TEMPERATURE PATTERNS IN CHAMPAIGN-URBANA, WINTER 1978-79

by
Douglas M. A. Jones
Illinois State Water Survey
Champaign, Illinois 61820

ABSTRACT

The records from seven temperature recorders sited about the contiguous cities of Champaign and Urbana, Illinois, were analyzed to show thermal patterns which might suggest the dynamics of the heat island under varying winds. The period of study was December 1978 through April 1979, the seventh coldest and the fifth snowiest winter in the history of the Urbana weather station. Particular emphasis was placed upon the movement of the heat plume with the different wind directions and the time of day. The heat island was most intense at 0300 CST during nights with no measurable wind and cold ambient temperatures. The heat plume was found to be deflected downwind with the prevailing wind. The distributed anthropogenic heat sources of the two cities were usually masked by solar heating during the daytime hours to the extent that a center of the urban heat island was not always apparent.

INTRODUCTION

The influence of man and his activities upon the local environment has been recognized for many years. Chandler (1970) quoted John Evelyn, writing in 1661 about London, "The weary traveler, at many miles distance, sooner smells than sees the city to which he repairs. This is that pernicious smoke which foils all her Glory superinducing a sooty crust upon all that it lights". In a later period I have had the experience, while in school in Chicago, of enjoying the transition from oppressive re-radiation of the sun's heat from the brick apartment houses lining the city streets, to the cooler environment of temporary, wooden housing for student war veterans. The transition was particularly noticeable on a calm summer evening. Such a cool oasis within the surrounding city is the opposite from the more normally experienced transition from the cooler rural areas to an urban area.

Generally, it has been noted that the intensity of an urban heat island increases as the size of the city increases. It is convenient to express this growth parameter in terms of population change. Oke (1973) has found that there is a relationship between the base 10 logarithm of the population and the intensity of the heat island in degrees Celsius. For North American cities this relationship was found to be

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

European cities were found to have the relationship

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

It is not known why the European cities have a lower rate of increase with increasing population than North American cities; but Oke suspected that it is related to the density of the buildings in the central core of the city, i.e., North American cities tend to have a greater concentration of tall buildings in their central cores.

In 1979 the contiguous cities of Champaign and Urbana in East Central Illinois had a combined population of 95,800. The average commercial building height is three floors. By Oke's equation the intensity of the heat island for the two cities should be about 8.3 °C. The greatest temperature difference observed during the operation of a special temperature-recording network in this study was 6.8 °C at 0300 CST on January 1979. As with the Oke equation, there was no wind to disturb the intensity of the heat island. It is likely that the lack of heavy industry and/or a centralized heat source in the two cities is the reason that the heat island is not as intense as the average of comparably-sized cities in North America. It is interesting that according to Oke, a European city with the population of Champaign-Urbana should experience a maximum heat island of 6.0 °C, which is reasonably close to the measured value for Champaign-Urbana.

A limited study of the rural-urban temperature differences for Champaign-Urbana was reported by Changnon (1961). That study reported only average temperature differences at 2-hr intervals for the four seasons of one year. Thus, the study did not address the instantaneous maximum temperature difference. The study did discuss the march of temperature from the records of three urban and one rural station. The growth of the cities in both area and population has been significant since 1961.

In 1979 the combined area of Champaign-Urbana was about 35 km^2. The cities consist of one- and two-storied family homes with a scattering of two- and three-storied multi-family units. Figure 1 shows the more concentrated heat sources and the areas paved with bituminous material, generally the parking lots of shopping areas. In essence, as a heat source, the two cities may be pictured as a uniformly heated flat plate with randomly serrated edges. The major axis is east-west.

