Heat Island Convergence in St. Louis during Calm Periods

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ABSTRACT

From Regional Air Monitoring System (RAMS) tower data recorded in St. Louis during 1976, time series of convergence, heat island intensity and solar radiation are presented for five calm periods each exceeding 12 h. The results demonstrate that heat-island-induced convergence is markedly stronger during the day than at night. There are indications of a periodicity of 1.5–2 h in the nighttime convergence, while the daytime convergence is more variable and cannot be characterized as periodic. An event recorded by one series is interpreted as storm cell development associated with the daytime convergence.

1. Introduction

In a previous analysis of tower data from the Regional Air Monitoring System (RAMS) in St. Louis, it was shown that heat island convergence tends to be stronger under daytime, unstable conditions than under nighttime, stable conditions with a well-developed heat island (Shreffler, 1978). This rather surprising conclusion was based on mean horizontal convergences derived from large samples of hourly averaged winds. The observation that stability rather than heat island intensity plays a key role in determining the strength of the circulation was recently anticipated in an independent numerical study by Vukovich and Dunn (1978). The hourly averaged data used by Shreffler (1978, hereinafter referred to as S78) were computed from 1 min average measurements taken throughout 1976. In this paper, several extended calm periods (>12 h) are examined with the aid of the 1 min data.

This detailed examination of calm periods has two motivations. First, there is a need to understand and verify on a case study basis the statistically based conclusion of S78. A second objective is to investigate the possible intermittent or periodic nature of the heat island circulation noted by Chandler (1961). Munn (1968) has suggested that stagnant air over a city, if viewed from above, would resemble an “amorphous, slowly-pulsating jellyfish.” The implication is that buoyancy, inertia and vertical stability could interact to produce a natural periodicity in the circulation.

2. Method

The present discussion assumes the reader’s familiarity with S78. This analysis focuses on Stations 101, 105, 106 and 107 in central St. Louis (Fig. 1) which have been shown to surround the center of mean heat island convergence. Schiermeier (1978) details the instrumentation of the RAMS network, and Auer (1978) presents a land-use map of the region.

Calm periods are determined from a listing of all hours during 1976 when the resultant speed of hourly averaged winds from the RAMS network is less than 1.5 m s⁻¹. These were the hours entering the basic analysis in S78. This strict speed criterion is relaxed somewhat in order to define long continuous calm periods. Of the data to be presented here, network resultant speeds exceed 1.5 m s⁻¹ in less than 15% of the hours and never exceed 1.9 m s⁻¹.

As in S78 (except for each minute), the network resultant wind is subtracted from the wind vector at each station to obtain a net circulation. Convergence is computed from the projections of the net wind vectors of Stations 101, 105, 106 and 107 on the perpendicular axes indicated by dashed lines in Fig. 1. It has already been shown (S78) that the net wind vectors of hourly averaged winds usually do not exhibit the clear centripetal pattern which emerges from long averages. There should be even less expectation that net vectors for minute data will be directed predominantly inward along the axes. Without verification of the location of the urban convergence zone provided in S78, reliable interpretation of convergence time series developed in this manner clearly would be impossible.

1 On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.
A representative urban temperature is computed as the mean from Stations 101, 105, 106 and 107. The rural temperature is taken as the mean from Stations 122–125, located 30–50 km from Station 101 on the major compass points. All temperatures are recorded at the 5 m level. Heat island intensity is defined by the urban-rural temperature difference and, due to the averaging, is somewhat less than the peak heat island value. Pyranometers (all wavelengths) located at Stations 103 and 104 provide a mean solar radiation for the downtown area. These pyranometer data are included to indicate sunrise, sunset and relative changes but should not be regarded as highly accurate.

In all, time series have been plotted for 25 calm periods of at least 5 h duration during 1976. Series from several long calm periods are presented in this paper. The plotted series have been smoothed with a five-point, unweighted, moving average.

3. Convergence: Strength and intermittency

Time series of convergence, heat island intensity and solar radiation have been selected to fairly represent nighttime and daytime situations as well as transition periods.

