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A Theoretical Study of the St. Louis Heat Island: Comparisons Between Observed Data and Simulation Results on the Urban Heat Island Circulation

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ABSTRACT

A three-dimensional primitive model was used to predict the early afternoon wind velocity field over St. Louis, Missouri. Four case studies were then performed where model results at various levels were compared with observed data from the METROMEX network. With proper initialization, the model very closely simulated actual conditions, the main feature of which was the urban heat island circulation. Inconsistencies were due mainly to synoptic-scale changes and air mass anomalies, which the model is not designed to handle, and to limitations in the data associated with the network density.

1. Introduction

Earlier papers (Vukovich *et al.*, 1976; Vukovich and Dunn, 1978) describe a three-dimensional primitive equation model and its application to the urban heat island circulation in St. Louis, Missouri. There are only limited comparisons between the model results and data (Vukovich *et al.*, 1979). In this paper, wind and convergence distributions over St. Louis, Missouri, that were obtained from the Illinois State Water Survey (ISWS) are compared with results of four case studies. The data for ISWS analysis were obtained during the METROMEX program.

In the METROMEX network, there were ten PIBAL and/or RAWINSONDE stations (Changnon, 1975), only four of which were located within the bounds of the 48 × 48 km grid used for the dynamic model (Fig. 1). Chosen were 3, 4, 7 and 8 August 1973 for the model prediction experiment because of the completeness of the METROMEX observations on these days and the presence of a heat island at the surface.

The model predicts the three-dimensional velocity at various levels. The 300 m above river level (m ARL) and 1000 m ARL were selected for comparison with METROMEX data. Since the Mississippi River at St. Louis is ~125 m above mean sea level (m MSL), these levels are actually 425 and 1125 m MSL, respectively. The nearest METROMEX analyses to these levels were at 350 and 1200 m MSL, and these were the levels selected for comparison. Model solutions that correspond in time to 1400 CDT, based on the initial conditions used, were chosen for comparison with the observed results. Solutions were chosen from computer simulations already available, or special simulations were performed if cases were not found in which there was a close comparison between initial conditions. Initial conditions were chosen from available data for a period three hours prior to the time of the solution. Table 1 gives the initial conditions used in the model versus the observed conditions. The model assumes the initial conditions to be geostrophic so that the observed conditions and the initial conditions will differ. The effect of friction in the model will soon produce a wind field comparable to the observed wind field at the initial time.

The model makes use of the hydrostatic approximation and assumes that the vertical derivative of the mass continuity equation is zero in order to obtain the pressure and the vertical velocity distribution. The lateral boundaries are open except for the upstream boundary which is closed. The rigid-lid approximation is used at the top of the model. At the surface, all three components of the velocity were zero; but the surface temperature, surface roughness, and terrain elevation including building heights were specified at each grid point.

It should be noted that the METROMEX wind flow, convergence and vertical velocity analyses are based on 10 upper air wind observations over the 5850 km^2 METROMEX study area. Since only four of these observations were made in the domain of the prediction grid, detailed comparisons between observed and predicted analyses are unlikely.

2. Case results

a. 3 August 1973

A broad, developing high-pressure system was centered over southwestern Missouri (1020.0 mb

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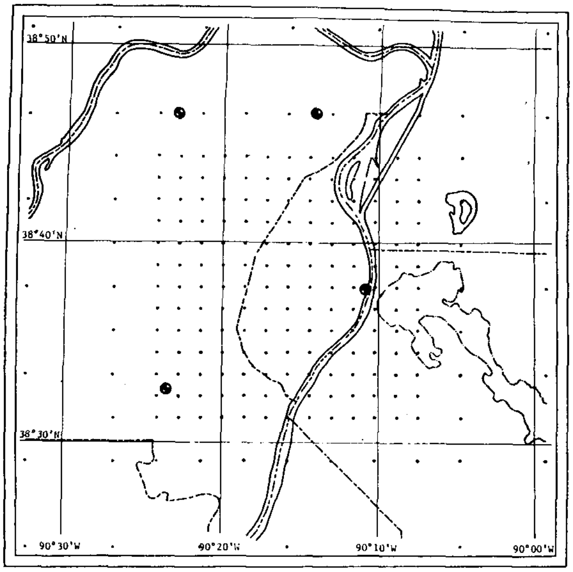


FIG. 1. The portion of the model grid used in this analysis is 48 × 48 km. The 169 grid points in the inner array are on 2 km centers; the outer points, on 8 km centers. The four METROMEX upper air stations [⊕] are shown. The southeast station was located at the Arch; the northwest station, at Lambert Field.

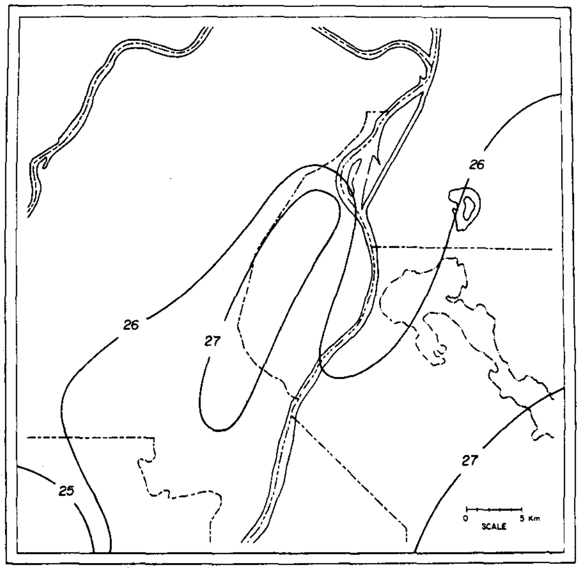


FIG. 2. Surface temperature (°C) distribution at 1330 CDT 3 August 1973.

central pressure) and dominated the weather in the central United States from the Rockies east to the Appalachians and from central Ontario southwest to the Texas Panhandle. The synoptic surface flow was essentially from the northwest in the Missouri-Illinois region. By 1400 CDT, differential heating produced a 2.5°C heat island at the surface over downtown St. Louis (Fig. 2) relative to the outlining rural regions. Daytime mixing produced an adiabatic layer near the surface that was approximately 1500 m deep by 1630 CDT. Winds through the adiabatic mixing layer were generally from the north and northwest and varied from 1 to 5 ms^{-1}.