DATA AND DATA REDUCTION

A mesonetwork of recording thermometers was installed in the Champaign-Urbana area through the winter of 1978-79. Seven hygrothermographs (locations show in Figure 1) meeting NWS Specification No. 450.8202 were installed in Cotton Region Shelters with maximum and minimum thermometers in Townsend supports, including the University of Illinois Morrow Plots Weather Station. It has been in continuous operation since 1886 and has been designated a Benchmark Station by the Environmental Data Service of the National Oceanic and Atmospheric Administration.

The mesonetwork lacked sufficient sites, particularly in the northeast and south to fully delineate the true shape of the heat island or islands. Early in the data collection period, there was a rural station, R, west of the cities. On the few occasions when data were available from this site, the additional information indicated that the isotherms tended to coincide with the periphery of the city. Therefore, the isotherm analysis was performed with the shape of the cities in mind.

The six additional stations were serviced once each week to change the 176-hr chart, record the maximum and minimum temperatures for the week, and reset the thermometers. The maximum and minimum temperature readings were used to establish regression relationships for the thermograph recordings to calibrate the network records to a common temperature standard of 1°C. In addition, all recorders were checked on a cloudy day against a standard mercurial thermometer whose indications are traceable to the U. S. National Bureau of Standards. A few sites, particularly C and J were visited several times during the week and the daily maximum and minimum temperatures noted on the thermograph charts on those visits. Analyses of the humidity traces were not attempted because of the gross lag of the hair hygrograph at temperatures below freezing.

It seems plausible that any anthropogenic heat source related to the two cities should be advected downwind in a direction dictated by the wind immediately prior to and prevalent at the time of observation. Nkemdirim (1976) reported the tilting of the plume above Calgary, Alberta, with the tilt in the direction of wind flow. His surface measurements were insufficient to delineate any shifting by the wind of the sensible heat away from its source.

Wind recordings were available for this study from an Aerovane anemograph system installed on a 3-m mast above the highest portion of the roof of the Water Resources Building, 0.9 km north-northwest of the Morrow Plots Station, P. The wind records were reduced by manually scanning clock-hourly periods and estimating the speed and direction for each hour. Speed was estimated to whole statute miles per hour and direction to an eight-point compass. Obviously, many small-scale features of the wind field were smoothed from the record. However, it is believed that the available detail from the smoothed records is sufficient for this study of the clock-hour temperatures measured at seven sites in the cities. Even though the temperature data used in the study are "instantaneous", the lag of the bourdon tube sensors, the timing rate changes of the mechanical chart drives, and the small scale of the chart recordings integrate the temperature data over a longer time.

The total 1978-79 winter wind records were searched for extended periods of constant wind direction. Such extended periods of nearly constant direction were found, one for each of the eight cardinal directions and one of almost no wind.

CLIMATE OF WINTER, 1978-79

The winter of 1978-79 was the seventh coldest and the fifth snowiest on record at the Morrow Plots Station. The months are summarized in Table 1.

Snowcover was continuous from 1 January through 6 March with as much as 44.5 cm at the close of January. This is the greatest snow depth ever measured at the Morrow Plots Station. It is not known how this season of below normal temperature affected the distribution of temperatures about the two cities as compared to a more normal winter. Intuitively, the intensity of the heat island should have been greater than normal since more energy would have been required to warm the buildings and would result in a greater contrast with the colder rural air.

RESULTS

Calm

The shape of the heat envelope over the two cities may be determined most easily when winds have been calm for a period of time. Such a period occurred from 2000 CST of 5 January until 0900 CST of 6 January 1979. The period of calm was in a stagnant high pressure cell after a light continuous snowfall.

The morphological development of the heat island overnight during this period of calm is of interest. At 1800 CST, 5 January, the temperature field of the cities showed little contrast (Figure 2a) with only a light wind. At 2100 CST an hour of no wind had passed and the heat island was established (Figure 2b), conforming to the outline of the areas of the cities. The lack of sufficient recording sites to the north and east of the cities is obvious and limit definition of the temperature field. However, an oval pattern is indicated with the center of warmer air somewhere near the centroid of the two cities.