Fig. 2 presents time series from 25 June, 1976 for 0300–1900 CST. Airport records from Lambert Field (20 km NW of Station 101) report sky cover ranging from 10/10 in the morning to 3/10 in the evening with a ceiling of 6000 m. There is no precipitation. A weak cold front has passed the area and is located 150 km to the SE at 0600 CST. With sunrise, indicated by the pyranometer series, the heat island intensity begins a decline from nearly 3°C to something less than 1°C. In the early morning, the convergence slowly alternates both positive and negative. With the collapse of the heat island, convergence becomes more variable but also stronger in the mean, increasing throughout the day and receding only near sunset as the heat island rebuilds. Increased opacity of the cloud cover during midday has no perceptible influence on the convergence or heat island intensity.

Fig. 3 presents daytime series from 2 October 1976 for 0300–1900 CST. Skies are clear during the entire period. Again, the computed convergence oscillates slowly in the early morning hours. Although not rising as definitively after sunrise as on 25 June the convergence nevertheless shows similar behavior.

Both the nights of 22–23 August and 31 October–1 November are clear and calm with fog reported at Lambert Field after midnight. Strong high-pressure systems dominate the region during both episodes. Time series are presented in Figs. 4 and 5. Convergence in both cases follows the slowly oscillating pattern suggested by the pre-sunrise records seen in Figs. 2 and 3.

The analysis in S78 shows that the mean hourly averaged convergences are $-0.9 \times 10^{-4}$ and $2 \times 10^{-4}$ s$^{-1}$ for the average night and day situations, respectively. From the records presented here, it is
reasonable to expect peak convergences to be about four times as great.

It is not difficult to conceptualize a basis for periodicity in the heat island circulation. Surface air possibly requires heating to some critical temperature before upward motion is initiated. Once vertical motion is established, it could temporarily exceed a rate sustainable by thermal input from the surface. That is, cooler air drawn in from the periphery of the heat island might not be heated rapidly enough to reach the degree of buoyancy which initiated the vertical motion. The result would be an intermittency in the convergence as the air moves upward, pauses, and then rises again. The nighttime cases are most interesting in terms of showing a possible periodicity. Three rather well-defined peaks of convergence with a separation of ~2 h are seen in Fig. 5. The early morning oscillations exhibited in Figs. 2 and 3 suggest periods of ~1.5 h. Spectral analyses were attempted on several series, although the problem of nonstationarity discourages this approach. The spectrum of the nighttime series in Fig. 4 indicates a dominant period of ~100 min. The spectrum for the 25 June daytime series (Fig. 2) from 1000 to 1800 CST shows most variance associated with periods of 25–50 min, but this is not very significant. Spectral analyses were unable to discern periodicity in the heat island series and hence correlation with the convergence series. However, heat island peaks occasionally appear to precede convergence peaks (e.g., Fig. 5).

If the obvious differences in regularity and fre-
Fig. 3. Time series of convergence, heat island intensity and solar radiation for the calm period 0300–1900 CST 2 October 1976.

Frequency content between day and night convergence series are due to atmospheric stability, the differences between individual nighttime series might also be explained in terms of stability. To investigate this point, Fig. 6 introduces an additional set of time series from 24–25 August; the daytime portion is discussed extensively in the next section. Two measures of the vertical lapse rate are available. First, there are radiosonde releases from upper air Station 141 (1.3 km WSW of 101) at 1 and 7 h prior to dawn. Second, there are values for vertical temperature difference DT, measured on each of RAMS towers 101, 105, 106 and 107. Because they are closer to the central business district, Stations 101 and 105 show less stability than Stations 106 and 107. To obtain a single lapse rate representative of the convergence zone and the period of interest, a mean DT is computed using data of all four towers from 2000 to 0400 CST. Table 1 presents the vertical (potential) temperature differences for the nighttime records from both sources.

Although there is no radiosonde release for 22 August the RAMS DT shows stability actually decreasing as the night progresses. As seen in Table 1, the radiosonde and tower measurements agree on the relative degree of stability on the various nights. Looking at the nighttime series in order of increasing attendant stability (Figs. 6, 4 and 5) as determined from these DT’s, it is suggested that regularity in the convergence record is positively correlated with the magnitude of the stable lapse rate. It may also be inferred that the period of the oscillation becomes longer as stability increases.

