P1.19 CONVECTIVE INITIATION VIA OUTFLOW BOUNDARY INTERACTION WITH QUASI-STATIONARY THERMAL CIRCULATIONS

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1. INTRODUCTION

On 22 June 2006, an outflow boundary produced by thunderstorms in east Alabama interacted with an apparent urban heat island circulation over Birmingham, enhancing and possibly initiating convection. The thunderstorms became quite intense, producing heavy rain and reports of hail 2.5 cm in diameter (NWS Storm Data), and a severe thunderstorm warning was issued for this storm by the local National Weather Service office at 0047 UTC (7:47 pm CDT).

In this paper, after a brief review of the dynamics of the urban heat island and outflow boundaries, this case will be examined in detail, using radar, surface, and satellite data.

2. THE URBAN HEAT ISLAND

2.1 *Thermal circulations*

Thermally-direct circulations are simply circulations in the atmosphere in which a horizontal thermal gradient exists and air is rising on the warm side of the circulation and subsiding on the cool side. At low-levels, the hydrostatically-induced pressure gradient force produces flow toward the warm side and subsequent convergence on the warm side of the circulation, consistent with the vertical motion pattern. Thermally-direct circulations produced by surface temperature discontinuities may be produced through a wide variety of meteorological and land-surface conditions, including sea breezes and land breezes; shores of inland lakes and rivers; gradients in soil moisture, cloud cover, or vegetation type; topography, and the urban heat island. In many of these cases, it is the differential heating of the surface which produces the horizontal gradients in temperature (e.g., Peilke and Segal 1986). Thermally-direct circulations which originate from a fairly stationary heat source and do not propagate away from the heat source as a density current are hereinafter referred to as "quasistationary thermal circulations."

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2.2 *Urban heat islands and convection*

The concept of the urban heat island was discussed as early as Duckworth and Sandberg (1954); DeMarrais (1961); and Pooler (1963). Urban areas tend to be warmer than surrounding rural areas, especially on days with relatively clear skies and light winds. Some factors contributing to the warmer temperatures in the city include the lack of evaporation from plants and soil during the day, higher rates of heat conduction by concrete than by plants, and waste heat produced by buildings and vehicles (Ackerman 2006).

The heat island is associated with a circulation, which has been shown to have an effect on rainfall and convection around cities. Several authors have discussed the rainfall anomalies located near cities (e.g., Changnon 1968; Changnon et al. 1991), and Bornstein and Lin (2000) found that the urban heat island in Atlanta, Georgia produced a convergence zone which initiated convection.

The effect of an isolated heat source placed within a non-sheared flow was studied numerically by Lin and Smith (1986). Their results for a surface-based heat source are shown in Figure 1. In this case, the heat source releases 0.35 J kg^{-1} s^{-1}, the background wind flow is U=5 m s^{-1}, and T=273 K. At the time of this figure, the simulation is at 20,000 s. Note that there is a slight downward displacement of air parcels near the heat source, then upward displacement downstream of the heat source. This is consistent with the enhanced rainfall downwind of cities.

Baik et al. (2001) simulated the effect of an urban heat island specifically. They also found that updrafts are produced on the downwind side of the heat island, as shown in Figure 2. In this simulation, background wind U=3 m s^{-1}, and heating is 1 J kg^{-1} s^{-1}. The city center is at x=50 km. The updrafts are concentrated about 20 km downwind of the center, with magnitudes approaching 1 m s^{-1}.

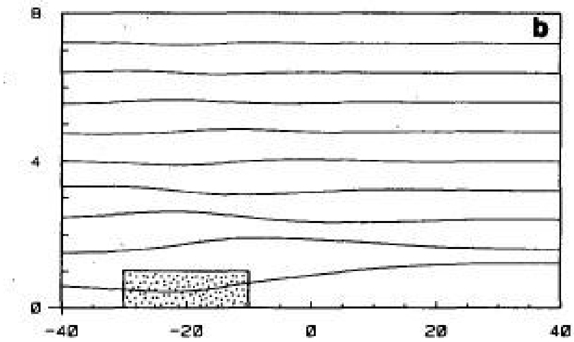

Figure 1. Model of flow past a heat source, from Lin and Smith 1986.

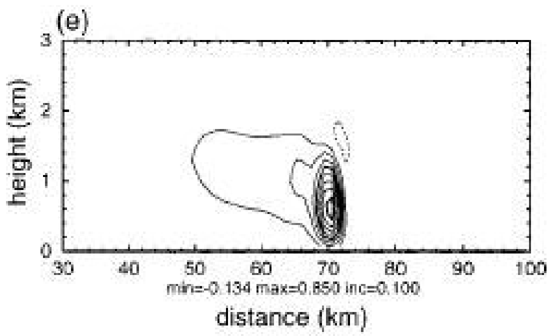

Figure 2. Perturbation vertical velocity associated with urban heat island located at x=50 km, at time t=4 h.

