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CITY SIZE AND THE URBAN HEAT ISLAND

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Abstract—The paper demonstrates the relationship existing between the size of a village, town or city (as measured by its population), and the magnitude of the urban heat island it produces. This is accomplished by analyzing data gathered by automobile traverses in 10 settlements on the St. Lawrence Lowland, whose populations range from 1000 to 2 million inhabitants. The locations of these settlements effectively eliminate all non-urban climatic influences. The results are compared with previously published data.

The analysis shows the heat island intensity under cloudless skies to be related to the inverse of the regional windspeed, and the logarithm of the population. A simple model is derived which incorporates these controls. In agreement with an extension of Summers' model the heat island appears to be approximately proportional to the fourth root of the population. With calm and clear conditions the relation is shown to hold remarkably well for North American settlements, and in a slightly modified form, for European towns and cities.

1. INTRODUCTION

THE ABILITY of a town or city to generate an urban heat island is now a well accepted fact. Indeed this is one of the most widely documented climatological effects of man's modification of the atmospheric environment. The great majority of studies refer to the unique form of the heat island in the particular town or city surveyed. It is now both opportune and important to seek generalizations from this mass of work. That is, it seems time to stress the similarities between heat islands rather than their differences. Such generalizations as are possible will be useful in climatic modelling, and may even be of value in urban planning and weather forecasting.

The objective of this paper is to demonstrate the form of the relationship between urban heat island intensity (difference between background rural and highest urban temperatures, ΔT_{u-r}), and city size (as measured by population, P). Most of the previous work in this area has been directed at evaluating the effect of a city's growth over time, on its heat island (e.g. ARAKAWA, 1937; FUKUI, 1957; MITCHELL, 1961; CHANDLER, 1964). These studies, however, are complicated by the need to separate the effects of city growth from the effects of regional climatic change. In this study heat islands from many settlement sizes are compared at the same period in time, thus eliminating these problems. The same approach was employed by DUCKWORTH and SANDBERG (1954).

At present there is no unanimity concerning any relations between city size, and heat island size. KRATZER (1956) noted that there must be such a relation, but CHANDLER (1962, 1964, 1967) feels that there is no linear relation between ΔT_{u-r} and city area or P, and even that they are not proportional.

In this study ΔT_{u-r} was measured for a range of settlement sizes under an experimental design which kept the following influences "constant":

(a) Topography—the survey was located on flat terrain.
(b) Water bodies—there were no lakes or other large water bodies in the vicinity of the settlements.

(c) Climate—all settlements were at approximately the same latitude, in the same climate region, and likely to have similar domestic heating requirements. To further simplify conditions, all observations were taken with clear skies.
(d) Time—all settlements were surveyed on the same evenings during the period when the heat island is usually most pronounced.
(e) Instrumentation—the same thermometer was traversed through each settlement thus eliminating errors due to inaccurate instrument comparisons.

In this way it is anticipated that inter-urban comparisons are valid, and ΔT_{u-r} should only be a function of urban influences and the prevailing regional meteorological controls, mainly windspeed ($\bar{u}$). Where pertinent these data are compared to those from other towns and cities under comparable conditions, and a simple model is suggested to enable prediction of ΔT_{u-r} when skies are clear.

2. SURVEY AREA AND PROCEDURES

The area chosen for the survey was the St. Lawrence Lowland region in the Province of Quebec, Canada (FIG. 1). The region is extremely flat (slope $< \frac{1}{2}°$) except for a few isolated volcanic hills, and is traversed by the St. Lawrence and a few other rivers. The predominant land use is agricultural, being composed of a large number of small arable and dairy farms.