The temperature gradient became most intense (6.7 °C/3 km) at 0300 CST, 6 January (Figure 2c). The timing of this event is in contrast to the conclusion of Oke and Maxwell (1975) who found that "the maximum heat island occurred 3-5 hr after sunset in both cities" (Montreal and Vancouver). However, Daniel and Krishnamurthy (1973) assumed that the maximum heat island intensity would occur near sunrise (0500 IST) for Poona and Bombay, India. The temperature field for 0700 CST is shown in Figure 2d. The temperature gradient relaxed when the heat core shifted toward the east.

At 1000 CST the hourly-average wind was from the southwest at 1.8 m s^{-1} and the temperature pattern indicated isothermal conditions northwest of the Morrow Plots Station (P) and cooler temperatures east as shown in Figure 2e.

The siting of the temperature-measuring instruments dictated that a downwind displacement of the heat island would be most likely detected during periods of northwest, northeast, and southeast winds. These wind regimes will be described next.

Northwesterly Winds

On 25 March 1979 the area winds were consistently from the northwest at speeds averaging between 3.1 and 4.5 m s^{-1} until after sunset at 1810 CST. During the evening the winds decreased to an hourly average of 1.8-2.2 m s^{-1}. Light snow showers occurred during the day with an accumulated depth of 1 cm. Gradient level air flow was from the north-northwest.

The temperature field during this 24-hr period began with the characteristic heat island located just east of the cities' center. This is shown in Figure 3a at its maximum during the early morning hour of 0300 CST. After sunrise at 0550 CST the pattern began to change such that the temperature gradient decreased and the coldest temperature was measured at the P site as shown in Figure 3b for 1000 CST. By 1500 CST there were two areas of warmer temperature, M and J, with K in the center of Champaign equaling S and C with the coldest temperatures. After sunset of 25 March the field reverted to the pattern of the night before.

Thus, it appears that solar heating during the day had the effect of overriding the anthropomorphic heat generated in the cities with sensible heat released from areas of lower albedo. Since only a trace of snow remained on the ground by sunrise of the next morning, selective melting of the snowcover could have contributed to the heat differential as evidenced by the cities' center being warmer than the outlying areas from 0900 CST through 1200 CST. Another possibility is that more anthropomorphic heat was being generated in the residential neighborhoods than in the center of the cities on that Sunday. If this last possibility is a valid reason, the difference in construction materials, their heat retention, and their albedo was sufficiently slight to permit the heat output from the commerical centers of the cities to be reduced below that of the residential areas on this day. Vehicular traffic is much lower on Sunday mornings so that the lack of this input would be a significant loss to the heating of the commerical areas of the cities by comparison with a weekday morning in the winter.

NORTHEASTERLY WINDS

Northeasterly winds prevailed during the 20-hr period from midnight of 16 February until 2100 CST of 17 February 1979. The winds turned to the east after 2100 CST. The period of easterly winds was partially cloudy, but without precipitation. There was a depth of 33 cm of snow on the ground. A surface high pressure center was over Lake Superior and easterly flow prevailed at the gradient level.

The orientation of the isotherms depicted in this situation (Figure 4a) was displaced from that of calm conditions (Figure 2). This configuration was maintained until 0900 CST when the pattern flattened such that the isotherms were more northwest-southeast, but the colder areas of the cities remained to the north. By 1200 CST there was a bulge in the isotherms with the coldest temperatures being recorded at M and K with a windspeed of 5.8 m s^{-1}. This temperature appears to have been the result of the strong northeasterly wind as shown in Figure 4b.

Perhaps the most striking example of the influence of the wind direction and speed occurred at 1600 CST (Figure 4c). The warmest temperature was measured at C in the southeast, the result of heat flow from a shopping center with large bituminous parking areas to the northeast of the recording site. The warmer temperatures at S and K would have been the result of the normal temperature pattern of the cities displaced somewhat downwind.