3. DENSITY CURRENTS

When a dense fluid is horizontally adjacent to a light fluid, hydrostatically the denser fluid will have a higher pressure at low-levels, producing a pressure gradient force toward the lighter fluid. This allows the dense fluid to overtake the light fluid. The dense fluid basically spreads out, similar to water poured out on a table. This type of flow is known as a density current (e.g., Simpson 1997)

Density currents are often produced by thunderstorms. Evaporation and melting processes cool the air within the storm downdraft, and when this air comes in contact with the ground, it spreads laterally as a density current. The leading edge of this cool density current is known as an outflow boundary, and often propagates far away from the storm which produces it.

A density current is more transient than a quasi-stationary thermal circulation. Density currents propagate forward into the less dense fluid as potential energy in the heavier fluid is being converted into potential energy (Simpson 1997). This produces a speed equation for the density current (Simpson 1997)

$$U = \left(\frac{\Delta\rho}{\rho} gH \right)^{1/2}$$

where U is the speed, $\Delta\rho$ is the density difference between the two fluids, g is the acceleration of gravity, and H is the height of the heavier fluid. Seitter (1986) developed an equation for the speed of density current propagation using only surface quantities for the base speed, but also including the effects of viscosity and background wind. The density current typically has rear-to-front relative flow, which produces convergence at the leading edge of the density current. This convergence produces rising motion at the outflow boundary, which sometimes initiates new convection, if the upward motion is sufficient to carry parcels to their level of free convection.

4. MESOSCALE ENVIRONMENT

4.1 *Thermodynamic Profile*

Surface temperatures were unseasonably hot over central Alabama on 22 June 2006, with temperatures rising above 35 C at many locations during the afternoon hours. The 00 UTC sounding at Calera, AL (about 40 km south of downtown Birmingham) is shown in Figure 3. Note the well-mixed adiabatic layer, with almost constant water vapor mixing ratio, roughly from the surface up to 750 hPa, or about 2500 m MSL). The lifted condensation level (LCL) (768 hPa), very close to the level of free convection (LFC) (751 hPa), are both rather high for the southeastern United States in Summer, due to hot temperatures and the deep mixed layer. The CAPE is modest at about 850 J kg^{-1}, but supportive of deep, moist convection if low-level parcels may be lifted to the rather elevated LFC.

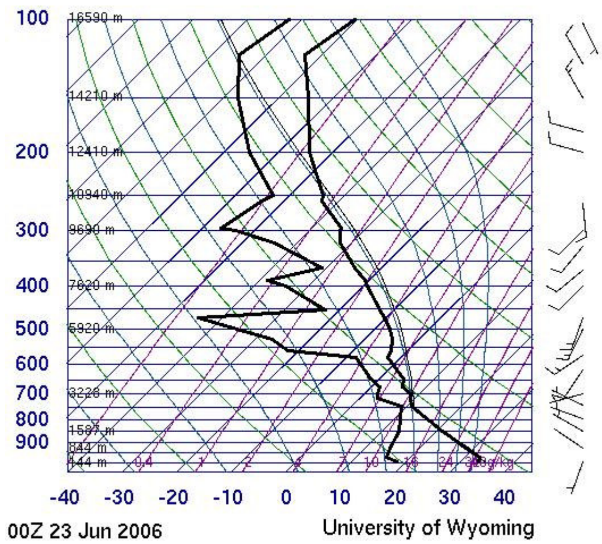

Figure 3. 00 UTC 23 June 2006 sounding at Calera, AL.

4.2 *Nearby convection*

Numerous convective cells formed into a fairly disorganized mesoscale convective system over east Alabama between 21 and 23 UTC.

Cells in east-central Alabama produced one outflow boundary, which propagated west after 23 UTC, but seemed to dissipate as it approached the Birmingham area, perhaps due to the fact that it had traveled over 50 km at that point and much of its cold pool had already spread out.

An additional outflow boundary was produced by cells in northeast Alabama, which traveled southwest toward Birmingham. The BMX (Birmingham) WSR-88D radar began to detect the outflow boundary as a fine line at low elevation scans by 2330 UTC, moving toward the southwest around 11.4 m s^{-1}.