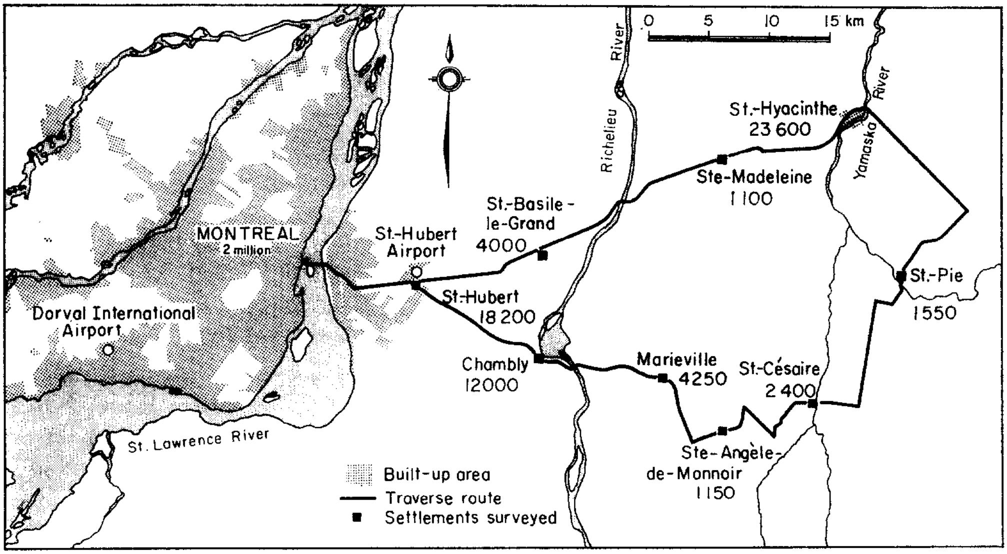

FIG. 1. Traverse route in the St. Lawrence Lowland, Quebec.

The traverse route (FIG. 1) was about 140 km in length, and took approximately 3 h to complete by automobile. The route was chosen to include 10 settlements (TABLE 1), whose population sizes ranged from 1000 to 2 million, and whose locations ensured that they would be free from topographic and water influences, with the possible exceptions of Montreal and the town of Chambly. The population sizes do not represent a "continuous" spectrum; there is a large gap between 24 000 and 2 million.

TABLE 1. ST. LAWRENCE LOWLAND URBAN HEAT ISLANDS AND ASSOCIATED METEOROLOGICAL DATA

Settlement population				Montreal 2 000 000	St. Hyacinthe 23 600	St. Hubert 18 200	Chambly 12 000	Marieville 4250	St. Basile-le-Grand 4000	St. Cesaire 2400	St. Pie 1550	Ste. Angele-de-Monnoir 1150	Ste. Madeleine 1100		
Date		$\bar{u}$* (m s^{-1})	Cloud*	Urban heat island intensity, ΔT_{u-r} (°C)†										r‡	r§
22 March	1969	WSW 4.0	AC 1	3.0		0.5	0.7			0.2					
6 May	1969	E 3.1	AC 1-Ci 1		3.6			1.6		1.6	1.3		0.9		
20 May	1970	ENE 3.1	0	6.0	3.4	2.7	2.8	2.5		3.1	2.0	1.6	1.6		
23 May	1970‖	WSW 4.5	0-AC 1	5.7	3.3	1.3	1.6	1.6	1.3	0.6	0.3	0.3	0.8	0.95	0.82
30 May	1970‖	SSW 3.1	0	5.1	2.8	1.1	1.9	0.8	1.1	1.3	0.4	0.4	0.3	0.96	0.83
27 October	1970‖	NNE 2.2	0	6.2	3.2	2.3	2.7	1.3	1.9	1.2	1.0	1.1	1.3	0.98	0.91
29 October	1970	NE 4.5	0-Ci 1	4.3	2.2	2.5	2.1	1.6	1.0		1.5	0.8	0.8		
30 November	1970‖	N 3.6	0-SC 1	3.2	1.0	1.2	2.2	0.8	0.6	0.8	0.3	0.3	0.2	0.91	0.75
15 December	1970‖	SE 0.9	Ci 1	*12.0*	*6.6*	*6.3*	4.5	*5.2*	*3.7*	*4.3*	*3.3*	*2.7*	1.2	0.97	0.89
29 December	1970	W 5.4	Ci 2-AC 10	2.5	1.8	0.7	1.4	2.0	1.5	1.1	0.9	0.8	0.9		
7 May	1971‖	NE 0.5	0-Ci 1	10.2	5.5	3.2	*5.1*	3.1	1.6	3.2	2.4	1.8	1.5	0.95	0.80
10 May	1971‖	SW 1.9	0-Smoke 1	8.3	4.2	2.6	3.5	2.9	1.9	3.9	1.1	1.0	*1.8*	0.92	0.69
9 June	1971‖	N 4.1	0	6.7	3.8	2.3	2.2	1.6	1.2	1.3	0.9	0.8	0.5	0.98	0.93
10 June	1971‖	N 0.5	0-Ci 1	9.7	6.0	5.2	3.6	2.8	2.4	3.1	2.9	1.7	1.6	0.97	0.91
23 June	1971‖	S 2.3	AC 1	7.4	3.9	2.4	2.2	2.2	2.7	3.0	2.2	1.1	1.1	0.93	0.69
12 June	1971‖	SW 1.8	0-Ci 1	7.8	4.5	2.8	3.0	2.7	2.1	1.9	1.9	1.1	1.5	0.98	0.90
Average		2.3		7.5	4.1	2.8	2.9	2.3	1.9	2.2	1.5	1.1	1.1	0.99	0.94