The predicted wind flow fields and streamline analyses for 300 and 1000 m ARL are shown in Fig. 3. The vectors extend from the grid point in the direction of the flow and are proportional in length to the wind speed. This analysis indicates an area of convergence over and slightly downwind of the central portions of the city and a corresponding area of divergence above at 1000 m ARL. The METROMEX analyses for 350 and 1200 m MSL are also shown in Fig. 3. The wind scale is defined in Table 2. A notice-

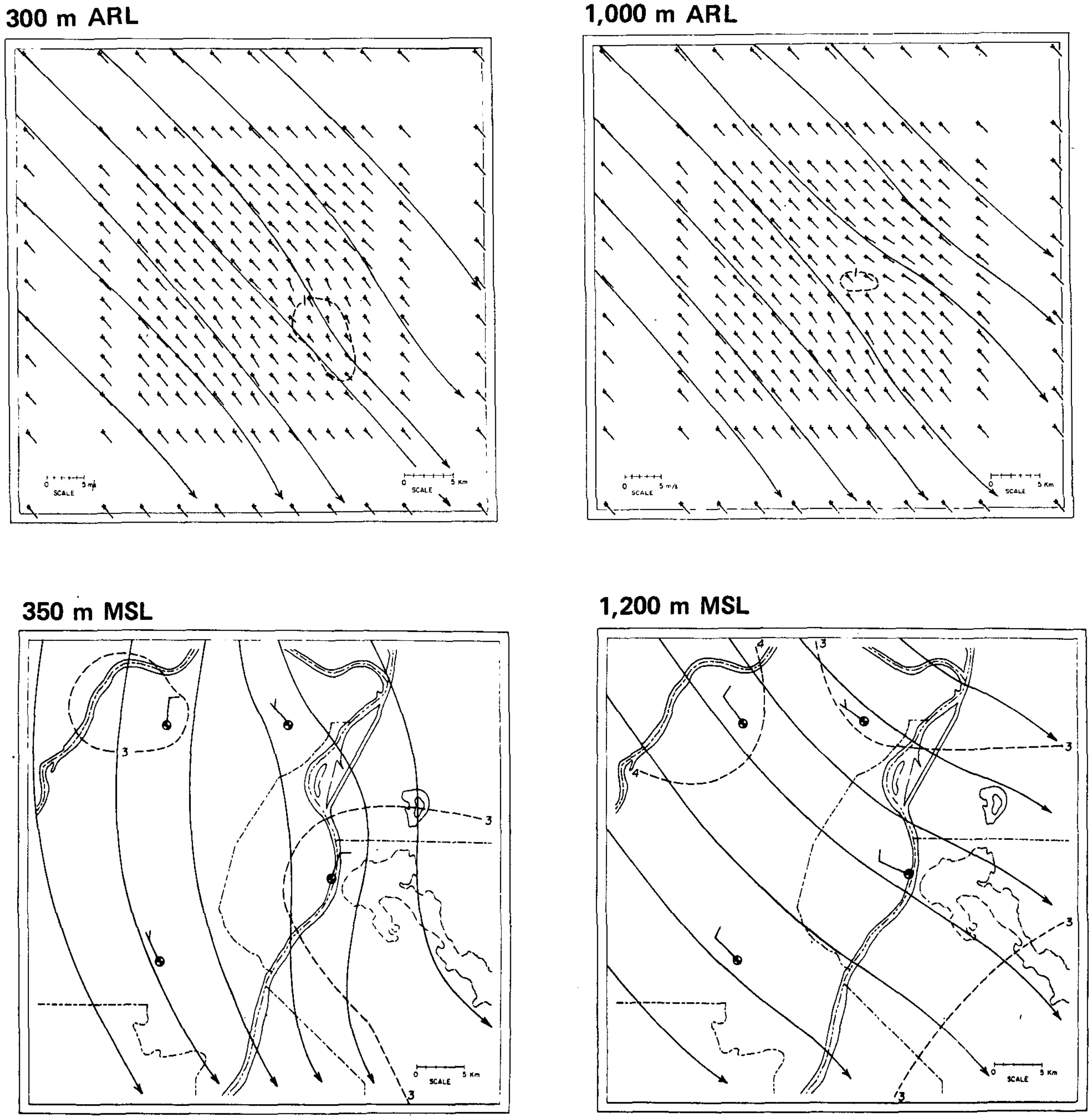
TABLE 1. Initial conditions for hydrodynamic model versus observed conditions (underlined values). The average wind shear and stability are values for the boundary layer.

Date/Time	Average 250 MSL wind speed*† (m s^{-1})	Average wind direction† (250 MSL)	Average wind shear* (s^{-1})	Stability
3 August 73/1130 CDT	2.0	NW	2.5×10^{-3}	neutral
	2.5	N	2.5×10^{-3}	neutral
4 August 73/1130 CDT	2.0	SW	2.5×10^{-3}	neutral
	2.5	W	2.5×10^{-3}	neutral
7 August 73/1130 CDT	5.0	SSW	6×10^{-3}	neutral
	6.0	SW	6×10^{-3}	neutral
8 August 73/1130 CDT	7.5	SSW	0	neutral
	8.5	SW	0	neutral

* Estimated from ISWS analyses and not computed from actual data.
† Average value using rural winds only.

able difference is seen in the direction of the flow at the lower level, although both analyses show a marked heat island perturbation. There is also a speed difference of ~1–1.5 m s^{-1}. These differences are believed to be a function of the initial conditions that were used for the model. It appears that during the prediction period there was a change in the synoptic wind which the model is not designed to handle.