In most cases, the direct effect of heat island in-
tension on convergence is obscured by substantial stability influences. However, the daytime series in Figs. 2 and 3 provide an interesting look at similar stability regimes. The average RAMS DT over the period 0900–1600 CST is −0.33°C on 25 June and −0.39°C on 2 October, indicating that the unstable lapse rates are comparable on the two days. On 25 June, the daytime heat island intensity runs ~0.5°C, while on 2 October, it appears to be near zero or even negative. Because it is improbable that measurements from individual towers are truly representative of the downtown area, the slight negative bias may be disregarded. There quite likely is some heat island on 2 October; however, the heat island intensity on 25 June, albeit small, is probably several times greater. These two daytime series demonstrate that, when stabilities are comparable and heat island intensities substantially disparate, the greater convergence is associated with the stronger heat island. A possible explanation for the differing heat island intensities on these two days may lie in the relative magnitudes of the sensible and latent heat fluxes. Daytime Bowen ratios are generally higher in the city (Ching et al., 1978), an observation associated with the availability of ground moisture in rural areas and the impermeability of the urban surface. Decreasing ground moisture would tend to increase the rural Bowen ratio and perhaps lower the urban-rural temperature difference, while, by similar reasoning, increasing ground moisture would tend to enhance the daytime heat island intensity. This explanation seems applicable to the periods.

Fig. 4. Time series of convergence, heat island intensity and solar radiation for the calm period 1900–0800 CST 22–23 August 1976.

Fig. 5. Time series of convergence, heat island intensity and solar radiation for the calm period 1900–0700 CST 31 October–1 November 1976.
under consideration. In the two days preceding 25 June rainfall at Lambert Field totaled 5.5 cm. On the other hand, significant rainfall was not recorded for four days preceding 2 October and September was a very dry month having only 2.3 cm of precipitation.

4. A thunderstorm record

Fig. 6 presents time series from the late evening of 24 August to midafternoon of 25 August. As previously noted, the nighttime convergence does not evince the regularity seen in other examples. As may now be expected, convergence becomes decidedly positive with sunrise. However, the importance of these series lies in the event they capture shortly after noon.

Between 1202 and 1207 (all times CST), the convergence pauses perceptibly at a level comparable to the maxima attained in the preceding several hours. Then, instead of retreating, the convergence begins a rapid increase. At 1204, recorded solar radiation diminishes abruptly. Convergence reaches a maximum of $1.7 \times 10^{-3}$ s$^{-1}$ at 1217 and then drops sharply. At the same time, heat island intensity also begins a steep slide into negative values. The heat island and convergence reach minimum values at 1239 and 1241, respectively, and then both move back toward normal levels.

These data clearly bear the signature of a thunderstorm (cf. Byers and Braham, 1949) to which the heat island updraft may be a contributing factor. On 25 August St. Louis is on the trailing edge of a high-pressure system, and conditions favor precipitation
Table 1. Vertical potential temperature differences (DT, °C) from urban radiosondes and RAMS towers during nighttime calm periods. The RAMS DT is the mean from Stations 101, 105, 106 and 107 taken 2000–0400 CST on the respective nights.

<table>
<thead>
<tr>
<th>Day 1976</th>
<th>Urban radiosonde</th>
<th>RAMS DT (5–30 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time DT (0–250 m)</td>
<td></td>
</tr>
<tr>
<td>22 Aug</td>
<td>0345</td>
<td>4.5</td>
</tr>
<tr>
<td>23 Aug</td>
<td>2150</td>
<td>1.8</td>
</tr>
<tr>
<td>24 Aug</td>
<td>0347</td>
<td>3.8</td>
</tr>
<tr>
<td>25 Aug</td>
<td>2352</td>
<td>3.8</td>
</tr>
<tr>
<td>31 Oct</td>
<td>0546</td>
<td>7.1</td>
</tr>
</tbody>
</table>

in the region. Noontime temperature is 30°C, and haze is reported at Lambert Field throughout the morning. In fact, Lambert Field reports thunderstorms between 1500 and 1800. However, interpretation of the event solely from these series is potentially misleading since it evokes an image of a perfectly defined, isolated and stationary storm within the convergence zone.

Sudden drops in solar radiation are recorded at Stations 114(1150) and 108(1209), in addition to those already noted at Stations 103 and 104(1204). Thus, clouds are forming rapidly over an extensive area. Initiation of temporary, sharp temperature declines during the period 1130–1300, possibly indicating rainfall at the surface, are recorded at Stations 119(1150), 112(1203), 106–107(1218), 102(1224), 101(1237), 108(1242) and 114(1244). Movement of a disturbance on a NNE track at ~7–8 m s⁻¹ is indicated. Radiosonde releases from upper air Station 141 at 0945 and 1546 show winds capable of such advection at 1500–3000 m. Pibal releases at 1202 and 1300 show calm and 4 m s⁻¹ (SSW) winds, respectively, at the ceiling height of ~1300 m.