* Dorval and St. Hubert airport averages for survey period, cloud values are total range observed.

† Using highest urban and "background" rural values.

‡ Correlation coefficient of ΔT_{u-r} vs log P regressions.

§ As for ‡ but omitting Montreal data.

‖ Nights used in regression model, and for average.

Italics = $\Delta T_{u-r(\max)}$ for each settlement.

Most of the villages and towns are composed of a mixture of wooden and stone buildings. The variety of functions performed increases with settlement size.

Temperatures were measured with a thermistor probe mounted at $\simeq 1.5$ m, and to one side of an automobile. The probe was shielded and aspirated at a rate of 3.5 m s^{-1}. The data possess a relative accuracy of ± 0.2°C (Oke and Fuggle, 1972).

On a survey night the car left downtown Montreal at about 2030 Eastern Standard Time (EST). Within settlements the traverse speed of the car was < 50 km h^{-1}. An event marker was activated to identify the entry to, and exit from, each settlement. No time corrections were deemed necessary since absolute temperatures were not required, and the time spent in any one settlement was < 10 min. The Montreal heat island intensity was sampled once on the outward, and again on the inward leg of the survey. The mean of these two values is used here. The route through Montreal was designed to include the core of its heat island based on previous work (Oke and East, 1971). For all other towns and cities the traverse route passed through the central part of the settlement. The previous study also showed ΔT_{u-r} to usually be at a maximum at about 2100–2300 EST. This timing of the maximum may not be strictly accurate for all settlement sizes or seasons, but the ΔT_{u-r} values presented here are probably close to the largest heat islands for each night.

Standard meteorological observations of wind (10 m) and cloud were provided by the Canadian Atmospheric Environment Service for Dorval International Airport, and the Canadian Forces Base at St. Hubert (Fig. 1). Both sets of data were averaged to approximate a regional picture for the St. Lawrence Lowland.

3. URBAN HEAT ISLAND DATA

A complete listing of the data collected for this study is given in Table 1, along with the associated general meteorological conditions. A total of 16 surveys were conducted, but only 11 incorporated the complete range of settlements, and conformed to the criterion of $< \frac{1}{10}$ cloud. The analysis is restricted to these 11 cases, which include both summer and winter nights.

