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Inferences about the heat-island circulation from a study on the evolution of the nocturnal heat-island at Pune

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सार — 22-23 जनवरी 1982 की रात को पुणे में ताप-द्वीप पैटर्न के क्रमिक विकास का एक अध्ययन किया गया था। ऐसे अध्ययनों के लिए प्रयुक्त उन शुद्धियों पर भी विस्तार से विचार हुआ है जिनकी मोबाइल सर्वेक्षण तकनीकी की सटीकता में वृद्धि करने में आवश्यकता पड़ेगी। विकासोन्मुख ताप-द्वीप पैटर्न तथा परिनालिकीय संचरण की उपस्थिति के मध्य परस्पर संबंध का पता लगाने के लिए एक प्रयास किया गया है। समताप रेखांओं के बदलते रूप का विश्लेषण करते हुए ऐसे संचरण की लचीली प्रकृति का निर्धारण किया गया है। भूभाग की प्रकृति तथा ऊर्ध्वाधर संचरण के वायवीय विस्तार द्वारा अदा की गई भूमिका इस अध्ययन से मालूम की गई है।

ABSTRACT. A study was made on the evolution of the heat-island pattern at Pune on the night of 22/23 January 1982. The corrections required to increase the accuracy of the mobile survey technique, used for such studies, have been elaborately discussed. An attempt has been made to find out a relationship between the evolving heat island pattern and the presence of a solenoidal circulation. The fluctuating nature of such a circulation has been determined by analysing the changing shapes of isotherms. The role played by the nature of terrain and the aerial extent of the vertical circulation have also been inferred from this study.

1. Introduction

The 'heat island' is a zone of positive temperature anomaly of the urban built-up area with respect to its surroundings. The relative warmth of the heat island area is due to the extra heat trapped by the building material and built up geometry. It is prominent only after sunset when the open grounds cool at a faster rate than the urban areas. The presence of vertical circulation of a shallow depth (of a few hundred metres) is another feature which has been observed over the night-time heat-island zones in several cities. The circulation is weak and not easily discernible due to the smallness of the spatial extent involved. Data from meteorological towers, special balloons-soundings and aircraft traverses have been obtained, revealing the existence of upward movement of air over a horizontal size scale of few kilometres and at rates of about 0.3 m/sec (Dannevik *et al.* 1974, Auer 1975). This magnitude is somewhat more than the synoptic scale values in the absence of precipitation. It has been conclusively established that all heat islands, whether strong or weak, have a circulation pattern of their own which are modified by larger scale conditions prevailing in the region.

Several heat island studies have been done for Indian cities also (Daniel *et al.* 1973, Mukherjee *et al.* 1976, Padmanabhamurty 1979, Krishna Nand *et al.* 1981). All of these have attempted to correlate the night-time thermal fields at the ground level with the urban topography, built-up area distribution, advection effects on a scale of few kilometres and also the prevailing windiness. Mukherjee *et al.* (1976) reported the most intense heat island from Bombay among other cities. The temperature excess of the urban area over the rural one was 11.0°C. Although in general the differences lay between 2.0° and 8.0°C at all places, there are indications of higher values occurring at Delhi. In winter the heat islands are most intense and in monsoon they are the weakest (Krishna Nand *et al.* 1981).

In all the above referred studies the ground distributions of a selected number of parameters from amongst temperature, humidity and wind were discussed, but Mukherjee *et al.* (1976) also incorporated the mixing effect of winds above the urban boundary layer to explain the vertical temperature profile over the urban area of Bombay. It may be mentioned that any modification of the regional scale wind field is due to locally induced vertical circulation, which in the case of an urban configuration is caused primarily by roughness induced forced convection and surface temperature gradient induced solenoidal convection. Now, given the presence of a heat island in the night and a vertical circulation, both of which are associated phenomena one can seek for a second order interaction between the two. This is to say that the heat island pattern itself may be subject to modification by the horizontal component of the circulation.

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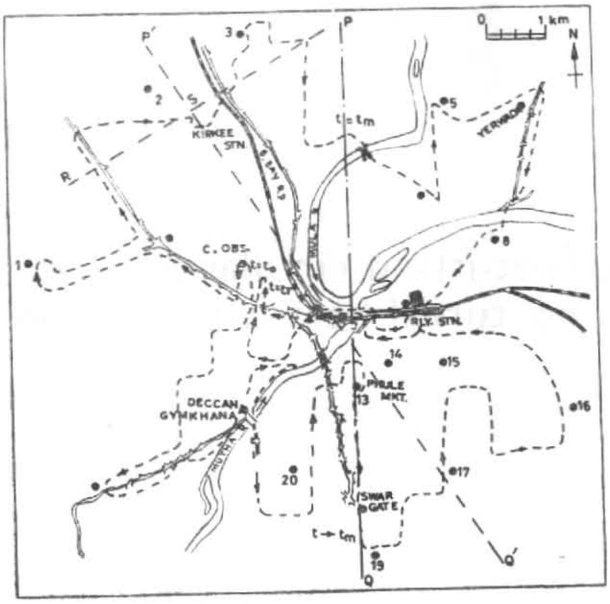


