol. Soc., Toronto.

SZEICZ, G., 1974: "Gaseous wastes and vegetation", Preprint Symposium on Waste Recycling and the Environment, Ottawa, 11 p.

TAM, Y.-T. and R.D. BORNSTEIN, 1975: "Anthropogenic moisture production and its effect on boundary layer circulations over New York City", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

TAYLOR, P.A., 1974: "Urban meteorological modelling - some relevant studies", in "Turbulent diffusion in environmental pollution", (F.N. Frenkiel and R.E. Munn, eds.), Advances in Geophys., 18B, Academic Press, 173-185.

TEBALDI, C., 1976: "A study of meteorological parameters relevant to air pollution modelling: heat island phenomena", Proc. Seminar Air Poll. Modelling, Venice, IBM Italy Scien. Center, Venice, 7.1-7.17.

TERJUNG, W.H., 1974a: "Urban climatology: with reference to the inter-relationship between external weather and the microclimate in houses and buildings, Ch. 4, Section 5, in "Progress in Biometeorology", (ed. S.W. Tromp), Vol. 1, Pt. I, Swets and Zeitlinger, Amsterdam, 168-180.

TERJUNG, W.H., 1974b: "Climatic modification", In "Perspectives on Environment", M. Mikesell and G.R. Manners, eds., Assoc. Amer. Geogr., Washington, D.C., 105-151.

TERJUNG, W.H. and S.S-F. LOUIE, 1973: "Solar radiation and urban heat islands", Annals Assoc. Amer. Geog., 63, 181-207.

TERJUNG, W.H. and S.S-F. LOUIE, 1974: "A climatic model of urban energy budgets", Geographical Analysis, 6, 341-367.

TEUNISSEN, H.W., 1975: "Simulation of the planetary boundary layer in a multiple-jet wind tunnel", Atmos. Environ., 9, 145-174.

TORRANCE, K.E. and J.S.W. SHUM, 1976: "Time-varying energy consumption as a factor in urban climate", Atmos. Environ., 10, 329-337.

TOUT, D.G., 1973: "Manchester sunshine", Weather, 28, 164-166.

TROUT, D.A. and H.A. PANOFSKY, 1974: "Mesoscale dispersion from a large city", in "Turbulent diffusion in environmental pollution", (F.N. Frenkiel and R.E. Munn, eds.), Advances in Geophys., 18B, Academic Press, 151-157.

TSUCHIYA, I., 1974: "Some features of the urban environment of Tokyo by remote sensing of ground surface temperature", Papers in Meteorol. and Geophys., Tokyo, 25, 147-158.

TULLER, S.E., 1973: "Microclimatic variations in a downtown urban environment", Geografiska Annaler, 54, Ser. A., 123-135.

TULLER, S.E., 1975: "The energy budget of man: variations with aspect in a downtown urban environment", Int. J. Biometeorol., 19, 2-13.

TYSON, P.D., GARSTANG, M. and G.D. EMMITT, 1973: "The structure of heat islands", Dept. Geog. and Environ. Studies, Univ. Witwatersrand, Occas. Paper 12, 71 p.

UNSWORTH, M.H., 1974: "Radiation measurements as indicators of natural and man-made atmospheric aerosol", WMO Spec. Environ. Report, No. 3, World Meteorol. Organiz., Geneva, 423-433.

UNSWORTH, M.H., 1975: "Long-wave radiation at the ground. II Geometry of interception by slopes, solids and obstructed planes", Quart. J. Royal Meteorol. Soc., 101, 25-34.

UNSWORTH, M.H. and H.A. McCARTNEY, 1973: "Effects of atmospheric aerosols on solar radiation", Atmos. Environ., 7, 1173-1185.

UNWIN, D.J. and V.J. BROWN, 1975: "Landuse and the urban heat island", paper to Assoc. Brit. Climat., Manchester.

UTHE, E.E. and P.B. RUSSELL, 1974: "Experimental study of the urban aerosol structure and its relation to urban climate modification", Bull. Amer. Meteorol. Soc., 55, 115-121.

VAN DER HOVEN, I. (ed.), 1973: "Urban planetary boundary layer studies (Oklahoma City)", in "Atmospheric Transport and Diffusion in the Planetary Boundary Layer", NOAA Tech. Memo. ERL ARL-39, 1-27.

VAN VALIN, C.C., PUESCHEL, R.F., PARUNGO, F.P. and R.A. PROULX, 1976: "Cloud and ice nuclei from human activities", Atmos. Environ., 10, 27-31.

VDOVIN, B.I., 1973: "Peculiarities of temperature stratification in the lowest 1 km layer of air over Leningrad according to helicopter measurements", Trudy Glavnaia Geofiz. Observ. No. 293, 201-208.

VENKATRAM, A. and R. VISKANTA, 1976a: "Radiative effects of pollutants on the planetary boundary layer", Environ. Monitoring Series, EPA-600/4-76-039, U.S. Environ. Protect. Agency, Research Triangle Pk.

VENKATRAM, A. and R. VISKANTA, 1976b: "Effect of elevated pollutant layers on mixed layer growth", Preprints, 3rd Symp. Atmos. Turb. Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 528-535.