Figure 2 results from a pooling of the ΔT_{u-r} data into gross averages for each settlement, and plotting against log P. This plot clearly supports the hypothesis that ΔT_{u-r} is an identifiable function of city size. The degree of explanation (97 per cent) is very high, and it could be argued that this is biased in a logarithmic relation by the very large P value for Montreal. A similar regression omitting Montreal however still results in an 88 per cent explanation of variance. One further point to note is that villages of about 1000 inhabitants exhibit heat islands (assuming 1°C is the minimum urban/rural difference of significance).

The success of Fig. 2 prompted an investigation of the relation between ΔT_{u-r} and log P on individual nights. Simple regression analyses were performed for each night and the relation was again found to hold remarkably well with $r > 0.9$ on all occasions. Again there is some loss of correlation when Montreal is omitted from the analysis, but the average explanation for individual nights is 70 per cent (Table 1). Plots of these relations clearly showed that the slope of each ΔT_{u-r}/log P regression line was mainly a function of windspeed. The slope of the regression decreased as $\bar{u}$ increased. Further regressions of log ΔT_{u-r} against log $\bar{u}$ indicated that the characteristic wind function was approximately $\bar{u}^{1/2}$ (see also Fig. 3). It is concluded that ΔT_{u-r} is directly proportional to log P, and inversely proportional to $\bar{u}^{1/2}$.

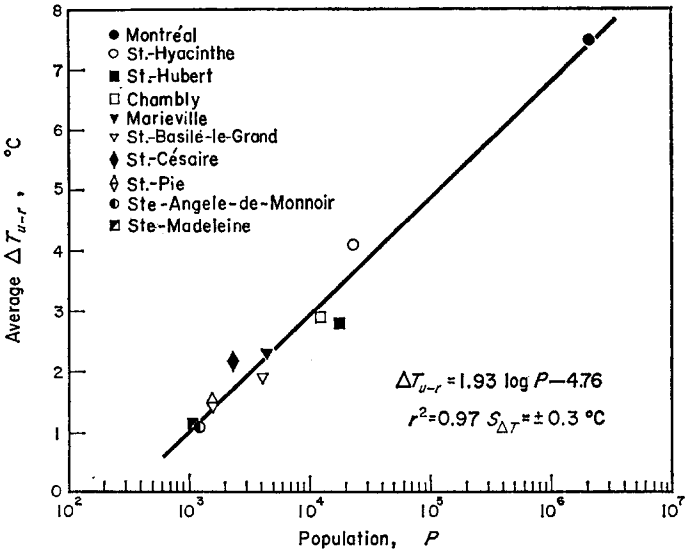

FIG. 2. Relation between the average survey ΔT_{u-r}, and city size (as given by P), for 10 settlements on the St. Lawrence Lowland. (Average windspeed 2.3 m s^{-1} and clear skies.)

4. HEAT ISLAND PREDICTION MODEL

SUNDBORG (1950), working in Uppsala, first demonstrated an empirical relationship between the urban heat island and meteorological controls of the form:

$$\Delta T_{u-r} = \frac{(a - b\,N)}{\bar{u}} \tag{1}$$

where, N = cloud amount; $\bar{u}$ = regional windspeed; a, b = constants for the city concerned. Similar relationships have been demonstrated for other cities (e.g. DUCKWORTH and SANDBERG, 1954; CHANDLER, 1965). In each case wind and cloud have emerged as the most important parameters, reflecting the importance of radiation, convection and advection in determining urban/rural heat balance differences. In this study we are only considering the special condition when $N = 0$, and we are interested not in the unique form for a single city, but rather the relations between ΔT_{u-r} and a range of settlement sizes within a region.