Fig. 1. Pune city, route map for mobile survey by the two vehicles. Site numbers of observing sites included in the study are marked

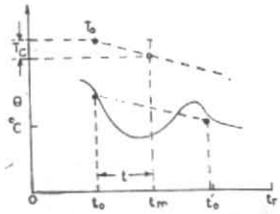


Fig. 2. Determination of temperature correction T_c (Note : $t_m = \frac{1}{2} t_r$)

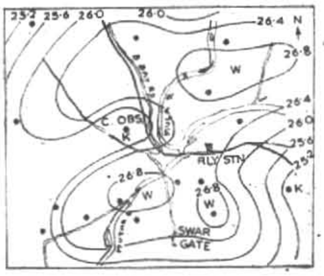


Fig. 3. Isotherm chart, 1800 hrs, 22 January 1982, Pune. Spacing of lines 0.4°C

The intention of this paper is to study the evolution of a heat island during the night and infer regarding the nature of the vertical circulation from it. A heat island survey was carried out over Pune (Lat. 73° 52′, Long. 18° 32′, Alt. 569 m a.s.l.), on the night of 22/23 January 1982. The results of this are reported herein, laying special emphasis on the pattern of inflow into the heat island zone at ground level.

1.1. *Background information*

The old city area of Pune which is the densest locality is situated to the south of the two rivers flowing through the city (Fig. 1). The western and south western sides are flanked by hills and other sides open into flat country side with a gentle slope from soutwest to the northeast. On the night of the survey the upper winds at 0.9 km a.s.l. were predominantly northerly and weak (05 to 10 knots during the different synoptic hours).

2. Methodology

2.1. Twenty locations were selected throughout the city as sites representatives of the area around them in respect of the radiative characteristics of the surface and also the topography of terrain. At six out of these locations thermographs were kept while the rest were covered by observers stationed at the spot who took dry bulb and wet bulb observations with a psychrometer at hourly intervals. Two mobile surveys were also conducted, one in the late evening, the other during late night. The observations at all sites were reduced to the medial time of the complete survey span by applying trend corrections. Trend corrections were derived from the averaged cooling curves of the nearest representative stationary site. It may be said here that errors in trend evaluation would be a function of space depending on the representativeness of the temperature monitoring point with it's surrounding domain. There would also be error in averaging the trend curve. The methods of reducing the errors for trend corrections are described below :

2.2. Let N be the total data points on each chart with temperature T_i , $i=1, N$.

$N=20$ for four fixed location survey charts and

$N=80$ for two mobile survey charts.

Now on each chart the isotherms are families of curves, where the kth isotherm can be represented mathematically as a relation, R_k, of T_i and T_j., i, j taking N_k values,

$$\text{Isotherm}_k = R_k(T_i, T_j) \quad (1)$$
$$i, j = 1, N_k$$

Thus the heat island intensity on each chart may be represented as,

$$\triangle T_H = T_{k\,(\text{max})} - T_{k\,(\text{min})}$$

It is quite obvious that all values of T_i s should correspond to the same instant of time. Thus, for fixed location survey charts these are all observed quantities while for the mobile survey ones they are derived quantities. For the latter type let T_0 be the observed temperature at any point 'i' and T_c be the temperature correction. Then the actual temperature T would be given by the relation, $T - T_0 = T_c$ (*see* Fig. 2) where :

$$T_c = \left(\frac{\triangle\theta}{\triangle t}\right)_{t_o - t_m}\left(t_0 - t_m\right) = \left(\frac{\triangle\theta}{\triangle t}\right)_{t'} t' \quad (2)$$

(*i*) θ is the temperature obtained from the nearest representative trend curve (psychrometer or thermograph records).

(*ii*) 't' is time.

(*iii*) 't_0' is the time of observation, 't_m' is the medial time of survey to which all observations are to be reduced.

(*iv*) $t' = t_0 - t_m$.

$(\triangle\theta/\triangle t)_t'$ is the estimated averaged cooling rate for the interval t'. For the purpose of this paper the shape of isotherms given in (1) are important hence all values of T_i should be relatively compatible for which the corrections T_c should be as accurate as possible. On taking differentials on either side of (2) we get the expression for error in T_c as :

$$\delta T_c = t'\,\delta\left(\frac{\triangle\theta}{\triangle t}\right)_{t'} + \frac{\triangle\theta}{\triangle t}\,\delta t' \quad (3)$$

To minimise δT_c we must have both terms on the RHS as small as possible.

2.2. (*i*) (a) $t'\,\delta(\triangle\theta/\triangle t)_t'$—The error in averaging the trend curve [*i.e.*, determining $\delta(\triangle\theta/\triangle t)_t'$] is a function of location as well as t'. To reduce the error due to locational differences the choice of a station for the trend curve was based on similar terrain features and not just considerations of proximity. In spite of this for the outskirts of the city where space variations of the trend are maximum this error is substantial, due to the limitation on the availability of such curves at close distances. Thus it was felt best to choose the survey path such that at least a part of this region could be covered at the time when $t' \rightarrow 0$.

