Analysis of Summertime Convective Initiation in Central Alabama Using the Land Information System

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1. Introduction

Forecasting afternoon thunderstorms during the summer months in the southeastern United States is a challenge for operational forecasters. Thunderstorm development during the summer months has been often referred to as "random" because atmospheric forcing mechanisms can be difficult to detect via satellite or radar when no significant synoptic features are present. A previous study in North Carolina (Koch and Ray 1997) identified many boundaries and convergence zones that led to convective initiation (CI). However, even with knowledge of these boundaries, there are still challenges in determining the precise locations of CI.

Goggins et al. (2010) previously studied summer convection over central Alabama to identify boundaries that led to CI during the summer of 2009. Radar data was the principal tool used for boundary identification and 1200 UTC soundings were used to determine the amount of instability present in the early morning conditions. Once these boundaries were identified, they were classified using methods from Koch and Ray (1997). About 20 percent of CI events could not be associated with an identifiable outflow, mesoscale, or synoptic boundary. Goggins et al. (2010) theorized that these areas of convection created by unknown causes could be the result of land and soil characteristics, with the biggest influence possibly coming from soil moisture.

Soil moisture depends upon several factors, including antecedent precipitation, surface conditions, the composition of soil, and its capacity to retain moisture. Soils may heat differently due to their disparate heat capacities (differential heating), which also varies with water content. Eltahir (1998) described how the net energy flux from the surface into the atmosphere increases over a moist soil compared to a dry soil. These moist soil conditions create a positive feedback between soil moisture and subsequent rainfall. As soil moistens, it increases the net radiation and total heat flux into the atmosphere. In addition, the boundary layer and cloud base heights are lowered due to lower surface skin temperatures and higher atmospheric moisture content over moist soils. This favors more precipitation, further enhancing the moisture content of the soil, thus repeating the cycle.

Vegetation aids the transfer of this moisture to and from the atmosphere through evapotranspiration and absorption (Pielke 2001). The horizontal heterogeneity of heat and moisture fluxes, brought about by contrasting land characteristics, may contribute to the mesoscale processes in the atmosphere by altering the surface fluxes. This can create areas of convergence or locally stronger updrafts favoring CI. Once storms have initiated, they create outflow boundaries that can lead to the development of additional storms.

With the use of 1-km grid resolution output from the NASA Land Information System (LIS; Kumar et al. 2006, 2007), and the theories described above, we attempt to classify and explain the unidentified CI events from summer 2009. The LIS is a land surface modeling system that provides high-resolution output of soil moisture, heat fluxes, etc. from a land surface model integration driven by atmospheric analyses and observations. Figure 1 gives a visual representation of the parameters and processes that are integrated to run the Noah land surface model within LIS (Ek et al. 2003). These non-standard fields can help give insight into how some mesoscale boundaries, related to CI, may be generated.

The soil types (STYP) and vegetation types (VTYP) in Alabama exhibit considerable horizontal variability. Figure 2 shows the State Soil Geographic Database classification of STYP and the United States Geological Survey classification of VTYP throughout Alabama, as used within LIS. One area of interest is the Black Belt, located in west-central and southern Alabama. This region consists mostly of clay soils and a mixture of crops and forests, which have very different characteristics than surrounding locations. These discontinuities in land surface properties lead to differential heating rates that can affect CI.

The main focus of this paper is to examine "random" convective events around central Alabama, specifically in the county warning area of the National Weather Service Office in Birmingham, Alabama (NWS BMX), during the summer months of 2009 (June through August). Another focus is to examine how specific land characteristics can influence areas of convection. The findings in this study will help to supplement the results presented in Goggins et al. (2010).

2. Methodology

An analysis is done on selected case dates throughout the summer months of 2009. During these days, the project focuses on the hours of 0900 to 2100 UTC to observe the effects of diurnal heating on the distribution of heat fluxes. Radar data are analyzed at 5-minute intervals to find the exact time and location of CI. This location is noted and then compared to soil characteristics within the LIS products in central Alabama.

Days in which CI was associated with synoptic forcing have been omitted from this study in order to identify convection that occurred under weak atmospheric forcing. These omissions are made by consulting both upper-air and surface maps and noting areas of synoptic boundaries where CI is most likely due to strong, surface based, atmospheric forcing. This will focus the analysis on the days of greatest interest to NWS BMX, where thunderstorms seemed to be "random" and the influence of soil moisture and differential heat fluxes may be significant. Once a "random" storm has formed, it can create others via outflow boundaries which can be identified by a forecaster with satellite and radar observations. Therefore, by identifying the likely location of the first storms of the day, forecasters can anticipate subsequent storm development.