The event is neither isolated nor stationary. Inferred rainfall at Stations 119 and 112 prior to the onset of strong convergence shown in Fig. 6 would indicate another storm in the area. A plausible interpretation is that a new cell is formed over the convergence zone when a developed cell moves into the vicinity. It has been suggested (Byers and Brahm, 1949) that precipitation from an overhanging cloud aloft can trigger the growth of an adjacent cell; certainly the central city exhibits conditions which would be highly sensitive to such triggering. Fig. 7 presents wind vectors during the period of the storm event. The intense convergence is seen developing between 1202 and 1217, and this is consistent with a growth phase duration of 10–15 min estimated by Byers and Brahm. From 1237 to 1247 the strong outflow recorded at Stations 101 and 105 is seen to veer as the storm moves northward in its downdraft stage. Substantial divergence is indicated NNE of the central city at 1247 and 1252. If one accepts this interpretation, these series illustrate the intensification of existing storm activity by an urban influence in St. Louis, a phenomenon for which statistical evidence has been presented by Schickedanz (1974), Huff and Vogel (1978) and Changnon (1978) from the METROMEX studies.

One reviewer of this paper has rightly pointed out that no evidence has been presented to support an assertion that the heat island caused the storm event. Also, whereas thunderstorms induce convergences of 10⁻³ s⁻¹ near the surface, one should inquire if such a convergence could produce vertical motions necessary to touch off a storm as air moves over the city. In the period of the event, winds are essentially calm through the lower 1000 m, but the storm activity is moving 7–8 m s⁻¹ at higher levels. Therefore, the convergence zone is traversed in only 20 min, and the storm-generating mechanism must act in a shorter time. By rough calculation from the observed heat island convergence, mean vertical motion over the central city is perhaps 0.1 m s⁻¹. Certainly, local speeds may reach 1 m s⁻¹ and lead to a 600 m displacement in 10 min. Under proper conditions this should be sufficient to initiate condensation, which would presumably occur at the 500–1500 m level. Is it reasonable that the accompanying latent heat release would then touch off a sustained updraft spreading rapidly to higher levels and leading to the surface record shown in Fig. 6? Questions concerning the boundary layer's potential degree and time of response to the heat island are vitally important to interpretation of any data associated with the urban effect on precipitation, but a detailed treatment of the problem lies outside the scope of this paper.

5. Conclusions

Records of convergence, solar radiation and heat island intensity plotted for each minute during long calm periods reinforce the conclusions reached on statistical grounds by Shreffler (1978). Specifically, heat island convergence is generally stronger by day than by night. It has been the traditional view (Chandler, 1965) that heat island circulation is more developed for strong heat islands (at night) when the temperature gradients and associated pressure gradients are steepest. A more accurate notion may be that the strong heat island is a response to the suppression of vertical motions over the city. Stably stratified air drifting in from rural and suburban areas must undergo strong heating near the surface in order to establish and sustain a heat island updraft.

There appears to be a periodicity of 1.5–2 h in the convergence records for nighttime heat islands. Chandler (1961) finds evidence for a reversal of flow associated with a heat island taking place in 47 min;
Fig. 7. Five-minute average wind vectors at central stations between 1140 and 1255 on 25 August 1976. The network resultant wind has been removed. The first pattern in the sequence gives selected station numbers and the scale for the wind speed. Wind blows from the direction toward which the tail points. The central Stations 101, 105, 106 and 107 have been accentuated for clarity.
this implies a period of slightly more than 1.5 h. The magnitude of the atmospheric stability likely affects the period and its definition. The computed convergence during the daytime is more variable and cannot be characterized as periodic.

For portraying the strength and periodicity of convergence, the series presented are fairly representative of the others examined in this study. The thunderstorm record is unique, however. Data tapes for 1975 were scanned in search of another such event, and none was found. The restriction of this study to calm conditions limits the time periods examined and drastically reduces the chances of finding a storm event. The striking record presented in Fig. 6 leaves an impression that the heat island is involved in promoting precipitation, and this mechanism may operate when winds are other than calm. On the other hand, one record of this type scarcely proves that the heat island is a causal factor in storm development, although, viewed in the context of the METROMEX evidence, the indication is of particular interest. An understanding of the potential response of the boundary layer to the urban updraft would be helpful in interpreting the record.

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REFERENCES