Now for t' slightly higher (upto *say* 5-15 min), the highly localised temperature fluctuations affect the selection of $\triangle\theta/\triangle t$. Again for $t'>1$ hour size of t' itself increases the error although the $\triangle\theta/\triangle t$ may be more representative. Thus, it is best to cover other parts of the outskirt regions at times at least 15 min either way of the medial time, but within 1 hour. Thus the routes as shown in Fig. 1 were planned in a criss-cross manner covering the outskirt regions around 40 min before the medial time itself and lastly around 40 min after the medial time.

2.2 (*i*) (b) — Herein it is worthwhile to mention that the trend curves for different sites are drawn from either of the following two types of observations. One that of instantaneous observations of psychrometers (averaged for 1 min) and the other as continuous records of the thermograms. The latter show that there are predominantly two different classes of thermal perturbations — one that of 5-10 min and the other that are more than 1 hour (*see* Fig. 11). For the purpose of the present study the latter mode is important. Hence the optimum frequency of psychrometer observations was chosen as twice per hour so that the first mode could be filtered out and the second mode could be somewhat retained. That this optimization was reasonably good is proved by comparing the thermograms with the psychrometer traces for the same stations (*see* Fig. 11 and Fig. 12 for corresponding sites).

2.2 (*ii*) — To understand the implications of the term $(\triangle\theta/\triangle t)\delta t'$ we must assign dt' the role of a range generated by choosing different values of t' in Eqn. (2). The variations in t' during the survey can at the most be 0 to t_m. Thus it is necessary to reduce this range by completing the survey fast. This was achieved by using two vehicles and splitting the first survey in two halves (cross check intercomparison of temperatures were done in the overlap regions). During the second survey in the late hours of night the trend curve itself had flattended out so that $\triangle\theta/\triangle t$ was very small, thus a higher range of time span was allowable. Hence each vehicle covered the whole area in about twice the amount of time, but moving in opposite directions. It is quite obvious that the respective halves of each for the two surveys complemented each other in terms of coverage of space. Hence effectively the time range was reduced to slightly greater than half of the duration each vehicle required for the whole area coverage. This gave us smaller value of t_m (as one survey would have given) as well lesser magnitude of $\triangle\theta/\triangle t$ during late night hours. Out of the two charts thus obtained only the first one is reported here because the last portions of the second one were covered after sunrise.

3. Results and discussions

3.1. *Analysis of isotherm fields at different times* — The isotherm fields for 1800 hr, 2030 hr, 2200 hr. 0200 hr, 0400 hr, 0530 hr and 0600 hr (Figs. 3-9) are analysed and reported here. In all these figures the observation points are located by dots.

