A Spatial Model of an Urban Heat Island

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ABSTRACT

Mean temperatures obtained from 28 midday motor traverses in the Durban area during the summer of 1968–69 show the center of the heat island to be displaced away from the central business district by the sea breeze. The spatial temperature wave across the center of the heat island is described by a simple harmonic model.

1. Introduction

The urban heat island is an integral part of city climates and represents the modification of local climate by the urban fabric. Elements of the city structure that contribute to the production and retention of heat have been described by Chandler (1965). The increased friction encountered by winds over cities result in lowered mean wind speeds (Maurain, 1947; Chandler, 1965) and the pre-existing radiation balance is upset by atmospheric pollution and city structure. Munn (1966) points out that the upward flux of longwave radiation is less than in country areas, particularly where buildings are tall and streets narrow, while longwave back radiation is greater. Climatic modifications such as these maintain higher temperatures within the city than without, so that a heat island may be found to occur throughout the day and night.

While heat islands are generally more intense by night than by day in both periods it is usually characterized by an isotherm configuration which, assuming low relief, conforms to the shape of the city. The nature of this cellular form may, however, show day-to-day changes, particularly when influenced by winds which tend to displace the heat island in a downwind direction (Sundborg, 1950; Chandler, 1961).

As an alternative to describing day-by-day changes of the urban temperature field, this paper presents an empirical model of the spatial distribution of mean midday temperatures recorded in Durban, South Africa, during the summer of 1968–69. To develop a quantitative model of the spatial variation of Durban's heat island, 12 equidistant points were linearly extrapolated along the section lines given in Fig. 1 and submitted to harmonic analysis (Conrad and Pollak, 1950; Brooks and Carruthers, 1953). The resulting equation describing the temperature field is of the form

$$T=\bar{T}_s+\sum_{k=1}^{6} a_k \sin\left(\frac{2\pi kd}{12}+\phi_k\right), \qquad (1)$$

where $\bar{T}_s$ is the space mean temperature, a_k the amplitude of wavenumber k with phase angle ϕ_k, and where $d=0, 1, \ldots, 11$ is measured in units of 0.5 km from the points of origin A, C, E, G and I on the section lines of Fig. 1.

2. Data collection

Traverses were carried out over a period of 28 days from late November 1968 to early February 1969. The traverse was started between 1200 and 1230 (local standard) and took ~1 hr to complete. Since temperatures at the beginning and end of the traverse seldom

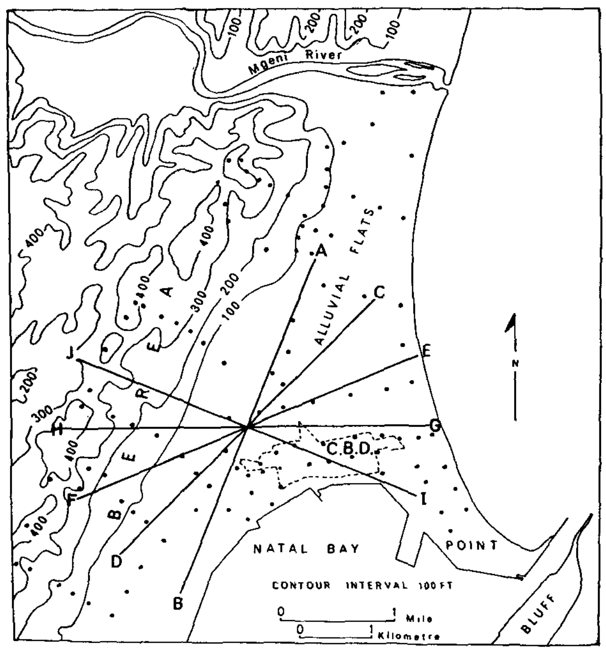

FIG. 1. Temperature recording stations (shown as dots) in the Durban area and the section lines used for the development of the model.