The data (TABLE 1) was subjected to stepwise multiple regression analysis. The combination yielding the highest explanation of variance was:

$$\Delta T_{u-r} = 1.91 \log P - 2.07\,\bar{u}^{\frac{1}{2}} - 1.73 \tag{2}$$

with, a coefficient of determination (r^2) = 0.82, and a standard error-of-estimate for ΔT_{u-r} ($S_{\Delta T}$) = ±0.9°C. Thus (2) gives a simple model for predicting ΔT_{u-r} for a wide range of settlements on clear nights. An alternative, but less discriminating relation is given by:

$$\log \Delta T_{u-r} = 0.27 \log P - 0.56 \log \bar{u} - 0.61$$

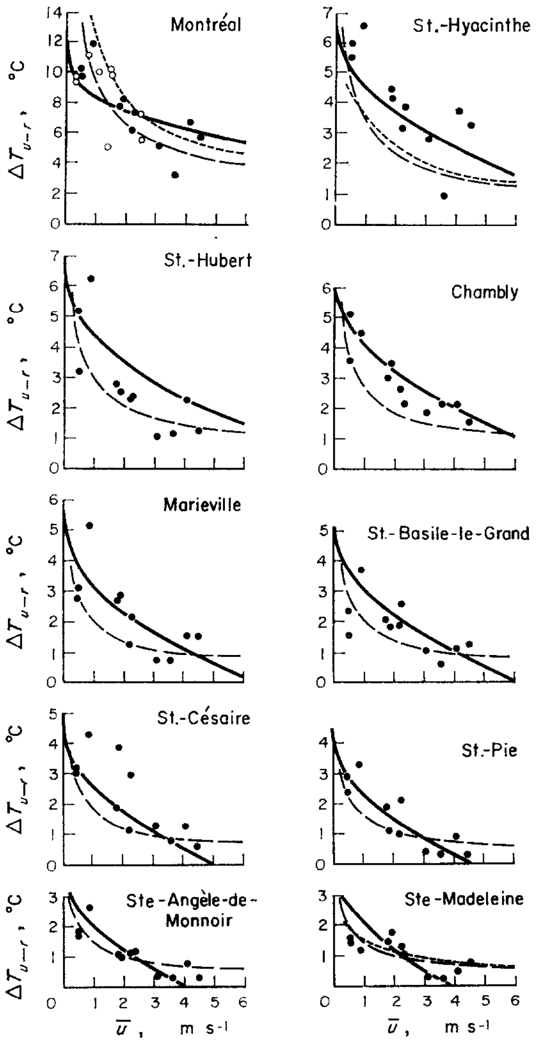

FIG. 3. Relation between ΔT_{u-r} and $\bar{u}$ for each of 10 Quebec settlements as given by the traverse data, and the proposed model. Solid line from (2), dotted from (3), and dashed from simplified form of (3). Open circles for Montreal from MAXWELL (1971). (Note compressed scale for Montreal.)

with $r^2 = 0.71$ and $S_{\Delta T} = \pm 1.6$°C. Which results in:

$$\Delta T_{u-r} = \frac{P^{0.27}}{4.04\,\bar{u}^{0.56}} \simeq \frac{P^{\frac{1}{4}}}{4\,\bar{u}^{\frac{1}{2}}}. \tag{3}$$

These formulae are compared to the field data in FIG. 3. It is gratifying to note that, although there is considerable scatter, there is general agreement between the formulae and the data for each settlement size category. That is, the predicted ΔT_{u-r} for settlements at any position in the size range do not consistently over- or underestimate. There is some reason to prefer the form of (2) over (3), on statistical grounds, but visually little to choose between them. The effect of simplifying (3) is greatest for large settlements (FIG. 3). For the others the effect is so small that only a few comparison lines are included.

Data from MAXWELL (1971) are included in the Montreal graph in FIG. 3, and are consistent with the data from this study. Both sets include summer and winter cases, but there appears to be no reason to differentiate between the seasons. Further Montreal data from OKE and FUGGLE (1971) follow the same trend but were not included because their traverse route did not pass through the heat island core and hence ΔT_{u-r} values are consistently low.