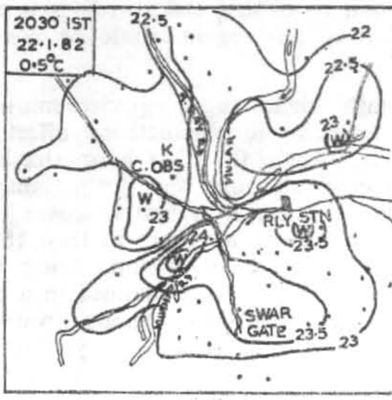


Fig. 4. Isotherm chart, 2030 hr, 22 January 1982, Pune. Spacing of lines 0.5°C

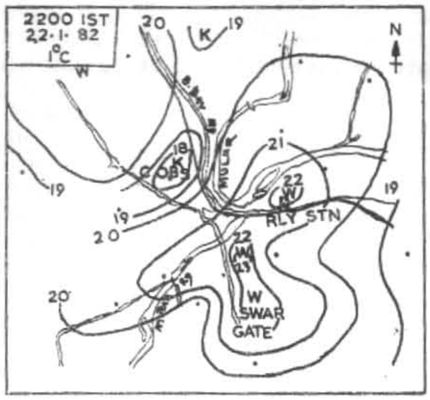


Fig. 5. Isotherm chart, 2200 hr, 22 January 1982, Pune. Spacing of lines 1.0°C

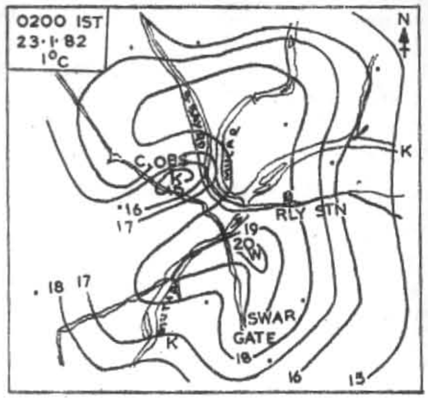


Fig. 6. Isotherm chart, 0200 hr, 23 January 1982, Pune. Spacing of lines 1.0°C

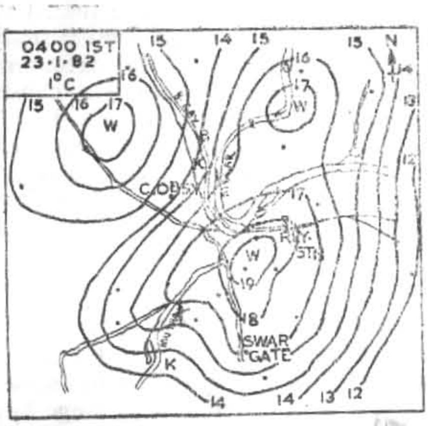


Fig. 7. Isotherm chart, 0400 hr, 23 January 1982, Pune. Spacing of lines 1.0°C

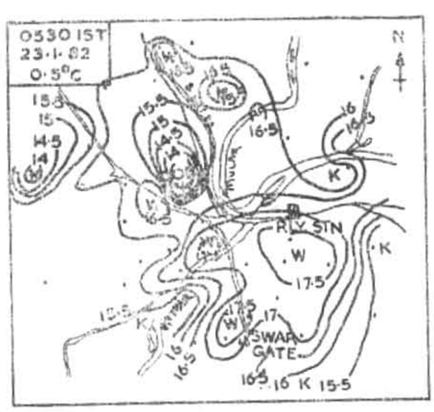


Fig. 8. Isotherm chart, 0530 hr, 23 January 1982, Pune. Spacing of lines 0.5°C

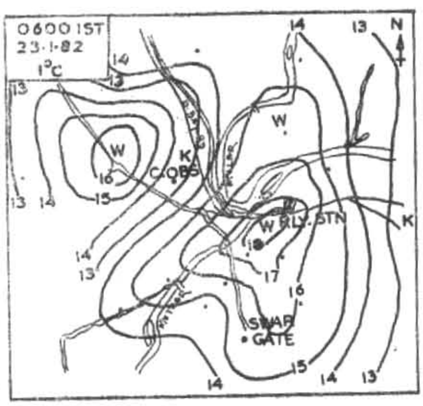


Fig. 9. Isotherm chart, 0600 hr, 23 January 1982, Pune. Spacing of lines 1.0°C

3.1.1. 1800 *hr* (Fig. 3) — This chart is drawn from a time just after sunset. During this period the cooling rates are most rapid at all locations but are higher for the outskirt of the city. This aspect of nocturnal cooling is responsible for the genesis of heat island zones. Three warm regions are observed on this chart. One lies over the NE sector where recent urban expansion has occurred. The second lies over Deccan Gymkhana area, in the SW sector. The third is over the Quarter Gate region in the SE sector. The latter two regions coincide with the heavily built up areas and high volume of vehicular traffic during these hours. The heat island intensity is yet low, just about 2.0°C.

3.1.2. 2030 *hr* (Fig. 4). — This data set is obtained from the first mobile survey A higher data density on this chart reveals finer details. The NE sector heat island has shrunk in size and appears to have moved southwards. The warmest pocket in this zone falls on the river. Two other heat slands can be seen on this chart over the eastern and western portions of the city. These two are later developments. Indicating that these areas have cooling rates intermediate to the rural and dense urban areas, so that greater time is required for the formation of detectable heat islands.

3.1.3. 2200 *hr* (Fig. 5) — On this chart the heat island of NE sector has vanished. It may well have still existed with a shrunken size, not enabling its detection. But the trend indicates it's diminishing intensity. The position of the eastern warm zone appears to have migrated slightly northwestward. These are not necessarily bodily movements of warm pockets. Changing patterns of relative temperature differences can also produce this effect. In the absence of a higher data density this cannot be resolved with certainty. There is evidence of a cold air incursion from SW which has resulted in the migration of the SW sector heat island to a more interior location. Existence of such an inflow can also be inferred from the intrusion of a cold tongue from SW. Cold air incursions from the east and north are also detectable on this chart. A cold area has developed over the Central Observatory at site No. 10, where vast open space has experienced unabated cooling.

3.1.4. 0200 *hr* (Fig. 6) — The incursion of cold air from SW continues and has shifted the centre of the heat island further NE to what was reported in section 3.1.3. The incursion from the east has ceased indicating that it had been a transient phenomenon. A cold area has remained over the Central Observatory.

3.1.5. 0400 *hr* (Fig. 7) — This chart shows a some what new aspect of the heat island history. The deep dents in the isotherms on the SW flank have smoothed out thereby allowing the central heat island to extend itself in space and intensity. Another feature is noticeable on the northern side. The upper air synoptic wind (0.3 km and 0.6 km), was NNE'ly during that night. This resulted in a southward dent in isotherms in the northern flank (2030-2200 hr). This southward dent was no longer seen at 0200 hr. At 0400 hr the northerly air penetrated right upto the Central Observatory and had merged with the cold pool there. This may also have been aided by the general tendency of the heat island bound inflow. The western part of the city which is a moderately populated area has become isolated from the surrounding cooler air and has developed a heat island of stronger intensity than earlier. In general the heat islands which had shrunken in the earlier chart have again spread and strengthened.