SOUTHEASTERLY WINDS

On 2 February 1979 southeasterly winds were recorded within the two cities. There was a weak southerly flow at the gradient level. There was no deviation from the southeasterly surface winds from 0000 CST until after 2200 CST on 2 February. Wind speeds were 2.7 m s^{-1} or less with an hour between 0300 and 0400 CST recorded as calm. The Parkland College site (R) was operating for this case study.

Figure 5a shows the temperature field at 0100 CST. The coldest temperature was recorded at C on the southeast edge of the cities with the warmest at K near the center of the cities. This pattern was clearest while the wind was calm at 0400 CST (Figure 5b). As the wind began to increase after the period of calm, the center of warm air moved to the northwest as shown in Figure 5c for 0600 CST. The temperature pattern became complex after sunrise at 0701 CST as warm air from the south was advected into the cities. The hourly observation which best exemplifies the complexity occurred at 1400 CST (Figure 5d). The warmest site at 1400 CST was S on the southwest edge of the cities. P recorded 2.2°C cooler as the coldest site at 1900 CST, but only 1.7°C warmer than R, one mile west of the cities. The warm air advection was well established at 2400 CST as shown in Figure 5e.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of the period of calm has shown that the nocturnal heat island matches the outline of the cities' boundaries quite closely. During the nighttime hours the prevailing wind forces the heat island downwind as shown by the periods of northwesterly, northeasterly, and southeasterly winds. Winds from the other directions studied, i.e., west, north, east, and south exhibited isotherm patterns which could not be clearly defined. This was due, in part, to the absence of measuring sites on the north and northeast edges of the cities.

Daytime temperature patterns tended to be poorly defined and bore little relation to the outline of the cities' boundaries. This complexity of daytime heat flux is attributed to the fact that there are no dominant heat sources (heavy industries) within the city centers. Rather, the heat sources are distributed about the cities and are relatively weak (light industry and commercial businesses). Thus, the pattern prevalent during the nocturnal periods of calm winds is easily destroyed by solar heating, shifting winds, and the removal of some heat sources during non-business hours.

Oujezdsky (1973) recorded the changes in the intensity of the heat island of Austin, Texas, over two 24-hour intervals, one in winter and one in summer. He found that the urban heat island is most pronounced in the wintertime but still detectable in the summertime. In contrast, Lyall (1977) studied the heat island of London, England, and found that the summer heat island is more intense than that for winter.

Changnon (1961) found that there was a heat island in Champaign-Urbana in the summer with a maximum average temperature difference of 1.3°C at 2000 CST between the cities and the rural airport. Temperature gradients reported herein were greater (as much as 2.2°C per km) than those reported by Changnon and were found to occur at a different time.

It would therefore be desirable to perform another study of the heat island of the cities of Champaign and Urbana during the summer months. This summer study should include additional sites on the north and northeast edges of the cities.

ACKNOWLEDGMENTS

This research was begun at the suggestion of S. A. Changnon, Jr., Chief, Illinois State Water Survey, and was performed under his supervision. The manuscript was reviewed by W. M. Wendland, Head, Climatological Section of the Illinois State Water Survey. Grateful acknowledgement is made of the help given by those persons who permitted the instruments to be placed on their property. At several of the sites these cooperators serviced the instruments as well.

REFERENCES CITED

Chandler, T. J., 1970: "Urban Climates." In WMO, No. 254, T. P. 141, p. 4

Changnon, S. A., Jr., 1961: "A Climatological Evaluation of Precipitation Patterns Over an Urban Area." SEC Tech. Rpt. A62-5, Air Over Cities, Dept. Health, Education, and Welfare, Public Health Serv., Taft Sanitary Engrg. Cntr., Cincinnati, Ohio, 6-7 November, 37-67.

Daniel, C. E. J., and K. Krishnamurthy, 1973: Urban temperature fields at Poona and Bombay. *Indian Journ. Meteor. Geophys.*, 24, 407-412.