A comparison of the lower level convergence and upper level divergence computations is given in Table 3. The difference in location of maximum convergence at the lower level is, in part, a function of



300 m ARL

1,000 m ARL

350 m MSL

1,200 m MSL

FIG. 3. Model wind field predictions are shown in the upper diagrams at the 300 and 1000 m ARL levels for 1330 CDT on 3 August 1973. Isotach (m-s^{-1}) and streamline analyses are superimposed over the vectors which extend from the grid point in the direction of flow and are proportional in length to the wind speed. The corresponding METROMEX wind field analyses for 350 and 1200 m MSL are shown in the lower diagrams. Isotachs (m s^{-1}) are shown, and wind barbs (Table 2) indicate the direction from which the wind is blowing.

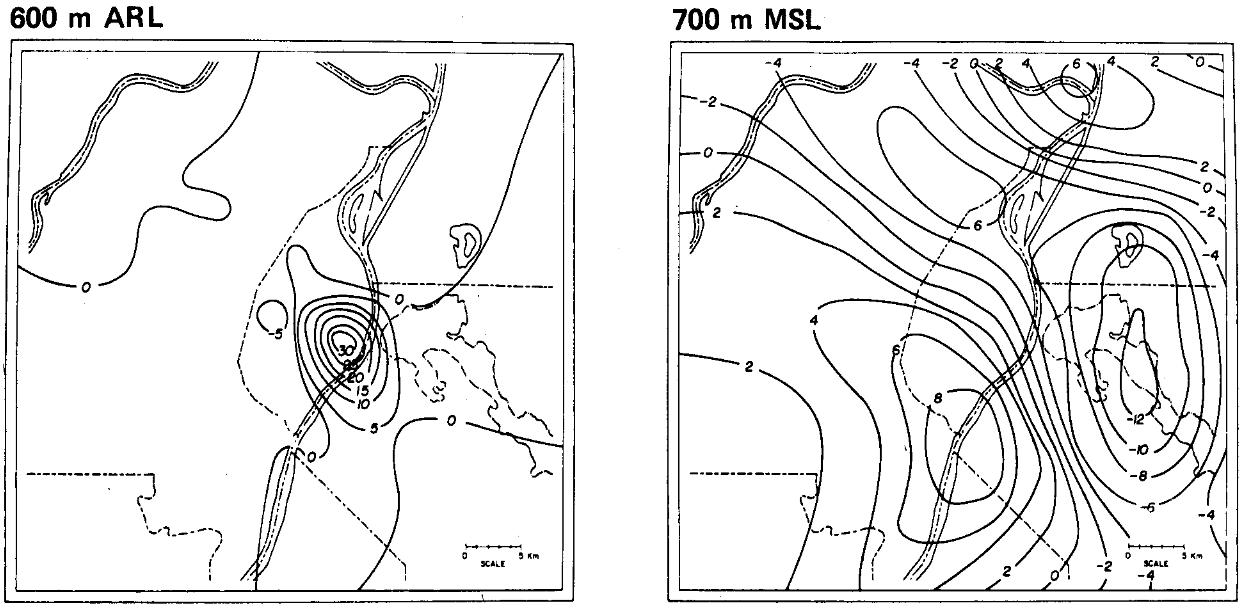
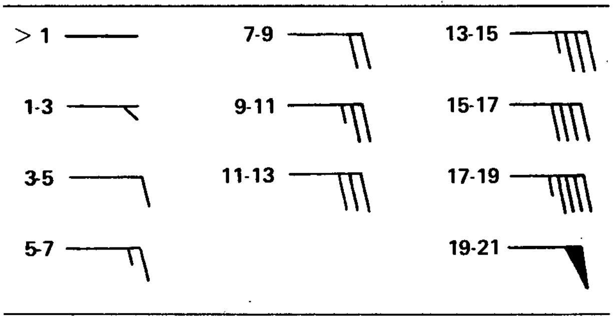


FIG. 4. The horizontal distribution of the vertical velocity (cm s^{-1}) predicted by the model at 600 m ARL (left) and computed by ISWS at 700 m MSL (right) are shown for 1330 CDT 3 August 1973.

the differences in the direction of flow at that level, although the observed and predicted values do compare well. The location of the centers of divergence at the upper level compare somewhat better due to more directional compatibility at that level. The magnitudes also compare reasonably well.

The horizontal distribution of the vertical velocity at 700 m MSL and 600 m ARL (Fig. 4) shows that the model predicts much stronger vertical motion than that computed from the METROMEX data. Furthermore, the center of the vertical motion was predicted to be over the city and the heat island,

TABLE 2. METROMEX wind scale (m s^{-1}) for observed analyses at 350 and 1200 m MSL.



>1	7-9	13-15
1-3	9-11	15-17
3-5	11-13	17-19
5-7		19-21

TABLE 3. Comparison of the horizontal convergence predicted at 300 m ARL and computed at 250 m MSL and the horizontal divergence predicted at 1000 m ARL and computed at 1200 m MSL on 3 August 1973 at 1330 CDT.

	Observed	Predicted
Center of maximum lower level convergence	2×10^{-4} s^{-1} 38°32′N, 90°16′W	1.2×10^{-4} s^{-1} 38°36′N, 90°12′W
Center of maximum upper level divergence	1×10^{-4} s^{-1} 38°33′N, 90°15′W	2.7×10^{-4} s^{-1} 38°36′N, 90°12′W

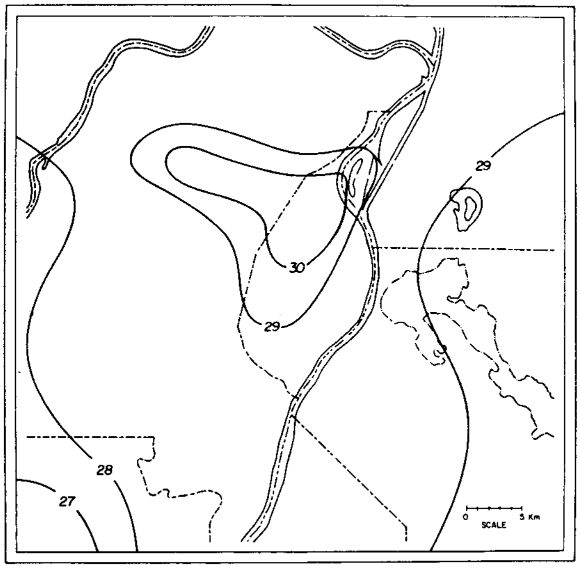


FIG. 5. Surface temperature [°C] distribution at 1330 CDT 4 August 1973.