3.1.6. 0530 *hr* (Fig. 8) — This is another mobile survey chart. Herein another burst of air inflow is seen in SW sector. This has pushed the main heat island of the city to its extreme north eastern position. Two small warm pockets have formed on either sides of the intruding cold tongue. The western fringe of the city has retained its heat island, while the Central Observatory now lies in the midst of an intense cold pocket.

It appears from the evidence of all the earlier charts that the cold flow from SW came in strong pulses. The existence of cold flow during 2200 hr and 0200 hr, its absence in 0400 hr and re-appearance on the 0530 hr chart gives 3.5 to 4 hr as the approximate duration of this transient phenomenon. If it is assumed for the present that these pulses are associated with a solenoidal circulation which remains for sometime and then weakens, then its periodicity would also be of about 4 hours. This duration is similar to the result of Dannevik *et al.* (1974) obtained for St. Louis, Missouri.

3.1.7. 0600 *hr* (Fig. 9) — This chart, for a time just half an hour later has shown some unexpected changes although the broad features remain similar. The major changes are the warming of areas which were colder on the earlier chart (Central Observatory and stations on the northern and eastern flanks). This warming is an anomaly super-imposed on the gradual radiational processes. The cause of the anomaly could be the only other important process apart from the radiation which is active during the night and that is the circulation produced by the heat island. The discussions on such warming events are done in section 5.

3.2. The following remarks are made to summarise the above findings for Pune city :

(1) The main heat island forms after sunset and continues to exist with fluctuating intensities till early morning.

(2) Small warm pockets also develop but gradually shift positions or even vanish.

(3) Ideally speaking, a radially symmetric heat island would give rise to solenoidal circulation with a similarly symmetric pattern of advection. But the actual urban configuration and topography would enhance certain portions of this circulation or influence oppositely. For Pune the influence of the slope of the terrain is well discernible. The cold air inflow from the SW is found to be more intense and longer lasting than the ones from other directions. The katabatic wind of the SW sector can be held responsible for this.

(4) The inflow into the heat island at the ground is observed to have a cyclic pattern. It is conjectured that since the inflow is a component of the heat island circulation which is a universally observed phenomenon, this circulation itself may have a cyclic nature.

4. The nocturnal solenoidal circulation over the city

4.1. Evidence of the horizontal inflow at ground level, arising out of the vertical circulation associated with the heat island have been discussed in the earlier sections. In the following sections, the evidences obtained from the change of temperatures at ground level, with time, at different locations will be discussed.

The positive temperature anomaly over the heat island would cause a lowering of density in that area, causing the isosteres and isobars to intersect each other (Fig. 10). Under such a condition the rate of change of circulation would be given by the equation:

$$\frac{d\vec{c}}{dt} = -\iint_s \left(\nabla\alpha \times \nabla p \right) . d\vec{s} \qquad (4)$$

where α is the specific volume, p is the atmospheric pressure and integral is evaluated within a bounded surface area. Hence $\vec{c}$ (anticlockwise), would continue to increase with time resulting in a cold inflow along the ground and a warm outflow aloft. But this is expected to reduce the 'α' field to a flatter one by the mixing caused by the circulation. Hence after a certain time:

$$\frac{d\vec{c}}{dt} \to 0 \qquad (5)$$

In other words, with the vanishing of density gradient due to mixing, the inflow in the lower levels along the isobars would cease to grow and later die down in due course being damped by the frictional drag. In case the thermal retention of the city area is large enough it would commence once again.