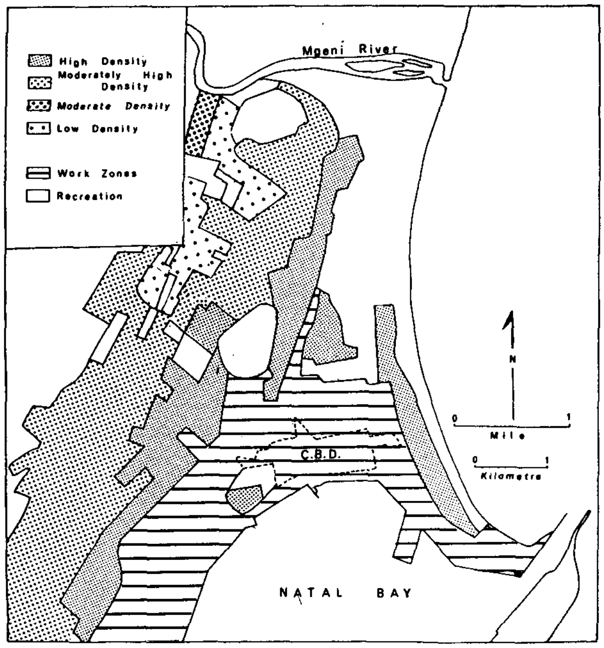

FIG. 2. Residential density, work zones and recreational regions in the fieldwork area [after Davies (1960) and Davies and Rajah (1965)].

differed significantly, no correction was applied to reduce temperatures to a common time.

To evaluate Durban's heat island in terms of purely urban conditions, height effects were eliminated by reducing all mean maximum temperatures to sea level using the observed lapse rate of 0.4C $(100\ \mathrm{m})^{-1}$ that prevailed between the lowest and highest stations. This lapse rate was determined by regression analysis of temperature on height based on data from nine Weather Bureau stations in the area ranging in height from 7 to 701 m.

3. The urban setting

The work zone shown in Fig. 2 is located on alluvial flats that surround the harbor at Durban and occupies land <9 m MSL. From the point of view of the urban temperature field the unifying characteristics of the region are the close proximity of buildings, which are bounded within a grid network of macadamized streets, the high density of motor vehicle traffic, and the lack, with one exception, of large open recreational space. Multi-storied apartments which line the seashore cause the high residential density in that area.

The alluvial flats are backed by a sand ridge known as the Berea which rises with a 6° slope to an altitude >122 m. The decrease in residential density up the Berea ridge is accompanied by a corresponding change in the urban fabric. The region of high residential density located along the lower slopes of the Berea ridge consists of single-storied, closely-spaced houses

TABLE 1. Percentage frequency of winds from various directions from December to February at Durban.*

Wind speed range (kt)	Wind direction								
	N	NE	E	SE	S	SW	W	NW	Calm
3–13	3	30	12	12	10	2	—	—	4
14–27	—	5	1	—	10	10	—	—	—
28–40	—	—	—	—	—	1	—	—	—

* See Meteorological Service etc., 1941.

set on small properties along narrow, macadamized streets. With increasing elevation up the ridge, decreasing residential density coincides with larger houses set on more spacious properties.

4. Discussion

It is apparent from Fig. 3 that in summer an elongated heat island extends along the foot of the Berea ridge with its center situated west of the central business district over a relatively open area occupied by a market, an extensive car park, wide streets and buildings which are lower than those in the business district. This anomaly is due to the displacement of the heat island by the sea breeze away from the heat sources provided by the business district. These breezes, strengthened by gradient winds, blow strongly during the summer months. Table 1 shows the high frequency of the northeast sea breeze which blows obliquely off the sea.