In order to correlate soil characteristics and the initiation of these storms, various LIS products are utilized. These include latent heat flux (LHFX), sensible heat flux (SHFX), 0–10 and 40–100 cm layer volumetric soil moisture content (SMC), soil type, vegetation type, relative soil moisture (RSM), and surface skin temperature (TSKIN). These parameters are analyzed to note patterns between surface fluxes, soil types, vegetation types, and areas of CI. A goal is to help operational forecasters integrate the LIS variables into their daily operational duties to help create a more accurate forecast for the public.

3. Results

a) 1 June 2009

During the hours of 0900 to 1900 UTC on 1 June, radar coverage in Alabama was void of convection. A surface analysis at 2000 UTC did not indicate any significant mesoscale or synoptic features of interest. Satellite imagery in Figure 3 showed only scattered clouds during the day in central Alabama, leading to substantial diurnal heating. Figure 4 represents a sea-level pressure analysis at 2000 UTC. A high pressure system off the Atlantic coast contributed to an east – southeasterly surface flow across the region, advecting ample moisture from the Gulf of Mexico and the Atlantic Ocean. The 500-mb analysis in Figure 5 also shows weak synoptic forcing across the southeastern United States.

CI began at approximately 2015 UTC over Birmingham, AL (Figure 6). There were no other areas of convection within a 100-km radius of this storm, making this convection uninfluenced by mesoscale outflow boundaries or synoptic features. Figure 7 shows the LIS parameter of interest for this case, TSKIN, at 2000 UTC. This parameter is highlighted in this case due to the potential correlation to the "urban heat island" effect. Convection formed slightly north of the maximum TSKIN, probably due to the southeasterly flow over Birmingham advecting air parcels northwestward.

Around the Birmingham metro area, a peak TSKIN value between 44°–46°C is seen at 2000 UTC. This peak temperature is due to the low concentration of vegetation and moisture sources that contribute to low LHFX in urban areas. Rural areas consist of more vegetation and moisture sources to create higher LHFX, lower SHFX, and lower TSKIN. The peak TSKIN value occurs because of the heat flux partitioning favoring SHFX over urban corridors.

An increased area of dry 0-10 SMC is seen over Birmingham along with a gradient towards wetter soil outside the Birmingham metro area (Figure 8). On 1 June, SMC percentage decreases from 30–33% in the rural areas to 18–21% within the Birmingham city limits. Air parcels upwind of Birmingham likely gained moisture from the increased LHFX found in the rural areas. These parcels then experienced the strong heating of the Birmingham urban corridor and were then able to reach their convective condensation level (CCL) which enabled CI at 2015 UTC.

b) 7 July 2009

Radar in the central Alabama region showed no convection occurring between 0900 and 1800 UTC. Surface data and radar images depict a large stationary front in extreme southern Alabama and Georgia throughout much of the day. Figure 9 depicts this feature across the extreme southeastern United States in sea level pressure. This created a north to northeasterly surface flow in central Alabama. Satellite imagery in Figure 10 shows that central and northern Alabama received adequate solar heating throughout the day with only scattered cloud cover, causing the increased skin temperatures prior to CI in central Alabama (Figure 11a).

NWS BMX noted an unknown stationary boundary on their surface analysis, unrelated to the previously-stated boundary, stretching over the Birmingham metro area at 2000 UTC. This boundary can be seen in Figure 10 on satellite imagery, but does not show up in the surface analysis in Figure 9. CI occurs along this boundary at 2000 UTC and movement of these storms is slow. This unknown boundary is hypothesized to be caused by land surface gradients depicted by the LIS output.

The LIS output field of interest to this case is the RSM. RSM is calculated by taking a ratio between the SMC and the saturation point of the soil, as shown in Eq. (1),

$$\boldsymbol{RSM = \frac{SMC - SMC_{wilt}}{SMC_{sat} - SMC_{wilt}}}, \qquad (\mathbf{1})$$

where SMC_{sat} is the SMC at saturation for a given soil type (i.e. field capacity), and SMC_{wilt} is the SMC wilting point for a given soil type. This field represents how much moisture is available to vegetation that can be transpired to the atmosphere. The amount of moisture available will then affect the partitioning of LHFX and SHFX.