Lyall, I. T., 1977: The London heat-island in June-July 1976. *Wea.*, 32, 296-302.

Nkemdirim, L. C., 1976: Dynamics of an urban temperature field - A case study. *J. Appl. Meteor.*, 15, 818-828.

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

Oke, T. R., and G. B. Maxwell, 1975: Urban heat island dynamics in Montreal and Vancouver. *Atmos. Environ.*, 9, 191-200.

Oujezdsky, T. W., 1973: "Diurnal and Seasonal Change of the Urban Heat Island in Austin, Texas." Rpt. No. 34, Atmos. Sc. Grp., Coll. Engrg., Univ. Texas, Austin, Jan., 52 p.

TABLE 1
WINTER CLIMATE, 1978-79
URBANA, ILLINOIS

MONTH	TEMPERATURE, °C				DEPTH, CM.	
	MAXIMUM	DEPARTURE FROM NORMAL	MINIMUM	DEPARTURE FROM NORMAL	SNOWFALL	DEPARTURE FROM NORMAL
DEC.	3.2	+0.1	-4.8	+0.4	1.8	—
JAN.	-6.3	-7.4	-14.5	-7.1	71.9	+58.9
FEB.	-3.7	-6.6	-12.9	-6.8	14.7	+1.3
MAR.	8.5	-0.7	-0.8	+0.2	12.4	+1.3
APR.	14.4	-2.2	4.7	-0.2	1.0	—

LIST OF ILLUSTRATIONS

1. The observational network of thermographs, winter 1978-79.
   The sites are designated by filled circles with letter identification. Isotherms are in °C. Wind is in m s^{-1} with a triangle equal to 5 m s^{-1} and each full feather equal to 1 m s^{-1}. Open circles are anthropogenic heat sources and open squares are bitumin-paved areas.
2. A period of calm to light wind.
3. A period of northwest winds.
4. A period of northeast winds.
5. A period of southeast winds.