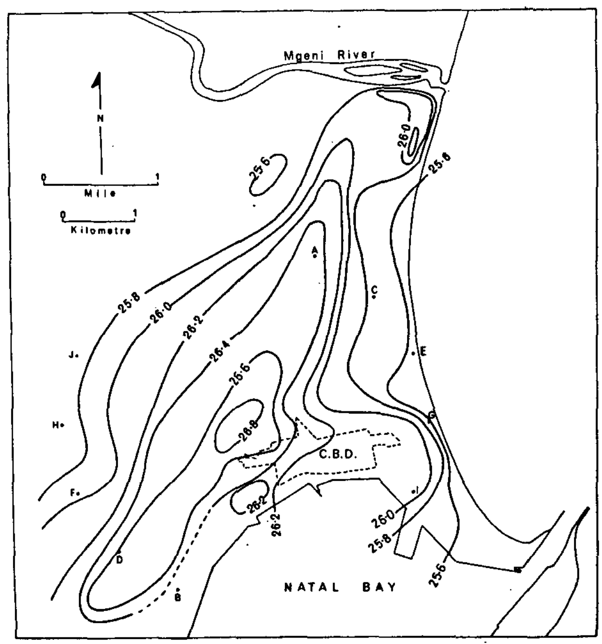

FIG. 3. Isotherms (°C) of mean midday reduced temperatures recorded over 28 days between November 1968 and February 1969.

Temperature gradients are relatively steep along the seashore east of the work zone and along the foot of the Berea ridge. The gradient is due in the former area to the presence of multi-storied apartments which block penetration of the sea breeze into the work zone; in the latter area the gradient is due to variations in the character of the residential setting. In general, however, reduced temperatures are lowest along the seashore and crest of the Berea ridge.

The heat island can be precisely described by determining the amplitudes and phase angles of the temperature variation along the section lines cutting the heat island. Table 2 shows the spatial variation of these parameters. The degree to which a particular wave fits the observed temperature variation through the heat island is given by the percentage variance contribution of the wave to the total variance and is expressed by

$$S_k=\frac{a_k{}^2 100}{2\sigma_T{}^2}. \qquad (2)$$

The first three sine terms in Eq. (1) are shown in Table 2 to account for phase angles involving more than 75, 87 and 95% of the variance about the space mean temperature. Phase angles for successive harmonics calculated along each section line do not vary greatly and amplitudes are approximately constant fractions of the space mean temperature. Mean amplitudes and phase angles may, therefore, be taken as representative of the area covered. Mean values of a_1, a_2, a_3 are, respectively, 1.6, 0.46 and 0.34% of the mean $\bar{T}_s$. The expression

$$\bar{T}=\bar{T}_s+0.016\bar{T}_s\sin(kd+272°) +0.0046\,\bar{T}_s\sin(2kd+121°) +0.0034\,\bar{T}_s\sin(3kd+314°), \qquad (3)$$

where $k=30°$ for $d=0, 1,\ldots 11$, describes the mean spatial temperature distribution.

5. Conclusion

Harmonic analysis provides a technique to ascertain the degree to which a symmetrical heat island over a city can be adequately described in a quantitative sense. The close correspondence of the mean spatial temperature wave over Durban to a single sine wave is demonstrated by the model which also provides for the prediction, from relatively few measuring points, of the spatial variation of temperature over the city. The extent of the influence of other factors such as winds which persist from one quarter or a steep temperature gradient at the edge of a built-up area, are also reflected in the amplitudes of the succeeding harmonics and the contribution of each wave to the total variance about the space mean temperature.

Table 2. Spatial distribution of space mean temperature, as well as harmonic amplitudes and phase temperature [expressed by Eq. (1)]. The values S_k denote the cumulative percentage contribution to the total variance.

Section	$\bar{T}_s$	a_1	ϕ_1	a_2	ϕ_2	a_3	ϕ_3	s_1	s_2	s_3
A-B	26.5	0.24	297	0.07	113	0.04	360	88	95	98
C-D	26.5	0.43	242	0.17	200	0.14	249	75	87	95
E-F	26.2	9.56	255	0.08	139	0.06	304	94	96	97
G-H	26.2	0.45	281	1.10	65	0.08	323	90	95	98
I-J	26.2	0.42	285	0.17	90	0.11	333	81	94	99
Mean	26.3	0.42	272	0.12	121	0.09	314	86	93	97

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