The fourth root of P result in (3) is most interesting. SUMMERS (1964) suggested a simple urban boundary layer model based on the progressive warming of rural air as it moves across an urban area. Assuming the urban area to act as a uniform heat source this model suggests ΔT_{u-r} to be proportional to the square root of the distance of travel in from the upwind rural/urban boundary to the centre of the city. Further, if we assume the city to be roughly circular, then this distance is proportional to the square root of the built-up area. Finally, since population is proportional to city area raised to an exponent not significantly < 1 for North American cities (e.g. TOBLER, 1969), then we may expect ΔT_{u-r} to be approximately proportional to $P^{1/4}$.

LUDWIG (1970) recognized this, and by constraining ΔT_{u-r} to be proportional to $P^{1/4}$ arrived at a relation of the form:

$$\Delta T_{u-r} = P^{1/4}\left(a - b\,\frac{\mathrm{d}T}{\mathrm{d}p}\right) \tag{4}$$

where, $\mathrm{d}T/\mathrm{d}p$ is the rate of change of temperature with pressure in the vertical, based on rural soundings. The present study which relies entirely upon empirical evidence, therefore provides important verification of the assumptions employed by LUDWIG (1970), and further indications of the merit of SUMMERS' (1964) approach.

This attempt at seeking order is necessarily crude. In particular there is an obvious need for similar information for more cities in the 5×10^4 to 10^6 gap, and also for cases with $\bar{u} > 5\ \mathrm{m\ s^{-1}}$.

5. DISCUSSION

The simple empirical model derived above requires to be tested against independent data if it is to achieve any generality. A literature search however did not produce a totally suitable set of heat island observations.

Although there is a lack of clear sky heat island data covering a reasonable range of windspeeds, there is a fund of information concerning "ideal" calm and clear conditions. Under these conditions the heat island is known to attain its maximum value ($\Delta T_{u-r(\max)}$). TABLE 2 lists values of $\Delta T_{u-r(\max)}$ from many North American and European settlements, and FIGS. 4 and 5 show the data plotted against log P. Clearly the logarithmic relation between ΔT_{u-r} and P is appropriate for settlements in general and is not just a feature of the Quebec data presented here. In fact the St. Lawrence Lowland data merge very well with the North American pattern given by:

$$\Delta T_{u-r(\max)} = 2.96 \log P - 6.41 \tag{5}$$

with $r^2 = 0.96$, and $S_{\Delta T} = \pm 0.7°\mathrm{C}$ (FIG. 4). Indeed further evidence of this is provided by the following example. When $\bar{u} = 0$, (2) collapses, to a simple form similar to (5).

TABLE 2. MAXIMUM HEAT ISLANDS ($\Delta T_{u-r(\max)}$) OF NORTH AMERICAN* AND EUROPEAN SETTLEMENTS

Settlement	Population ($\times 10^3$)	$\Delta T_{u-r(\max)}$ Observed (°C)	Predicted† (°C)	Author
1 North America				
Montreal, P.Q.	2000	12.0	10.3	OKE and EAST (1971)
Vancouver, B.C.	1000	10.2	9.7	OKE (1971)‡
San Francisco, Calif.	784	11.1	9.5	DUCKWORTH and SANDBERG (1954)
Winnipeg, Manitoba	534	11.6	9.2	BELL (1972)§
Edmonton, Alta.	401	11.5	9.0	DANIELS (1965)
Hamilton, Ont.	300	9.5	8.7	OKE and HANNELL (1970)
San Jose, Calif.	101	7.7	7.8	DUCKWORTH and SANDBERG (1954)
Palo Alto, Calif.	33	6.9	6.9	*Ibid.*
Corvallis, Ore.	21	6.1	6.5	HUTCHEON *et al.* (1967)
2 Europe				
London, U.K.	8500	10.0		CHANDLER (1965)
Berlin, Germany	4200	10.0		GRUNOW (1936)
Vienna, Austria	1870	8.0		SCHMIDT (1927)
Munich, Germany	822	7.0		BÜDEL and WOLF (1933)
Sheffield, U.K.	500	8.0		GARNETT and BACH (1966)
Utrecht, Netherlands	278	6.0		CONRADS and VAN DER HAGE (1971)
Malmö, Sweden	275	7.4		LINDQVIST (1972)§
Karlsruhe, Germany	160	7.0		PEPPLER (1929)
Reading, U.K.	120	4.4		PARRY (1956)
Uppsala, Sweden	63	6.5		SUNDBORG (1950)
Lund, Sweden	50	5.8		LINDQVIST (1972)§