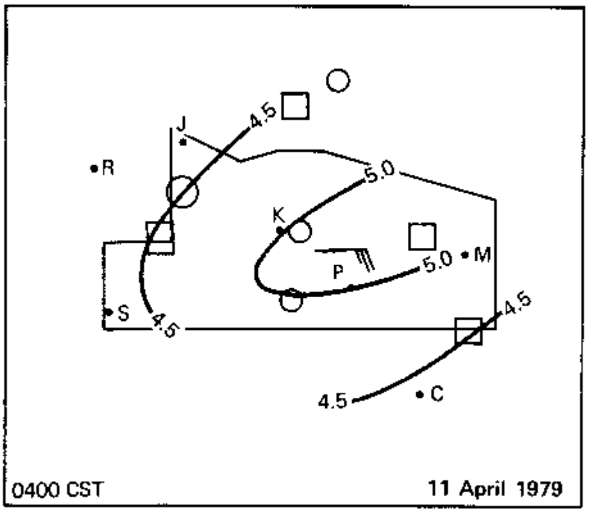
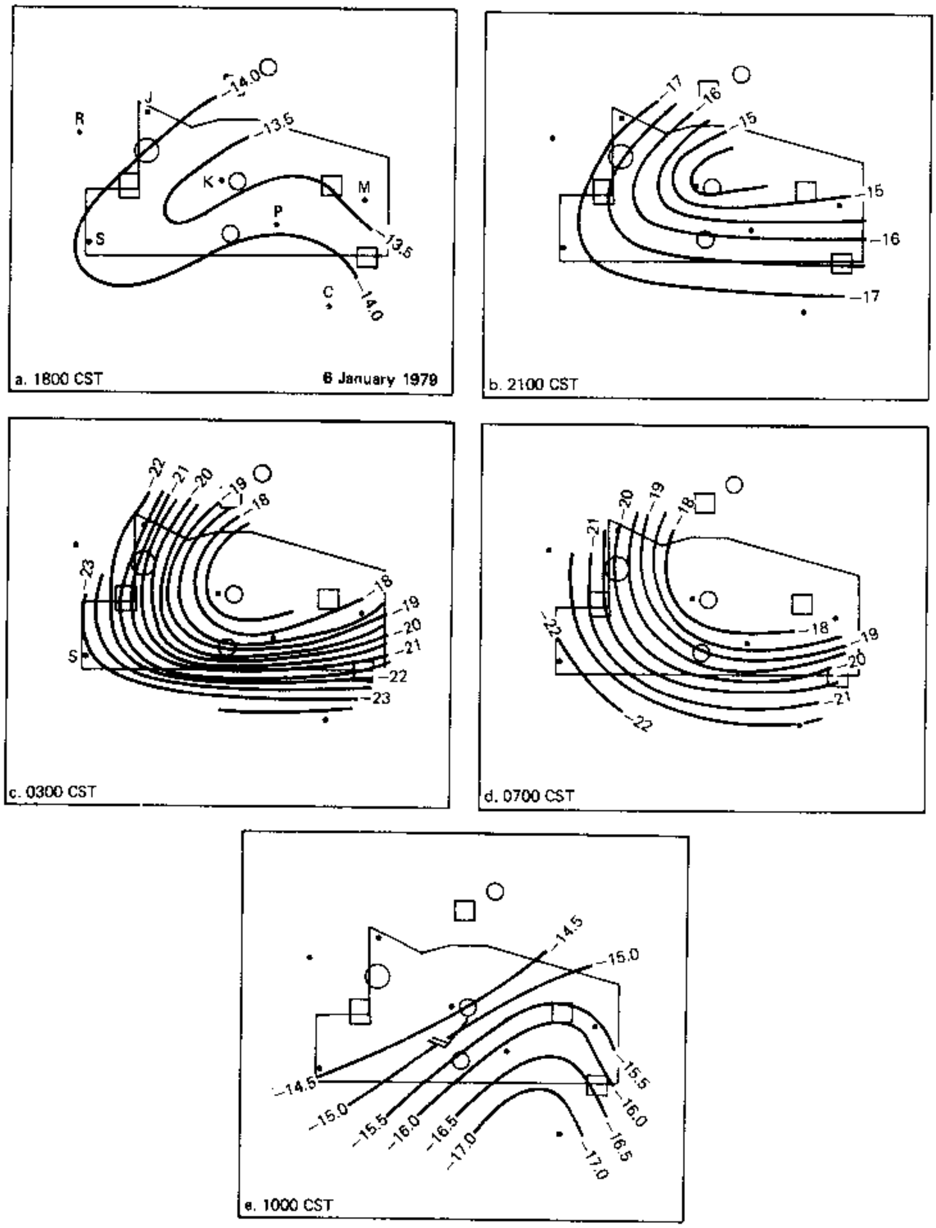


Figure 1



a. 1800 CST
6 January 1979
R
J
K
M
P
S
C
-14.0
-13.5
13.5
14.0
b. 2100 CST
-17
16
-15
-15
-16
-17
c. 0300 CST
-22
-21
-20
-19
-18
-23
S
18
-19
-20
-21
-22
-23
d. 0700 CST
-21
-20
19
-18
-22
-18
-19
-20
-21
22
e. 1000 CST
-14.5
-15.0
-14.5
-15.0
-15.5
-16.0
-16.5
-17.0
15.5
16.0
16.5
17.0