Figure 11b shows the RSM across central and northern Alabama on 7 July. The unknown boundary sets up directly along the axis of lowest RSM in central Alabama. This may have led to atmospheric forcing similar to sea-breeze circulations where the warm, dry soil over central Alabama acts as land, while the cool, wet soil in the rural areas acts as water. This would cause winds at the surface to converge over the area of drier soil, creating the unknown boundary and CI observed at 2000 UTC.

c) 14 August, 2009

Clear skies were found over much of central Alabama during the morning hours of 14 August. Radar in central Alabama was void of convection until 1630 UTC. Diurnal heating was significant during this day, which led to high skin temperatures and ample amounts of SHFX coming from the surface. TSKIN values observed in the suburban and rural areas during the afternoon of 14 August were higher than those observed on 1 June. This increase in TSKIN was likely due to the drier 0–10 cm layer SMC observed on 14 August (Figure 8b).

Figure 12 illustrates high pressure dominating the southeastern United States, with average sea level pressures of 1018 mb and no significant synoptic features present. Winds were light out of the southeast, bringing in moisture from the Atlantic Ocean and Gulf of Mexico. These features combined to create weak atmospheric forcing and a good opportunity to observe potential convective influence by land characteristics.

CI occurred at 1800 UTC just northwest of Birmingham. Figure 13 shows TSKIN in the Birmingham metro at 1800 UTC with a maximum temperature between 44°–46°C. As mentioned before, the suburban and rural areas of Birmingham reach slightly higher TSKIN values (~40°–42°C) than 1 June. SHFX values were also higher in the rural areas due to the higher TSKIN values. Winds out of the southeast move parcels across the urban area and may have helped to initiate the convection northwest of Birmingham.

With similar synoptic conditions on both dates, it is interesting to note some of the features that correspond to both dates. CI occurred over the Birmingham metro area in the presence of southeasterly flow advecting ample moisture. Downwind of this flow, a stronger storm formed in northwestern Jefferson County after CI. Figure 14 is a comparison of 1 June at 2215 UTC and 14 August at 2015 UTC, approximately 2 hours CI on each date. Given the similarity of these events, other scenarios should be studied to document the effects of other flow regimes on CI over the Birmingham urban heat island.

d) 15 August 2009

For the case of 15 August, the focus is on the corridor of clay-type soils in west-central and southern Alabama, also known as the Black Belt. As the summer of 2009 progressed, the RSM decreased, particularly in the Black Belt, by about 15–20 percent. These dryer soils create lower values of LHFX and higher values of SHFX which can inhibit convection, based on the feedback processes described in Eltahir (1998).

The synoptic conditions on 15 August were similar to the previous case on 14 August. Scattered clouds throughout the day created a good opportunity for diurnal heating to occur. As temperatures rose, net energy flux from the surface increased creating more favorable conditions for convection to occur. CI began at 1800 UTC throughout much of the central Alabama region. Numerous small storms moved from southeast to northwest with the atmospheric flow. Most of these storms were weak and short-lived. Figure 15 shows that, as time progresses, storms became scattered across much of central Alabama. The white outline shown on Figure 15 depicts the approximate location of the Black Belt. This figure shows that storms generally occurred around the boundaries of the Black Belt, but convection was mostly void within those boundaries. Throughout the day, storms that entered this boundary dissipated rapidly within 30 minutes of entry.

There are a number of possible factors that could cause the lack of convection within the Black Belt. According to Eltahir (1998),the total energy flux into the boundary layer is decreased above a drier soil. However, not only is the total energy flux decreased, but the partitioning of LHFX and SHFX is different than that of moist soil. Figure 16 shows the LHFX and SHFX over central Alabama around the time of CI. Regions covered by the Black Belt with clay soil experience lower LHFX values of 50–150 W m^{-2} and pockets of SHFX that are increased by 50–100 W m^{-2}.

These differences in heat fluxes create a slightly different environment in the Black Belt, possibly leading to a stabilization of the atmosphere that could prevent storms from initiating and/or cause dissipation upon entry. The higher TSKIN values within the Black Belt (Figure 17) are expected to increase the height of the boundary layer, making cloud development more difficult over the Black Belt. The increased height of the boundary layer can create a barrier for weaker storms to sustain themselves, as well as inhibiting their ability to initiate over the Black Belt.