where it is generally expected to be found. The analysis from the observed data shows the center of upward motion to be south of the center of the city. ISWS computed these vertical velocities by using the available data. Again, since only four soundings were available within the domain of the model grid, differences in results must be attributed, at least in part, to the resolution of the observed data.

b. 4 August 1973

The high-pressure system covered basically the same geographic area as on 3 August but had grown more intense. Also, the center had shifted to central Ohio although a secondary center still remained over the northern Ozarks. At 1400 CDT, a 3.5°C heat island existed over downtown St. Louis (Fig. 5). By

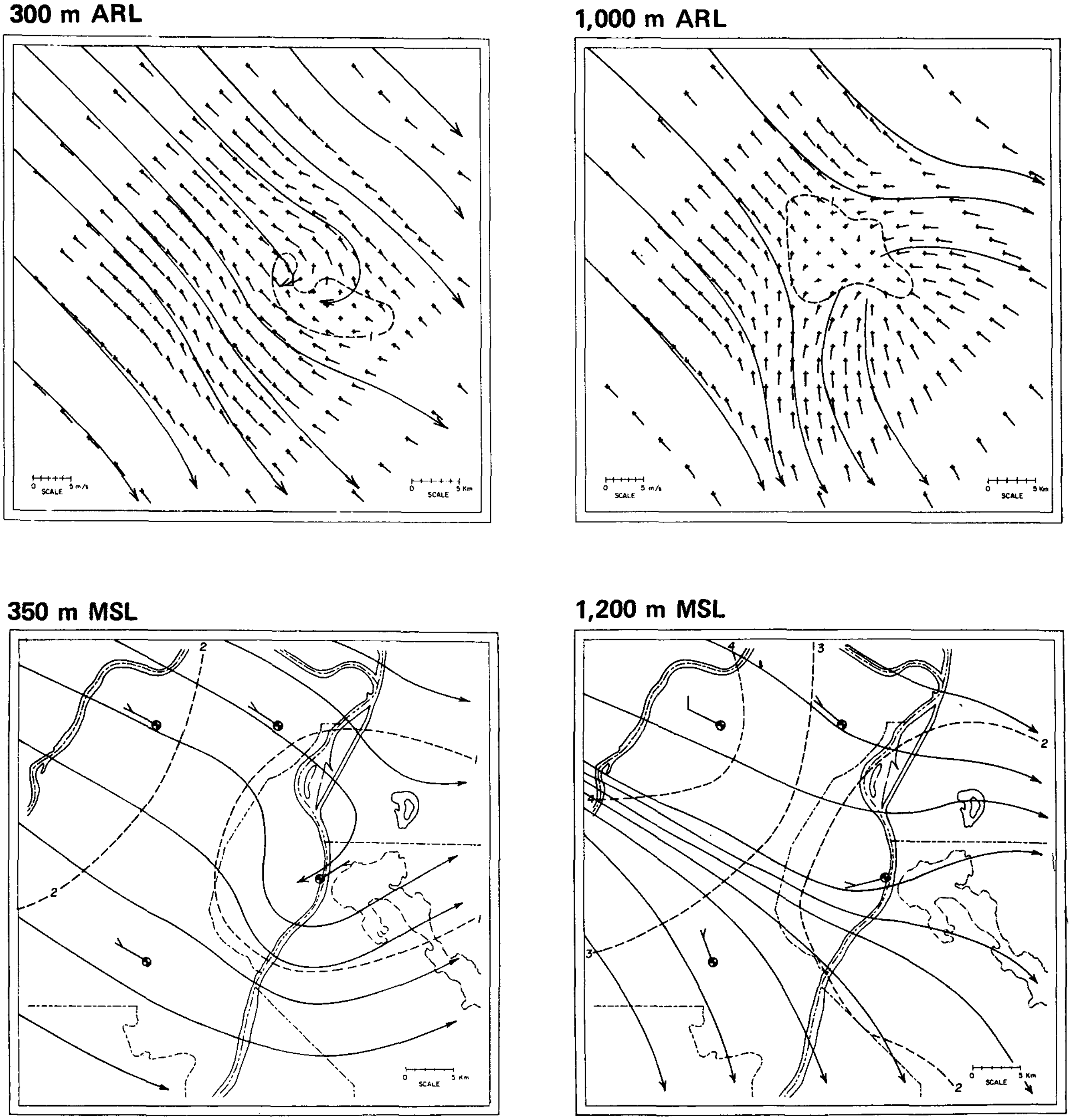


FIG. 6. Model wind field predictions are shown in the upper diagrams for 300 and 1000 m ARL at 1330 CDT on 4 August 1973. The corresponding METROMEX wind field analyses for 350 and 1200 m MSL are shown in the lower diagrams.