4.2. However, in a real situation such a simple dynamics would not explain the details. The most

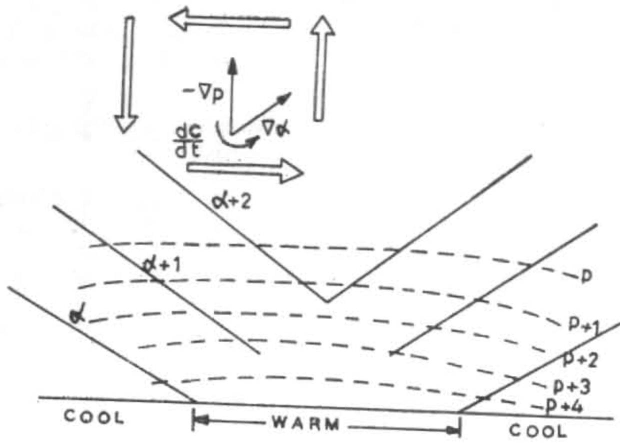


Fig. 10(a). Solenoidal circulation of the heat-island

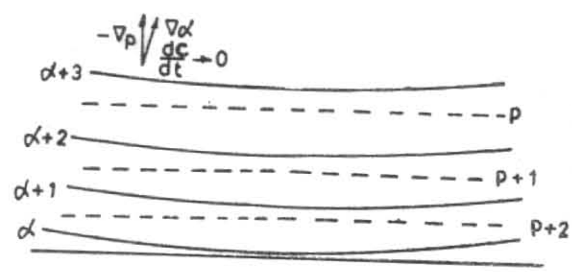


Fig. 10(b). Weak phase of the solenoidal circulation

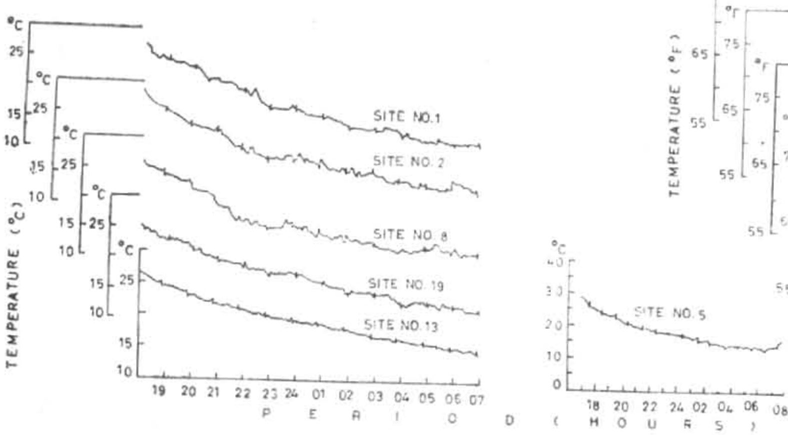


Fig. 11

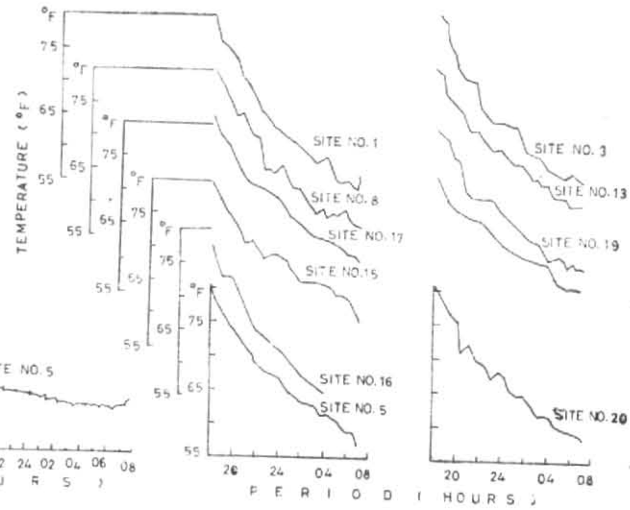


Fig. 12

important characteristics envisaged for a real situation are the following :

(1) The phenomenon takes place in the turbulent planetary boundary layer. As a result of this no smooth flow of air can occur. Hence the circulation would be in short pulses the magnitudes of which would increase during the more intense phase of the circulation.

(2) There may be competing circulations existing side by side due to the existence of several warm pockets in proximity. As a combined effect of all of these, the events of inflow, rising motion, outflow and subsidence are not necessarily perfectly sequential at a given place and lack of geometrical symmetry should be discernible.

One obvious conclusion from the presence of a solenoidal circulation is that, since the subsiding air originates over the heat-island and descends over the cold pocket, it is warmer than the ground air with which it mixes after descending. This phenomenon of warming incidences are seen on thermograph records as well as hourly instantaneous values of temperature recorded at fixed places. Such observations are described in detail in the following section.

5. Temperature records at fixed locations

Psychrometer plots are shown in Fig. 12 for sites numbered as 1, 3, 8, 13, 17, 19, 15, 14, 16, 5 and 20. These are all plotted in degrees Farenheit (but it may be mentioned that the corrections for isotherm charts as described in section 2.2 are done after conversions to celsius). The thermograms are shown in Fig. 11 for sites 1, 3, 8, 19, 13 and 5. These are all in celsius. Since only a qualitative discussion is intended in this section there is no need to have the same units for all the figures. The only point of interest is the phase of the thermal perturbation.

In the first instance all the above diagrams can be classified into four categories; first containing Fig. 11, sites 1, 3, 8; Fig. 12, sites 1, 3, 8 and 20; the second containing Fig. 12, sites 16, 5, and 6; the third containing Fig. 11, site 19 and Fig. 12, site 19 and the fourth containing Fig. 11, site 13; Fig. 12, sites 13, 17, 15 and 14. The reasons for categorization are given below :

5.1. *The modulation on the average cooling trend* — Supporting what has already been mentioned in section 2.2 (*i*) (b), the thermograms show the presence of short duration perturbations (5-15 min). These are present only in Fig. 11, sites 1, 3 and 8 which are in the outskirts of the city. It is not seen in Fig. 11, site 13 which is in the centre of the heat-island zone. This indicates that pulses of forced convection which have small size scales are probably responsible for these thermal perturbations over the outskirt areas. The mechanism of warmings could be warm air mixing from aloft or warm air incursion from adjoining warmer pockets. The thickness of the turbulent layer is more over the heat island hence thermal inhomogeneities are in a size scale larger than those of forced convection of the nocturnal surface layer. This explains the absence of such pulses in Fig. 11, size 13. The absence of warm pulses in Fig. 11 site 19 would be explained in the following section. In addition to short duration perturbations one can also see the presence of larger duration ones. The nature of these longer duration warming events are utilized to define the following four categories.