4.3 *The urban heat island*

By late afternoon, a fairly intense heat island formed over the Birmingham area, especially near downtown. This heat island is somewhat discernable on GOES infrared satellite imagery (Figure 4), and shows up in surface temperature observations (Figure 5). Notice the temperature of 36 C at Birmingham International Airport, with temperatures at most surrounding locations between 31 and 34 C.

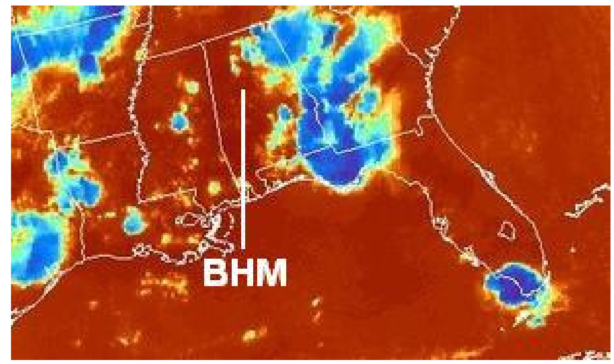

Figure 4. GOES infrared satellite image at 00 UTC 23 Jun 06. Note apparent maximum in brightness temperature near Birmingham. (NCAR)

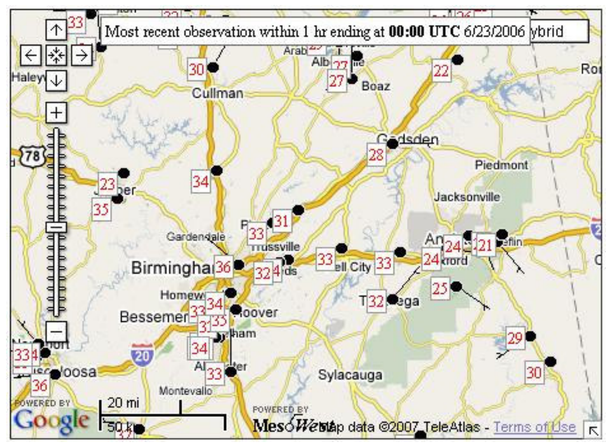

Figure 5. Observed surface temperatures at 00 UTC.

5. CONVECTIVE INITIATION AND OUTFLOW BOUNDARY INTERACTION

Around 0015 UTC, a cross-section of reflectivity from the WSR-88D radar at azimuth 10 degrees indicates an elevated convective cell at a range of about 45 km, or over the eastern suburbs of Birmingham (see Figure 6). Most of the precipitation associated with this convection is between 4 and 9 km AGL, consistent with a new updraft and the high LCL. Reflectivities in the storm are below 40 dBZ. Since the low-level flow is extremely weak and from the northwest, this convection could be due to the urban heat island.

Meanwhile, the outflow boundary from earlier convection is approaching from the NE. As it passes Springville, AL (about 35 km northeast of the convective cell) just after 2330 UTC, winds pick up and shift from NW to the ESE (indicating convergence), the temperature drops, and *the dewpoint rises by 1.5 degrees* (see Figure 7).

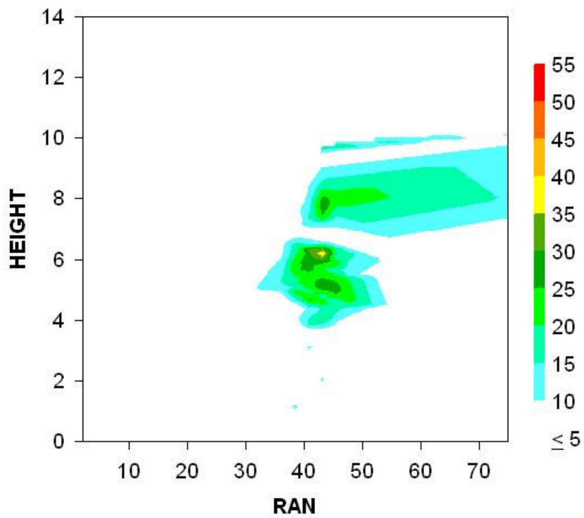

Figure 6. Reflectivity cross-section from KBMX radar at 10 degrees azimuth, 0015 UTC.

The outflow boundary interacts with the convective cell around 0028 UTC. Immediately after the intersection with the outflow boundary, the cell intensifies, with reflectivities above 45 dBZ at 11 km AGL, and heavy rain reaching the surface by 0032 UTC (see Figure 8).