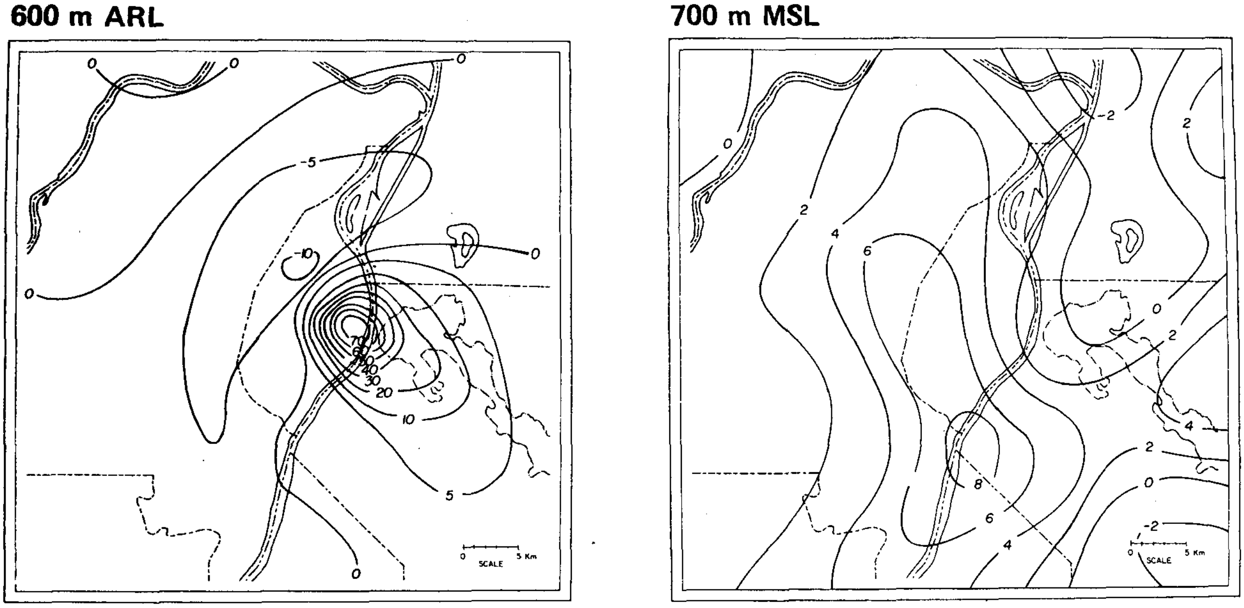


FIG. 7. The horizontal distribution of the vertical velocity predicted by the model at 600 m ARL (left) and computed by ISWS at 700 m MSL (right) are shown for 1330 CDT 4 August 1973.

1540 CDT, the adiabatic mixing layer was approximately 2 km deep with winds from the west to west-northwest at 3 to 5 m s^{-1}.

The predicted wind fields with streamline analyses for 300 and 1000 m ARL are shown in Fig. 6. The model predicts a pronounced heat island perturbation over and downwind of the city. An area of strong horizontal convergence (Table 4) and inflow is seen at 300 m ARL over the heart of the downtown business district. At 1000 m ARL, equally strong divergence is predicted directly above the 300 m ARL convergence zone.

The METROMEX streamline analyses for 350 and 1200 m MSL (Fig. 6) show excellent agreement with the model output both qualitatively and quantitatively. However, the magnitudes of the lower center of convergence and the upper center of divergence are less than those predicted by the model (Table 4). Also, the observed divergence center is shifted downwind to the southeast of the center city.

TABLE 4. Comparison of the horizontal convergence predicted at 300 m ARL and computed at 350 m MSL and the horizontal divergence predicted at 1000 m ARL and computed at 1200 m MSL for 4 August 1973 at 1330 CDT.

	Observed	Predicted
Center of maximum lower level convergence	1.5×10^{-4} s^{-1} 38°39′N, 90°18′W	5.7×10^{-4} s^{-1} 38°37′N, 90°13′W
Center of maximum upper level divergence	2.0×10^{-4} s^{-1} 38°30′N, 90°07′W	6.5×10^{-4} s^{-1} 38°37′N, 90°11′W

An examination of the predicted and observed vertical velocity distributions at 600 m ARL and 700 m MSL, respectively (Fig. 7), shows major differences. The model predicts a center of upward motion immediately over the downtown portion of the city with maximum vertical velocity of 70 cm s^{-1}. A plume of upward motion extends eastward. The vertical velocities computed from the METROMEX data are an order of magnitude smaller, and the center of upward motion is shifted to the south. Differ-