5.1.1. *Category* 1 — All these are outskirt sites and show warming events more than once during the night. All these stations are within 2-3 km of the nearest heat-island sites. This indicates that subsidence of warm air had taken place over these sites more than once during the night.

5.1.2. *Category* 2 — These are also outskirt stations but more than 3-4 km away from their nearest heat island zones. The absence of warming events in these figures indicate that the horizontal extent of the circulation may have been less than 3-4 km.

5.13. *Category* 3 — This corresponds to the thermogram and psychrometer traces of a southern outskirt site. Here warming pulses are not very much evident but sudden dips in the thermogram are seen on three occasions. This could probably have been due to pulses of cold air flowing over this place under the combind influence of the solenoidal circulation and favourable slope. If the thickness of this incoming air flow is more than at other outskirt sites, then obviously the descending branch would not be able to reach the ground to cause the warming incidences. A schematic diagram for this model has been drawn in Fig. 13 as a north-south vertical section through the centre of the city.

5.1.4. *Category* 4 — These correspond to sites located inside the heat island. Since this is a zone where no descent of air is likely to take place (even if it takes place it is most unlikely that the descending air is warmer) hence no warming incidences are expected to be seen. All the thermal traces for sites 13, 17, 15 and 14 confirm to this. By the time the suburban colder air penetrates to these regions, they themselves get warmed. As a result sudden drops in temperature are also not seen.

One observation that can be made on the Fig. 12, sites 14, 15, 17 and 19 is the arresting of cooling rates at regular intervals. This indicates that some warm subsidence does take place even near the central heat island zone (about 1-2 km away from the centre) but the thermal contrast being weak is unable to show up as a warming incidence. In sites 17 and 19, this effect is more than others because these sites are farthest (among the others) from the heat island zone. The complete absence of such events for site 13 inside the main heat island proves that these warmings are caused by the subsidence branch of the solenoidal circulation. In all these sites 14, 15, 17 and 19 there are two such events and matching almost in phase too. This indicates that more vigorous subsidence is a periodic phenomenon as was conjectured in section 3.1.6.

5.2. A one to one correspondence between all thermal dips and cold air incursions as visualised on isotherm charts are not being attempted because there are many other factors involved due to the complex nature of air flow and its advection characteristics inside the city that tend to reduce the correlation. But the major events as discernible on the charts are represented on temperature plots also. We may cite for example Fig. 12, sites 14, 15 and 20 in which the cold air incursion seen in Fig. 5 at 2200 hr are well represented by cooling tendencies. Such a sharp cleft is again seen at 0530 hr on Fig. 8 (next chart after 0400 hr) from the S.W. direction. Fig. 12, sites 14 and 20 also show a cooling trend after 0400 hr at the corresponding sites.

From the north an indication of south bound incursion is seen on the 2200 hr chart (Fig. 5) which is also corroborated from Fig. 12 for site No. 3. At 0530 hr such an event is seen on the northeastern section (Fig. 8) and is supported by both Figs. 11 and 12 for site No. 8.

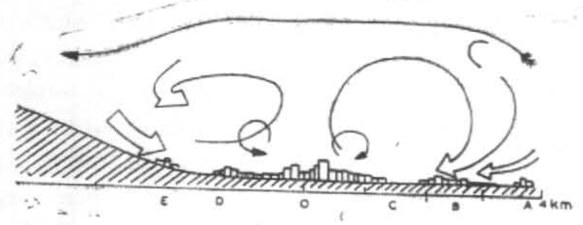


Fig. 13. Terrain effect on heat-island circulation. A N-S vertical section through the centre of the city

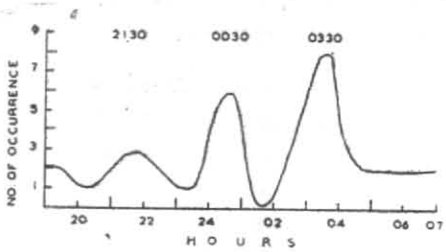
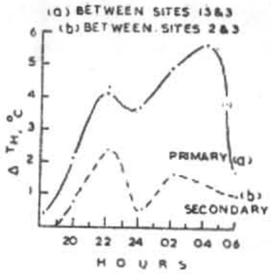


Fig. 14. Composited frequency of ocurrences of warming events



Figs. 15 (a & b). Changing heat-island intensity with time (a) between sites 13 and 3 (Primary) and (b) Between sites 2&3 (Secondary)

It may be mentioned here that site No. 10 is in the midst of a basin like terrain with vast open grounds and with a major slope from SW to NE. Hence once the cold pool develops it maintains itself throughout the night. Periodically it is found to merge with cold air from the north thus forming an open channel running between the two warm pockets.

The general inference that can be drawn from the observations made in sections 5.1 and 5.2 is that the monitoring of temperatures at certain fixed locations within the city can help identifying the phases of the time variation of the heat island circulation.