The rapid intensification of the thunderstorm upon interaction with the outflow boundary is also very clear in constant-elevation radar reflectivity images. In Figure 9, a series of 0.5 degree elevation radar images from 0000 through 0041 UTC, the outflow boundary can clearly be seen as a fine line moving into Jefferson County, Alabama (the county containing

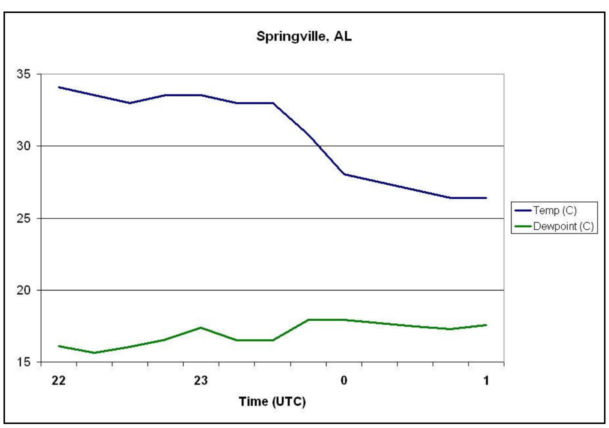

Figure 7. Temperature (blue) and dewpoint (green) (in degrees C) from Springville, AL. Note the drop in temperature at rise in dewpoint with passage of the outflow boundary just after 2330 UTC.

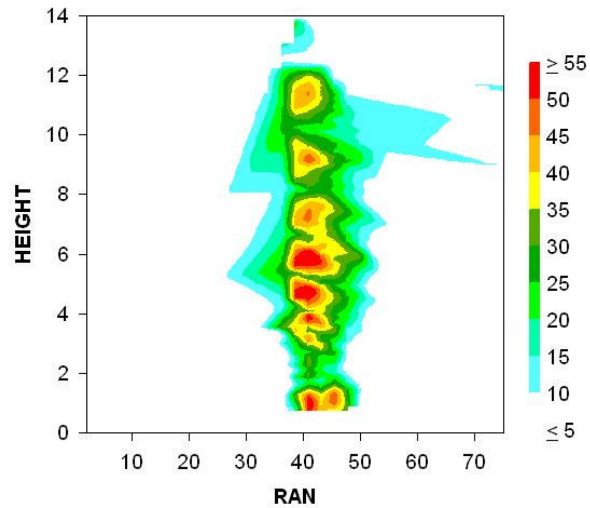

Figure 8. Reflectivity cross-section from KBMX at 10 degrees azimuth, 0032 UTC.

Birmingham) from the NE. One can see weak low-level indications of the convective cell through 0024 UTC, and then the rapid intensification of the cell at low-levels between 0028 and 0041 UTC.

6. DISCUSSION

This case illustrates an interesting interaction between a weak convective cell, apparently due to the urban heat island, and an outflow boundary from other storms. It is difficult to say that convective initiation occurred entirely due to the interaction of the two, since a weak, elevated cell existed before the boundary intersected it. There are several possibilities explaining why the convection intensified so rapidly upon interaction with the outflow boundary. It could be that a new convective cell developed to the northeast of the initial cell, where the outflow first interacted with the urban heat island. It is also possible that, given the high LCL and LFC in the environment, and the fact that the convection was initially elevated, that the increase in dewpoint behind the boundary lowered the LCL, aiding in the rapid development. Also, convergence ahead of the outflow boundary could have enhanced upward motion in the storm. It is unclear which of these mechanisms played a role here, and further examination of this case is required.