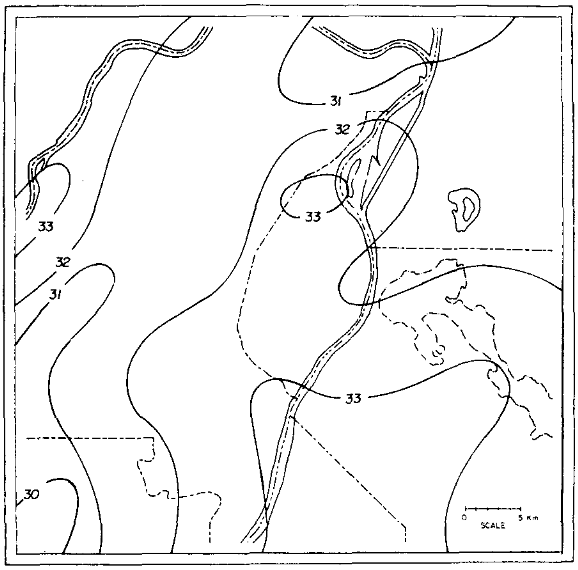


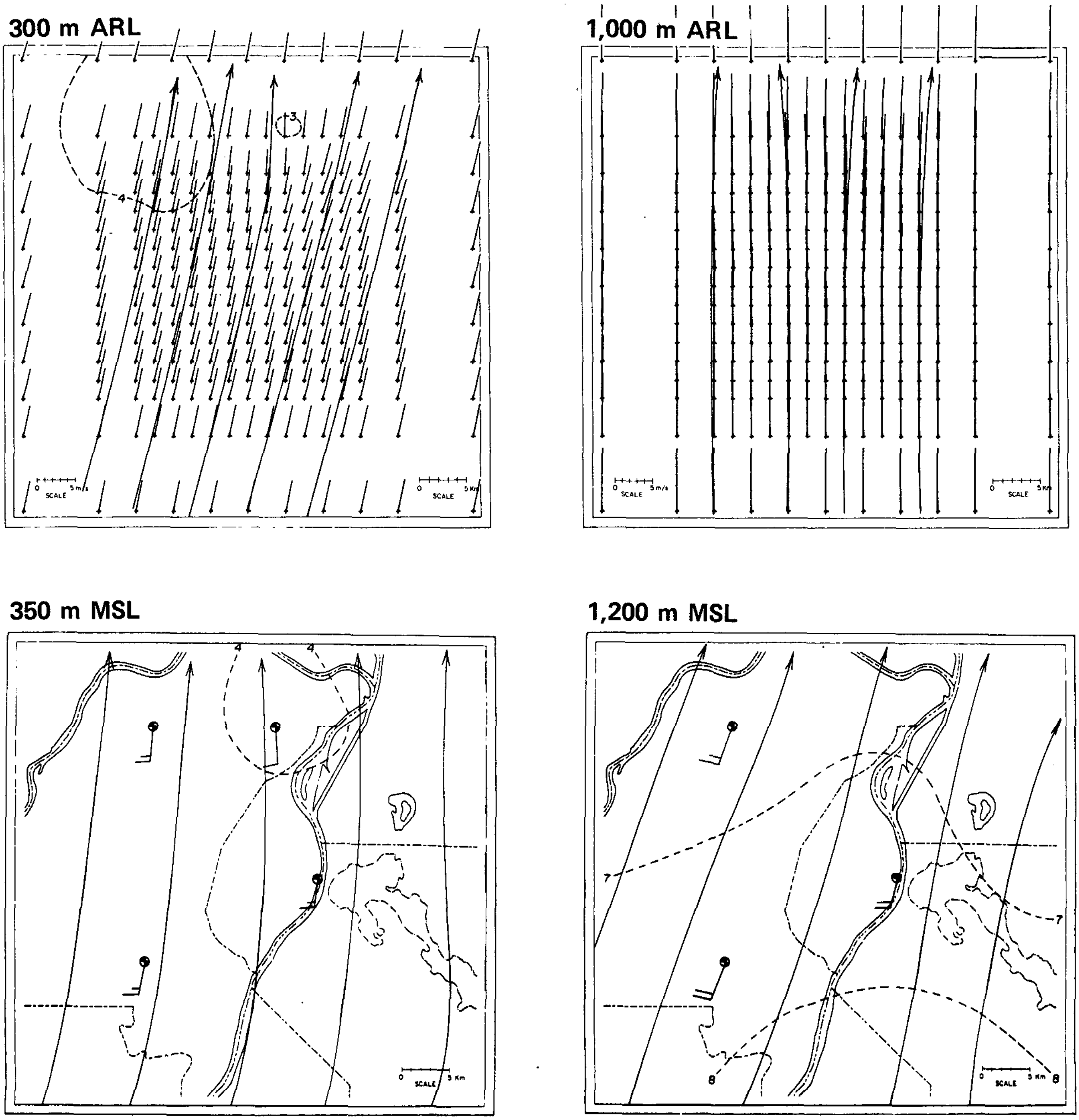
FIG. 8. As in Fig. 5 except for 7 August 1973.

ences must be due, in part, to the METROMEX data resolution.

c. 7 August 1973

The high-pressure system had crossed the mountains and was now situated along the northeastern seaboard. By midday, the surface-based adiabatic mixing layer was 1500 m deep and was capped by a weak but persistent subsidence inversion. Winds in the mixed layer were generally from the south-southwest throughout from 4 to 12 m s^{-1}. By 1400 CDT, a 2–3°C heat island existed over the northern part of the city (Fig. 8). It is noted that there are areas to the south and west having temperatures identical to that in the heat island. By late afternoon, some small air mass showers had developed west and north of St. Louis, but only a few produced radar echoes that reached the ground (Changnon and Semonin, 1975).

The predicted wind flow fields and streamline

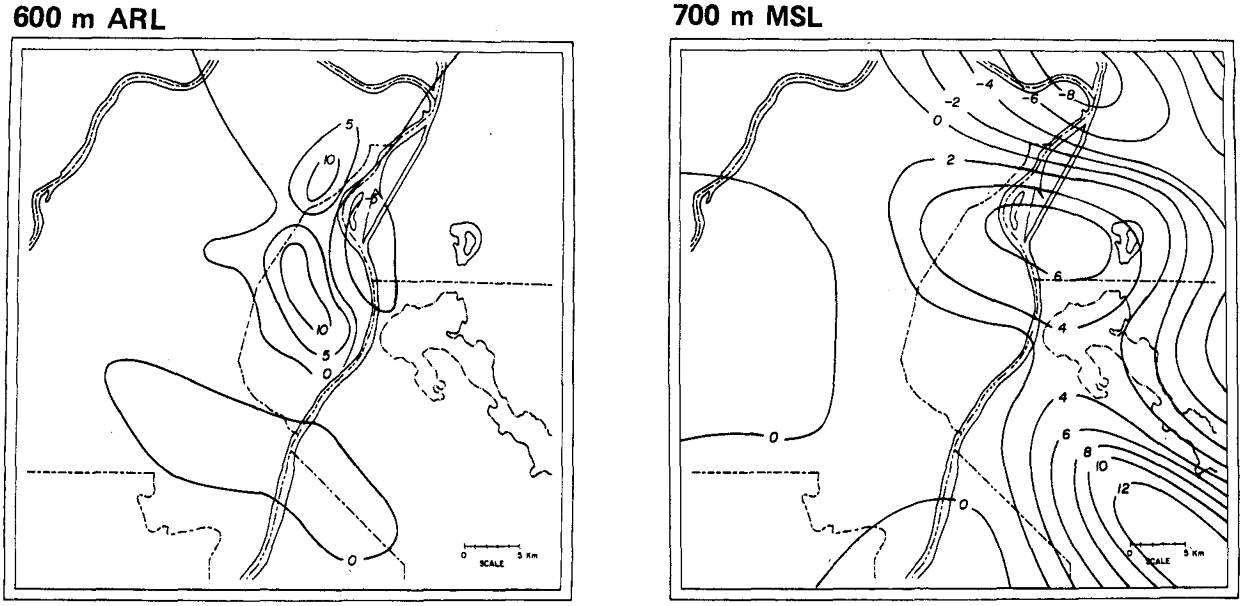

300 m ARL

1,000 m ARL

350 m MSL

1,200 m MSL

FIG. 9. As in Fig. 6 except on 7 August 1973.