VENKATRAM, A. and R. VISKANTA, 1976c: "The contribution of pollutants to the urban heat island and 'crossover' effects", Preprints, 3rd Symp. Atmos. Turb., Diffusion and Air Quality, Raleigh, Amer. Meteorol. Soc., Boston, 536-542.

VERESHCHAGIN, M.A. et al., 1974: "O temperature vozdukha vg. Kazani", in "Meteorologicheskiye klimaticheskiye usloviya srednego Povolzh'ya", Kazan, R.S.F.S.R. (European) Univ., 162-183.

VIEZEE, W., DABBERDT, W.F. and G.E. SHAW, 1975: "Lidar studies of the urban atmosphere in Fairbanks, Alaska", Final Tech. Report, NSF Grant GV-41040, Stanford Res. Instit., Menlo Pk., Calif., 45 p.

VISKANTA R., JOHNSON, R.O. and R.W. BERGSTROM, 1975: "Effect of urbanization and industrialization on the thermal structure in the atmosphere", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

Von STROBEL WOODS, 1976: "Vertical and temporal variations in heat and moisture over an urban area", unpubl. M.Sc. Thesis, N. Carolina State Univ., Raleigh.

VUKOVICH, F.M., 1973: "A study of the atmospheric response due to a diurnal heating function characteristic of an urban complex", Mon. Weath. Review, 101, 467-474.

VUKOVICH, F.M., 1975: "Study of the effect of wind shear on a heat island circulation characteristic of an urban complex", Month. Weath. Rev., 103, 27-33.

VUKOVICH, F.M., DUNN, J.W. III and B.W. CRISSMAN, 1976: "A theoretical study of the St. Louis heat island: The wind and temperature distribution", J. Appl. Meteorol., 15, 417-440.

WAGGONER, A.P. AHLQUIST, N.C. and R.J. CHARLSON, 1972: "Measurement of the aerosol total scatter back-scatter ratio", Appl. Optics, 11, 2886-2889.

WAGGONER, A.P., BAKER, M.B. and R.J. CHARLSON, 1973: "Optical absorption by atmospheric aerosols", Appl. Optics, 12, 896.

WEICKMANN, H.K., 1974: "The mitigation of Great Lakes storms", In "Weather and Climate Modification", W.N. Hess (ed.), John Wiley and Sons, New York, p. 330.

WESELY, M.L., 1975: "Measurements of atmospheric turbidity in an arc downwind of St. Louis", Radiol. and Environ. Res. Div. Annual Report, Argonne Nat. Lab., Argonne, Ill., 22-30.

WESELY, M.L. and R.C. LIPSCHUTZ, 1976: "An experimental study of the effects of aerosols on diffuse and direct solar radiation received during the summer near Chicago", Atmos. Environ., 10, 981-987.

WILLIAMS, G.P., 1976: "Design heat requirements for snow melting systems", Canadian Building Digest, 160, National Research Council, Ottawa, 4 p.

WILSON, D.J. and D.D.J. NETTERVILLE, 1975: "Effluent plume impingement on downwind buildings", Proc. 2nd U.S. Nat. Conf. Wind Engineer. Res., WERC/NSF Ft. Collins, Colo., I-21-1 to I-21-3.

WMO (1970): "Urban Climates", WMO Tech. Note No. 108, WMO-No. 254, TP 141, Geneva, 390 p.

YAMASHITA, S., 1973: "Air pollution study from measurements of solar radiation", Archiv. Met. Geophys. Bioklim., B, 21, 243-253.

YAMASHITA, S., 1974: "A comparative study of turbidity in an urban and a rural environment at Toronto", Atmos. Environ., 8, 507-518.

YAP, D.H., 1973: "Sensible heat fluxes measured in and near Vancouver", unpublished Ph.D. Thesis, Univ. of British Columbia, 174 p.

YAP, D., 1975a: "Seasonal excess urban energy and the nocturnal heat island - Toronto", Archiv. Meteorol. Geophys. Biokl., Ser. B, 23, 69-80.

YAP, D., 1975b: "A preliminary investigation of the nocturnal temperature structure above the city of Edmonton, Alberta", paper presented to SUNY/USFS/AMS Conf. Metro. Phys. Environ., Syracuse, N.Y.

YAP, D.H. and T.R. OKE, 1974: "Sensible heat fluxes over an urban area - Vancouver, B.C.", J. Appl. Meteorol., 13, 880-890.

YOSHINO, M.M., 1975: "Climate in a Small Area", Univ. Tokyo Press, 15-16, 23-26 and 80-119.

YU, T-W., 1973: "Two-dimensional time-dependent numerical simulation of atmospheric flow over an urban area", Atmos. Sci. Group, Report No. 32, Univ. of Tex., 114 p.

YU, T-W. and N.K. WAGNER, 1975: "Numerical study of the nocturnal urban boundary layer", Boundary-Layer Meteorol., 9, 143-162.

ZANELLA, G., 1976: "Il clima urbano di Parma", Rivista di Meteorol. Aeronautica, 36, 125-146.

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