4. Conclusions and Future Work

This paper presented a study in which land surface model output from LIS is used to help explain CI events over Alabama during weak synoptic forcing. In the cases of 1 June and 14 August 2009, LIS showed the effect of increased sensible heat flux from urban heat islands on downwind convection. On these dates, convection was favored at skin temperatures in urban areas greater than or equal to 44 °C. It is also important for forecasters to note the gradient of TSKIN from rural to urban areas, as this can also play a role in CI. For these case dates, the TSKIN gradients were on the order of 6–8 °C, creating more positive buoyancy over urban areas. Outside the Birmingham corridor, where SMC was higher, the flux of moisture from the soil was greater. Once these moist air parcels traveled over Birmingham, the increased buoyancy due to the high TSKIN values caused them to reach their CCL and CI then occurred slightly downwind of Birmingham.

Land surface gradients were shown to play a role in the 7 July case. Differences in RSM led to differential heating, which may have created a solenoidal-type circulation across central Alabama leading to a convergent boundary and CI. The 15 August case showed of how the soils of the Black Belt region can create locally more stable conditions. As the Black Belt soils became drier during the summer, there was an increased partitioning of SHFX compared to earlier in the summer which helped to prevent weak showers from forming in these regions.

More research is needed to see the impacts of the Black Belt on stronger convection.

Future research will focus on transitioning LIS products into operational forecasting by demonstrating how to utilize LIS to make more accurate forecasts. More case studies should be analyzed to find patterns in LIS fields that correspond to areas of CI. These fields can be used not only in Alabama, but across the southeastern United States where summertime CI can be a significant forecasting challenge.

5. Acknowledgements

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An additional acknowledgement is given to the National Mosaic and Multi-sensor QPE Composite Radar Reflectivity for providing radar and satellite images of the summer of 2009, and to Plymouth State University for providing an archive of surface and upper-air weather maps for the summer of 2009. Special thanks to Michelle Cipullo, Danielle Kozlowski, and Jessica Showers for their collaborative efforts and inputs into the methods and results of this project.

6. References

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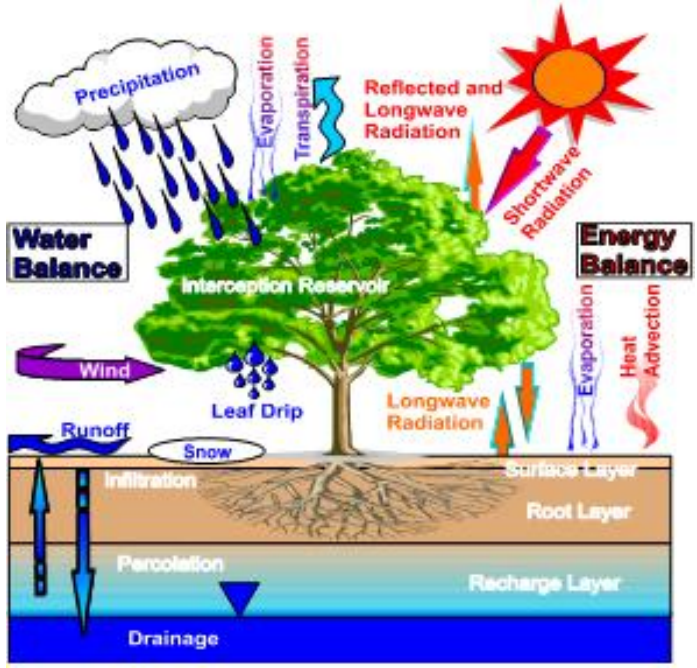

Figure 1. Visual representation of variables integrated within LIS.