600 m ARL

700 m MSL

FIG. 10. As in Fig. 7 except on 7 August 1973.

analyses for 300 and 1000 m ARL are shown in Fig. 9. This day proved to be an interesting case in that the center of the heat island was shifted north due to strong horizontal advection. The heat island was elongated along a south-southwest to north-northeast axis with the wind. As a result, the heat island perturbation shows up well north of downtown, just west of the confluence of the great rivers where a distinct area of horizontal divergence exists (Table 5). The model does a credible job of predicting the divergence and its magnitude. The warm areas to the south and west do not effect the flow because these areas are in a rural region where the magnitude of surface roughness is considerably smaller than in the city. The surface roughness has a marked effect on producing local sensible heat that will effect the pressure field. In this case, the sensible heating associated with the warm areas in the rural regions was not sufficient to affect the pressure field and, therefore, the flow field.

The METROMEX streamline analyses for 350 and 1200 m MSL are also shown in Fig. 9. The heat island perturbation is quite similar in the observed data, though a small difference appears in the flow pattern at the upper level where a slight veering of some 20° is observed to occur while the model is predicting a slight backing of similar magnitude.

The computed and predicted velocities at 700 m MSL are shown in Fig. 10. The model shows two small regions of upward motion (maximum upward speed, 10 cm s^{-1}), one over the center city and the other to the north. The observed data show a broader, less concentrated area of upward motion (maximum upward speed, 6 cm s^{-1}) centered to the north of the city and east of the zone of upward motion in the prediction results. The stabilizing influence of the

TABLE 5. Comparison of the horizontal divergence predicted at 300 m ARL and that computed at 350 m MSL near the confluence of the Mississippi and Missouri Rivers on 7 August 1973 at 1330 CDT.

	Observed	Predicted
Center of maximum lower level divergence	1.5×10^{-4} s^{-1} 38°49′N, 90°08′W	1.2×10^{-4} s^{-1} 38°43′N, 90°12′W

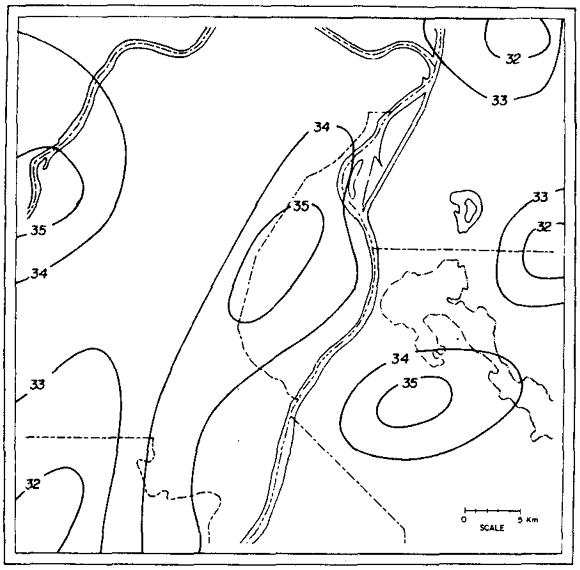


FIG. 11. As in Fig. 5 except for 8 August 1973.

capping subsidence inversion and the strong horizontal advection was probably responsible for the low magnitudes of both the predicted and observed vertical velocities (Vukovich, 1975; Vukovich and Dunn, 1978).

d. 8 August 1973

The high-pressure system (now dominating the whole of the eastern seaboard) in combination with a longwave trough running from the Great Lakes to southeastern New Mexico, was pumping warm Gulf air up the Mississippi River valley. The METROMEX radar detected convective activity to the west of the downtown area and immediately over one of the upper air stations. Surface winds were steady and southerly all day, averaging over 6 m s^{-1}. At 1400 CDT, a 2.5°C heat island existed over the west edge of downtown St. Louis (Fig. 11). However, other local "hot spots" are noted to the west and