* For $\Delta T_{u-r(\max)}$ values from this study see TABLE 1.
† Using (2) with $\bar{u} = 0$.
‡ Unpublished.
§ Personal communication.

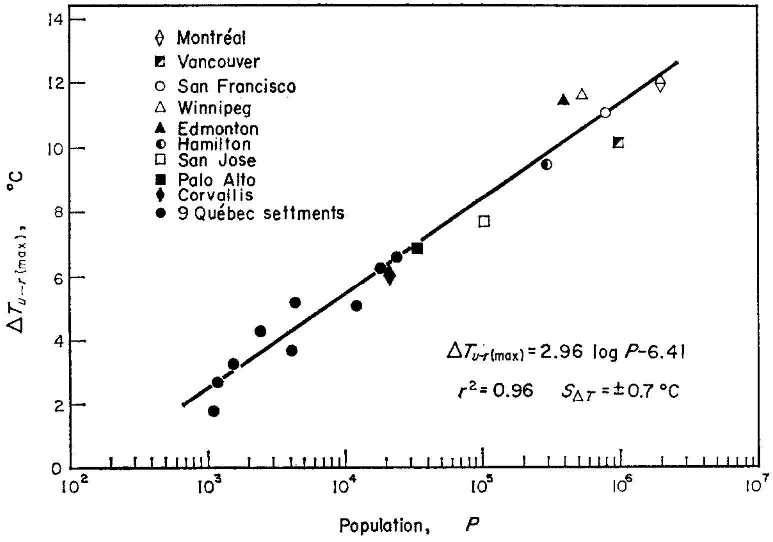

FIG. 4. Relation between $\Delta T_{u-r(\max)}$ and log P for North American settlements (Source: TABLES 1 and 2).

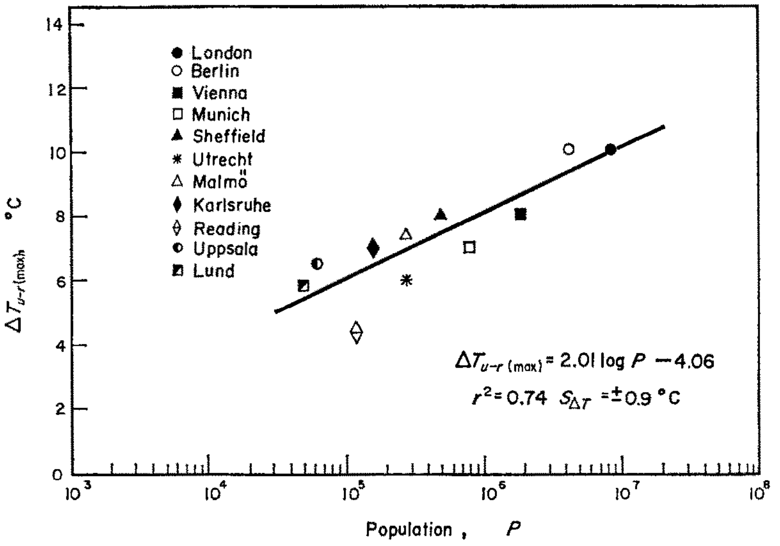

FIG. 5. Relation between $\Delta T_{u-r(\max)}$ and log P for European settlements (Source: TABLE 2).