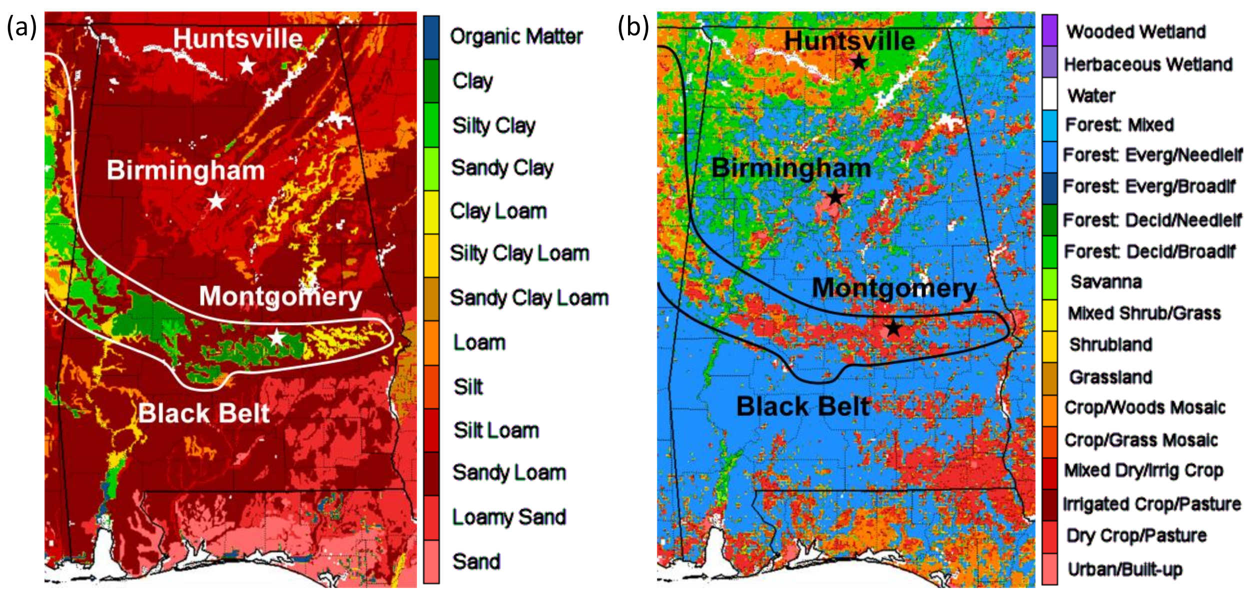

Figure 2. Comparison of (a) STYP and (b) VTYP in Alabama as depicted within LIS.

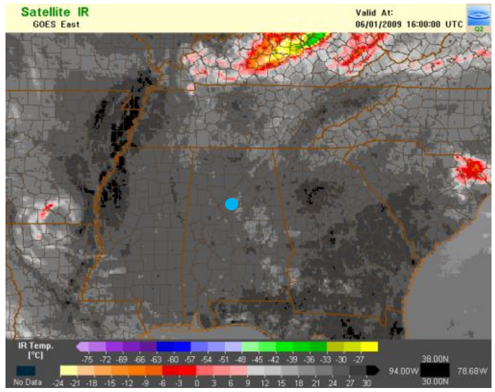

Figure 3. Satellite IR at 1600 UTC on 1 June 2009, depicting scattered clouds over central Alabama. Birmingham is denoted by the blue dot. (Image taken from the National Mosaic & Multi-sensor QPE Satellite Infrared)

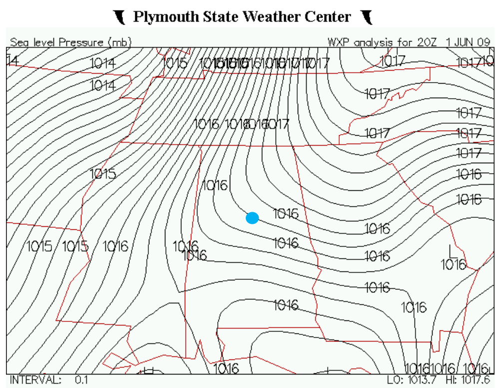

Figure 4. Sea level pressure (contours of 0.1 mb) at 2000 UTC 1 June 2009. Birmingham is denoted by the blue dot. (Image taken from the Plymouth State Weather Center)

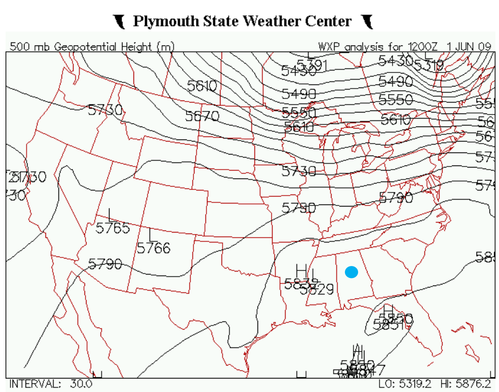

Figure 5. Geopotential Heights at 500 mb (contours of 30 dm) at 1200 UTC 1 June 2009. Birmingham is denoted by the blue dot. (Image taken from the Plymouth State Weather Center)