Figure 2

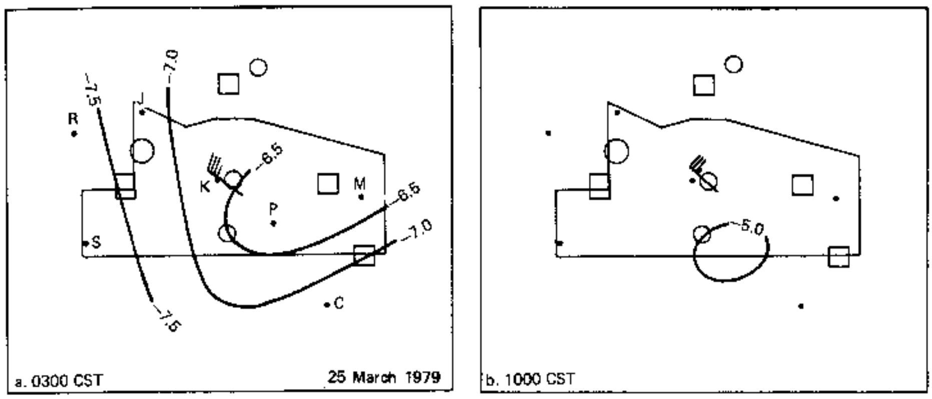


Figure 3

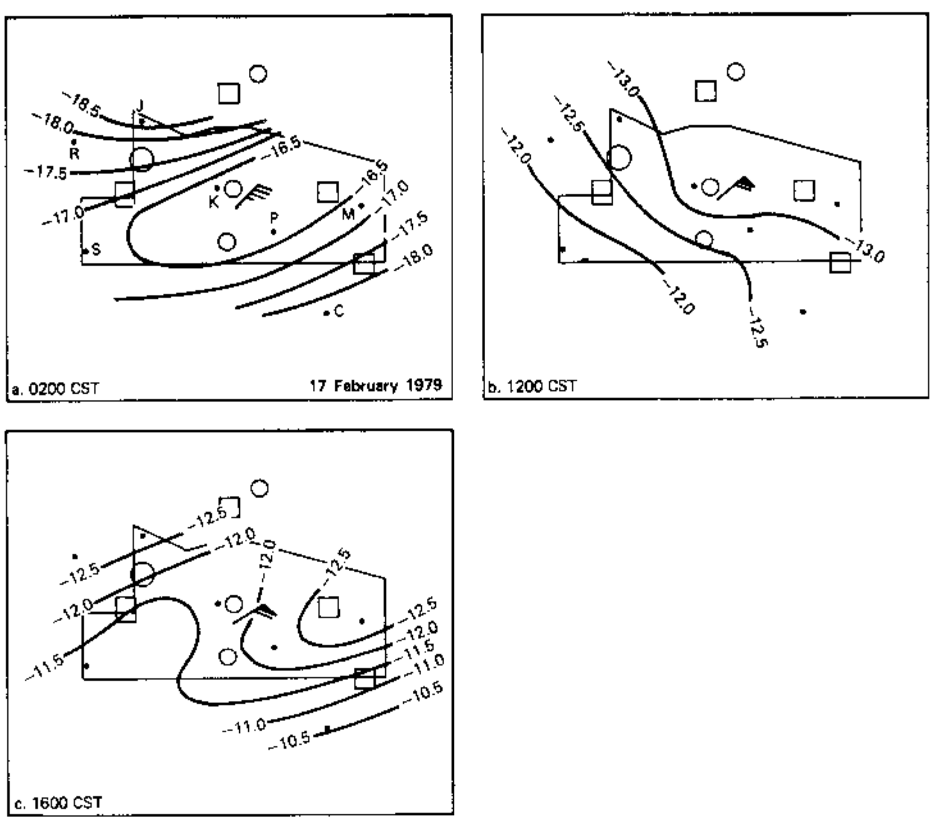


Figure 4

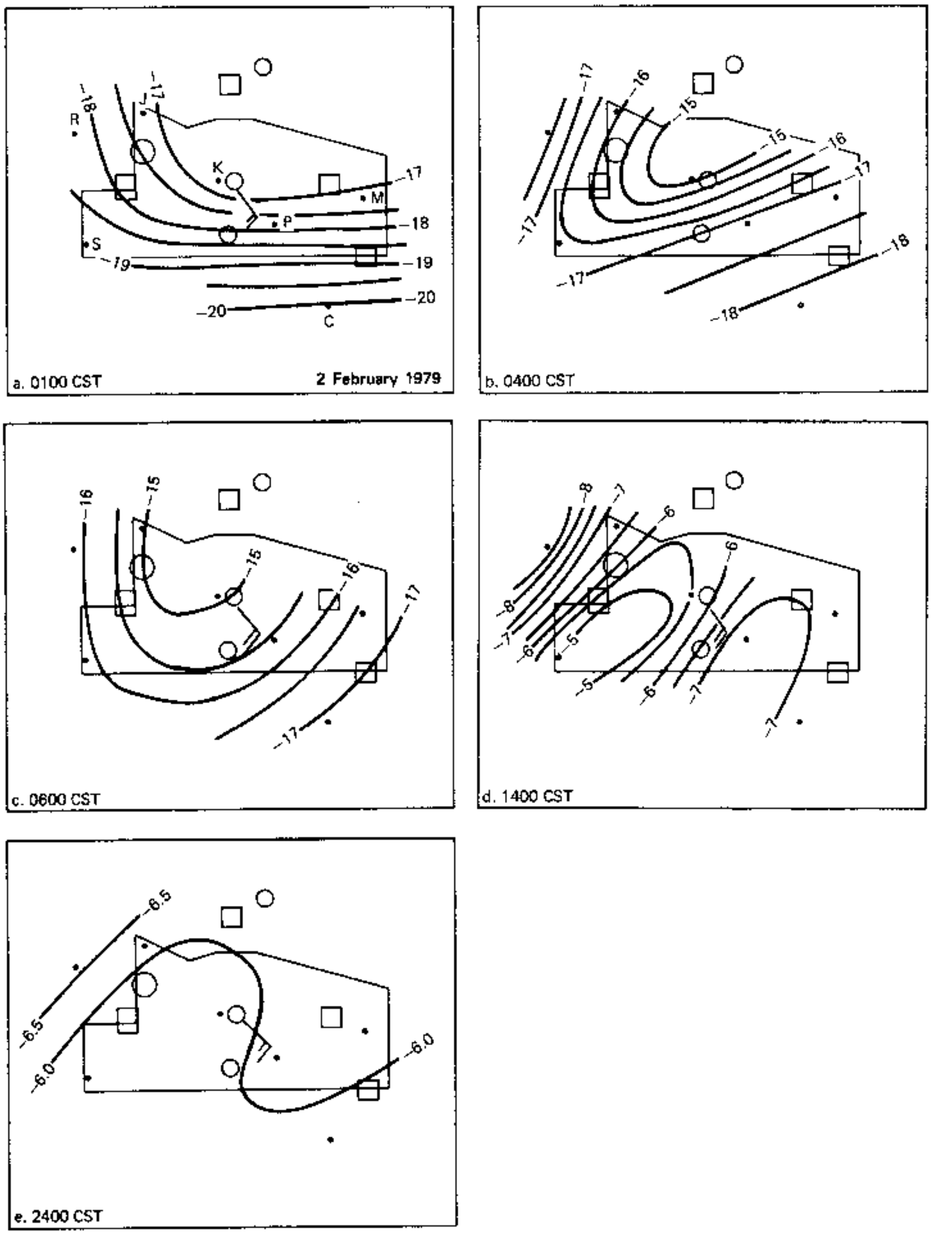

a. 0100 CST
2 February 1979
R
S
J
K
P
M
C
–17
–18
–19
–20
b. 0400 CST
–15
–16
–17
–18
c. 0600 CST
–15
–16
–17
d. 1400 CST
–5
–6
–7
–8
e. 2400 CST
–6.0
–6.5

Figure 5