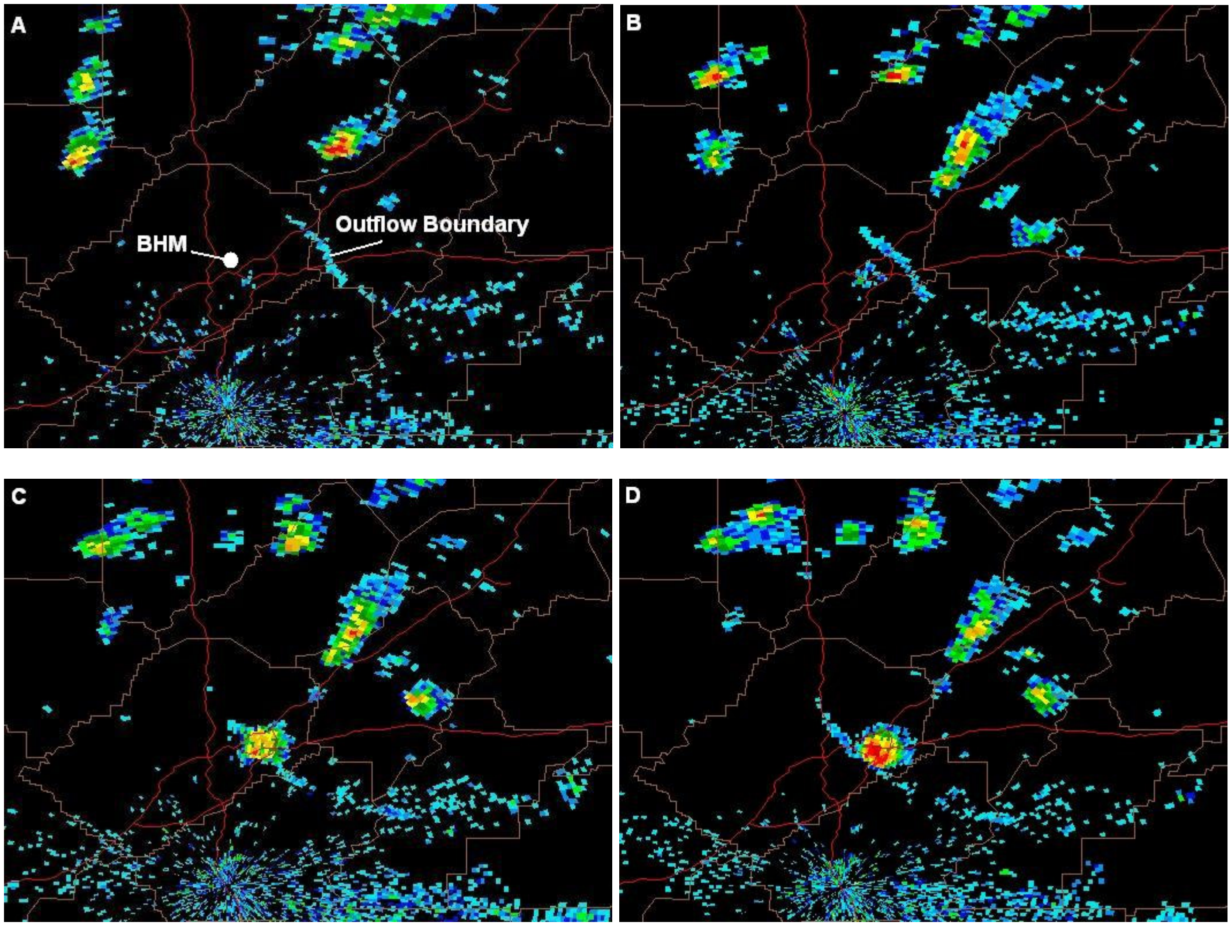

Figure 9. 0.5 degree elevation reflectivity from KBMX WSR-88D radar at a) 0000 UTC; b) 0020 UTC; c) 0032 UTC; and d) 0041 UTC.

REFERENCES

Ackerman, S., 2006: Urban heat island. Educational module. URL: http://cimss.ssec.wisc.edu/wxwise/heatisl.html

Baik, J. –J., Y. –H. Kim, and H. –Y. Chun, 2001: Dry and moist convection formed by an urban heat island. *J. Appl. Meteor.*, **40**, 1462-1475.

Bornstein, R. D., and Q. Lin, 2000: Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmos. Environ.*, **34**, 507–516.

Changnon, S. A., 1968: The La Porte anomaly: Fact or fiction? *Bull. Amer. Meteor. Soc.*, **49**, 4–11.

Changnon, S. A., R. T. Shealy, and R. W. Scott, 1991: Precipitation changes in fall, winter, and spring caused by St. Louis. *J. Appl. Meteor.*, **30**, 126–134.

DeMarrais, G. A., 1961: Vertical temperature difference observed over an urban area. Bull Amer Meteor Soc., 42, 548-554.

Duckworth, F. S., and J. S. Sandberg, 1954: The effect of cities on horizontal and vertical temperature gradients. Bull Amer Meteor Soc., 35, 198-207.

Lin, Y. –L., and R. B. Smith, 1986: Transient dynamics of airflow near a local heat source. J. Atmos Sci., 43, 40-49.

National Weather Service, 2006: Storm Data.

Pielke, R. A., and M. Segal, 1986: Mesoscale circulations forced by differential terrain heating. In Mesoscale Meteorology and Forecasting, P. S. Ray, ed., 793 pp.

Pooler, F. P., 1963: Airflow over a city in terrain of moderate relief. *J. Appl. Meteor.*, **2**, 446-456.

Seitter, K. L., 1986: A numerical study of atmospheric density current motion including the effects of condensation. J. Atmos. Sci., 43, 3068-3076.

Simpson, J. E., 1997: Gravity currents in the environment and the laboratory. 2nd ed. 244 pp.