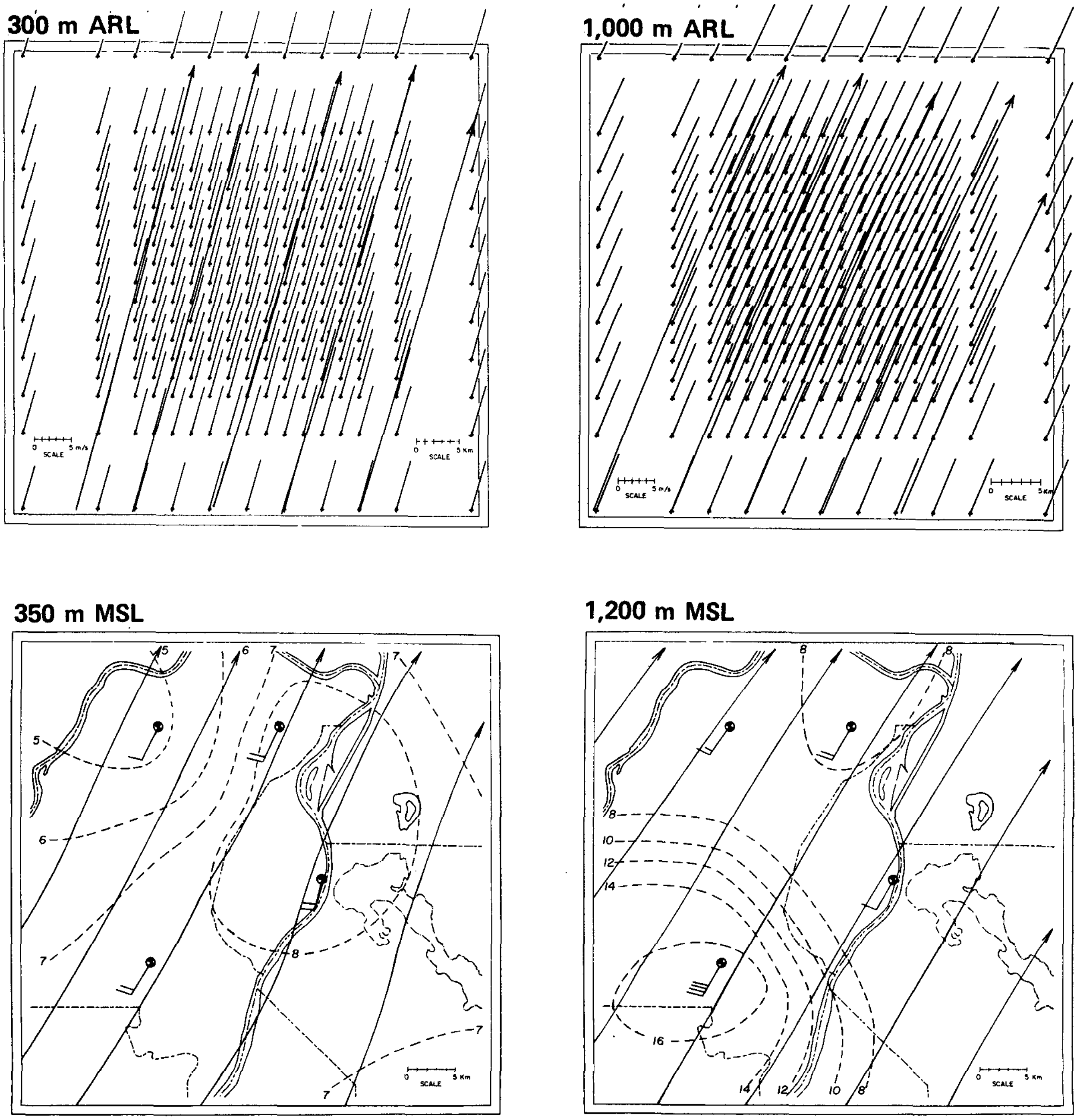


FIG. 12. As in Fig. 6 except on 8 August 1973.

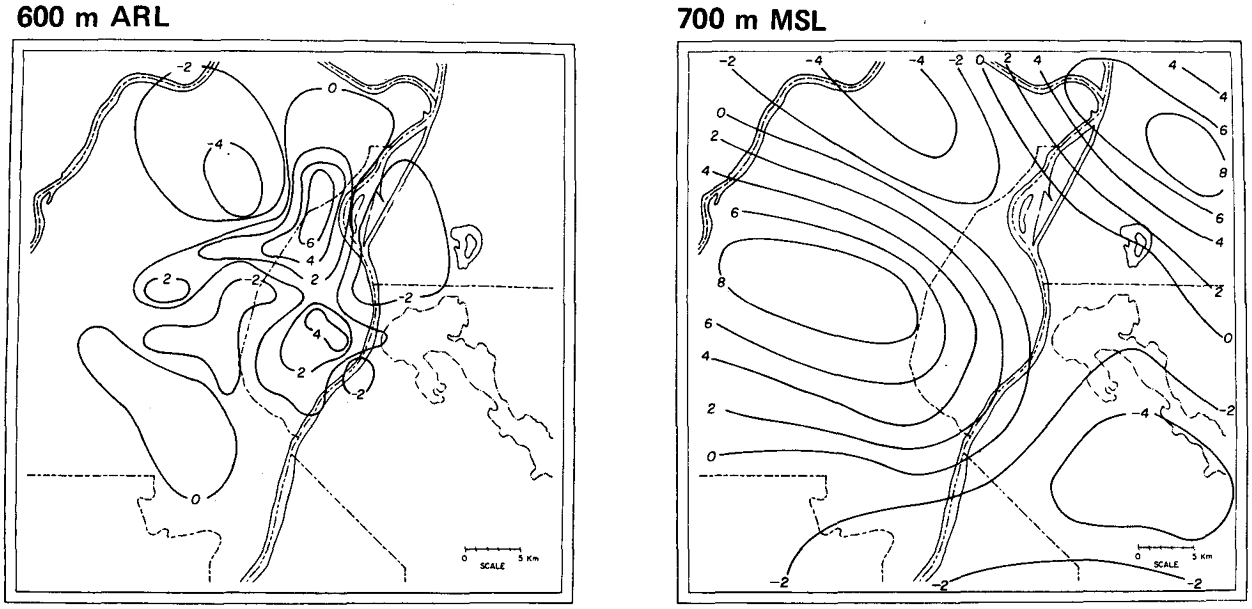


FIG. 13. As in Fig. 7 except on 8 August 1973.

southeast of the city. By 1515 CDT, the surface-based adiabatic mixing layer was 1500 m deep with southerly winds ranging from 4 m s^{-1} near the surface to 11 m s^{-1} aloft.

The wind field and streamline analyses predicted by the model for 300 and 1000 m ARL are shown in Fig. 12. The only visible evidence of the heat island perturbation appears due north of the center city where a slight reduction in the wind speed at 300 m ARL indicates an area of horizontal convergence (0.2×10^{-4} s^{-1}). The METROMEX streamline analyses for 350 and 1200 m MSL (Fig. 12) show the effects of convective activity to the west of downtown, presumably produced by air mass instability. The dramatic reduction in wind speed at 1200 m MSL to the west of downtown produced an area of strong convergence (7×10^{-4} s^{-1}). Since the model is a dry model, it cannot predict this behavior.

The vertical velocity distribution (Fig. 13) for the observed METROMEX data shows a broad area of upward motion (maximum upward speed, 8 cm s^{-1}) at 700 m MSL over the area of the convective activity west of downtown. A second center of upward motion (maximum upward speed, 8 cm s^{-1}) is noted to the northeast. The model predicts a principal center of upward motion (maximum upward speed, 10 cm s^{-1}) immediately to the north of the city, with a secondary center (maximum upward speed, 4 cm s^{-1}) over the city.

3. Conclusions

It is shown that the three-dimensional, primitive equation model can predict the air flow over and around an urban complex with reasonable success in a variety of synoptic situations. The accuracy of these predictions depends primarily upon the accuracy of the initial conditions. Errors arise due to synoptic-scale changes such as the effect of the cool air advection or due to air mass anomalies such as the convective activity noted on 8 August upwind of the city. The model is not designed to incorporate such effects. Differences in vertical velocity and divergence analyses result probably from the density of the METROMEX observational network over the region of interest.

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