Using (2) based on Quebec data values of $\Delta T_{u-r(\max)}$ were computed for the non-Quebec cities contained in the North American section of TABLE 2. The predicted values agree credibly well with those observed (TABLE 2). There is, however, some evidence of underestimation for large settlements. This may reflect the small number of large cities included in the Quebec relation.

The European relation (FIG. 5) is given by:

$$\Delta T_{u-r(\max)} = 2.01 \log P - 4.06 \tag{6}$$

with $r^2 = 0.74$ and $S_{\Delta T} = \pm 0.9$°C. The main difference between (5 and 6) is the slope of the regression. Thus for a given city size (P) the European heat island will be smaller. This might appear a little surprising since European cities have greater population densities, and might therefore be expected to show more concentrated modification of the temperature field. To explain this one might ascribe the result to such factors as lower artificial energy flux densities, lower heat capacity of the urban fabric, or greater evapotranspiration in European cities. On the other hand it may be sufficient to note that, if we apply the same argument used to explain why ΔT_{u-r} is proportional to $P^{\frac{1}{4}}$ in North America, but using typical European densities (TOBLER, 1969), then ΔT_{u-r} is likely to be proportional to approximately the fifth root of population.

It would be wise to note some of the obvious limitations of the proposed model. The nature of the model implicitly assumes some degree of functional or structural similarity between settlements of the same size, and/or a continuous hierarchy of functional or structural properties linking settlements of different sizes. Within a given cultural context such relations have been identified by urban geographers. It is quite easy however to envisage anomalous situations, especially if population is the surrogate for city size. For instance Dorval airport (FIG. 1) has been shown to possess its own heat island (OKE and EAST, 1971), and other specialized functional units may be expected to do the same. High-latitude settlements, where energy-consumption *per capita* is high (e.g. Fairbanks, Alaska; SMIC, 1971) and rural radiative cooling is favoured in dry air masses, may well show higher ΔT_{u-r} values than predicted here. Very large ΔT_{u-r} values are found in northern Finland (HUOVILA, Personal communication). Conversely it may be argued that humid–tropical cities may show lower than predicted ΔT_{u-r} values. Similarly it is hard to provide an answer for the results of CHANDLER (1967), who shows heat islands in London and Leicester, to be comparable on the same night, yet their areas and populations are radically different.

Notwithstanding these obvious limitations it still would appear that there is an underlying relation between city size and the heat island intensity. This relation is not precise but its form is at least recognizable.

In conclusion it seems appropriate to make comment concerning possible physical controls underlying the logarithmic relation which has emerged from this study. This means that for a given increment in P, ΔT_{u-r} increases more for a town than for a large city. This was first noted by DUCKWORTH and SANDBERG (1954) in their classic survey of three cities in California. Presumably the physical arguments proposed earlier to account for the $P^{\frac{1}{4}}$ relation (or $P^{\frac{1}{5}}$ for Europe) play the major role in this apparent insensitivity of large cities. It also seems pertinent to point out two other factors which may operate to limit the size of ΔT_{u-r} for a large city. Firstly, we must recognize that there is a finite limit to any phenomenon such as a heat island, and that is the energy available to support it. The differential warmth of the urban atmosphere is a function of urban/rural energy-source, and energy-partitioning differences. The energy-source difference is due to heat released in combustion, and it could be that large cities approach a limiting artificial energy flux density compatible with their population density, and climatic setting. Energy-partitioning differences are mainly due to the heat storage capacity of urban building materials, and to the supposed lack of evapotranspiration in the city combined with enhanced turbulent transfer characteristics. It is conceivable that by intensive urbanization large cities have restricted their land-use options sufficiently that the addition of more urban fabric becomes increasingly less significant climatically. For example beyond a certain level of urbanization creation of new structures often results in destruction of old ones rather than the takeover of already scarce parkland.

Secondly, when a city attains a large heat island the urban/rural temperature gradient often becomes sufficient to induce a convergent thermal breeze circulation. This airflow will prevent complete stagnation from occurring, and provides a built-in limit to further heat island growth.

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