5.3. It is also worthwhile to inspect the data further to see whether the cyclicity of the heat island circulation as hypothesised in section 4, can be detected. For this site Nos. 1, 3, 7, 8, 10, 11, 14, 15, 18, 19 and 20 were selected. A frequency distribution of the times of occurrences (denoted by commencement) of thermal perturbations (large duration ones) has been shown in Fig. 14. This shows three peaks at intervals of three hours each. Although all the observation sites do not show the existence of three peaks each but when the events for the entire city are composited together the cyclicity with a period of 3 hr is discernible. With a different set of sampling points the timings and relative magnitudes of the peaks could well have been different, but it is not likely that the periodicity would be drastically affected. This periodicity of 3 hours is somewhat less than the periodicity of 4 hours as had been mentioned in section 3.1.6. It may be mentioned here that the latter was determined from the cold air incursions mainly from the SW branch where an increased bias for cooling due to the effect of terrain slope may reflect as a longer periodicity.

5.4. The presence of several warm pockets existing side by side is evident on many of the charts, whether they do so with competing heat-island circulations resmains to be verified. For this the heat-island intensities between some of the outskirt sites and a central heat island site on one hand and a nearby warm pocket site on the other were plotted. Almost all of them showed similar patterns. Hence the intensity variations of site Nos. 13 with 3 and 2 with 3 are being reported in Figs. 15 (a & b) respectively. If the periodic fluctuation of the intensity is an indication of the dynamic existence of a heat island, then definitely there exists a heat-island type of flow relation between site No. 2 and 3. A much greater data density would be required to show the relative significance of two side by side existing circulations but it appears that the secondary heat island circulation is much weaker than the primary and hence would only succeed in modulating the latter. This is the reason why one-to-one correlations were not attempted for all warming and cooling events at all the sites.

5.5. *The conceptual model of the heat island circulation at Pune*

The heat island circulation zone is an anomaly superimposed on the ambient wind flow. The roughness induced convergence within the city's built up region and the rising branch of the solenoidal circulation create an updraft over the heat island zone which coincides with the densest built up area. Simulation experiments (Oke 1978, on scale modelling of urban circulations), have generated circulation patterns by considering the above two forcings. The ascent has been, as anticipated, found over the warmest area while the descent is seen both at the upwind edge and the down wind edge of the city, thus breaking the circulation into two cells and bringing the warm air originating over heat island down right upto the ground levels. Upto this is confirmed by seeing the warming events on the thermograms at both the upwind and down wind regions of the city. The outer limit of this descent has been identified from those observation points beyond which this phenomenon is not seen, as mentioned under category 2 in section 5.1.3. In the conceptual model of the circulation given in Fig. 13, which is N-S vertical section containing the line PQ in the plan view of Fig. 1, this limit is marked as A. Thereafter, the absence of such warm descents at a site which is expected to be within the descent zone (earlier referred to as category 3 in sec 5.1.3) gives a clue that the descending branch probably loses its warmth in getting mixed with the katabatic type of flow down the terrain slope. Thus in this case the down wind (Fig.13) circulation in the periphery of the city is almost out off from the ground. These places are marked as E in Fig. 13.

Region B on Fig. 13 shows the most prominent effect of the warm descent and is explained under category 1 in section 5.1.1.

The region C to D forms the heat island zone and as such no warming incidences are seen over these regions (category 4 in section 5.1.4). But even in this zone one can identify an inner region near O on Fig. 13, where the surface layer is well mixed by turbulence and is reasonably homogeneous so that it cools gradually with the passage of night. The outer fringes of the heat-island C and D do experience some warming influence of descending air. But the descending air does not have sufficient strength to show up as discontinuous processes after getting mixed with the surface air. Nevertheless an arrest in the cooling rates is not to be missed at these sites as mentioned in section 5.1.4. The line PQ in Fig. 1 passes through only the central heat island. But if it is rotated, say, along P′Q′, then it would include two heat islands. Both are centres of solenoidal circulation. The only difference is that the weaker one lies within the field of flow of the stronger. So its effect would be masked. To remove this possibility the axis was chosen as PR. The heat island intensity pattern which was taken as the temperatuie difference between P and S, reveals the existence of the periodic variation just as seen for the more intense one. It has been inferred in section 5.4 that a characteristic circulation exists in this case too.

6. Conclusions

Changing shapes of isotherms in the ground level thermal field of the city indicate ground level air flow associated with the heat island circulation. The same has been cross checked with incidences of thermal fluctuations at different locations. The analysis reveals the existence of a cyclicity in the overall intensity of the circulation with an approximate period of 3-4 hours. The thermal mixing effected by the circulation on one hand and the thermal retention within the urban canopy on the other, cause the heat island intensity and extent to vary with the night in a cyclic fashion. The relation between the heat island intensity and vertical circulation is complicated by the presence of other warm pockets nearby. The crux of the whole study is essentially to relate the wind field fluctuations with thermal field fluctuations.

In t his paper an attempt has been made to form certain hypotheses regarding the nature of the heat island circulation and verify them in a self contained way without taking recourse to direct wind field analysis.

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