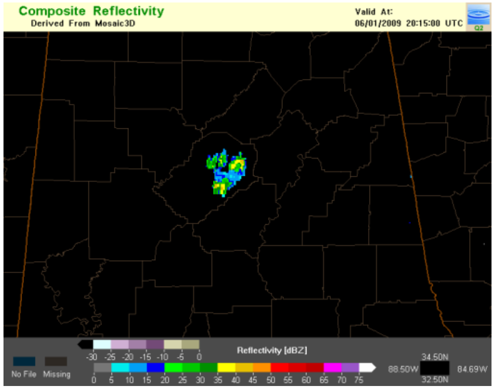

Figure 6. Composite Reflectivity at 2015 UTC June 1st, 2009, near Birmingham, AL. (Image taken from the National Mosaic & Multi-sensor QPE Composite Radar Reflectivity)

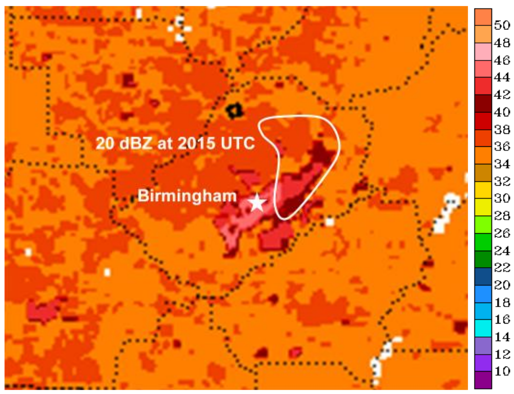

Figure 7. TSKIN (°C) near Birmingham, AL at 2000 UTC 1 June 2009. White outline shows approximate location of convective initiation at 2015 UTC.

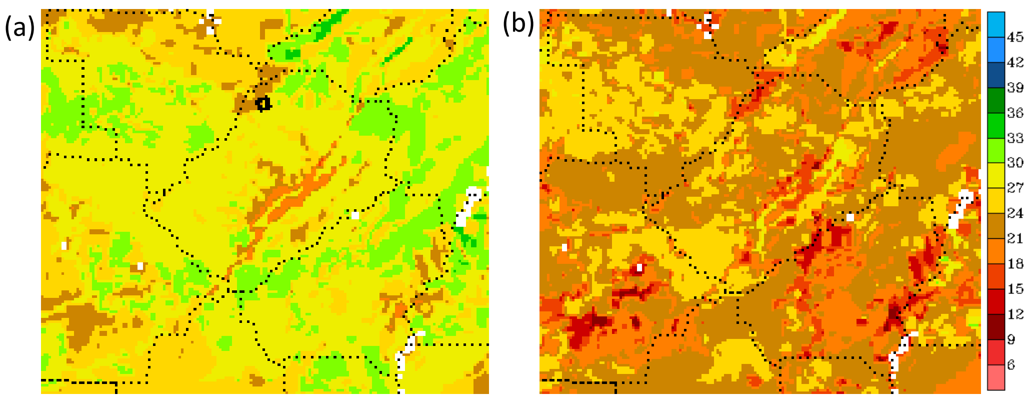

Figure 8. Comparison of 0-10 cm layer SMC around Birmingham, AL at (a) 2000 UTC 1 June 2009 and (b) 1800 UTC 14 August 2009. (Units are percent of soil volume occupied by water)

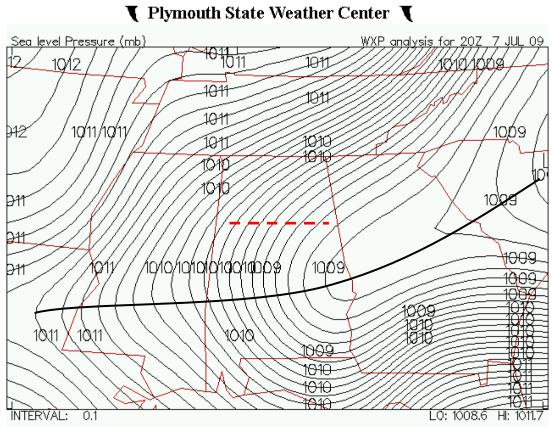

Figure 9. Mean sea level pressure (contours of 0.1 mb) at 2000 UTC 7 July 2009. Solid black line represents synoptic front, red dashed line represents the unknown boundary; both identified by NWS BMX at 2000 UTC 7 July 2009. (Image taken from the Plymouth State Weather Center)

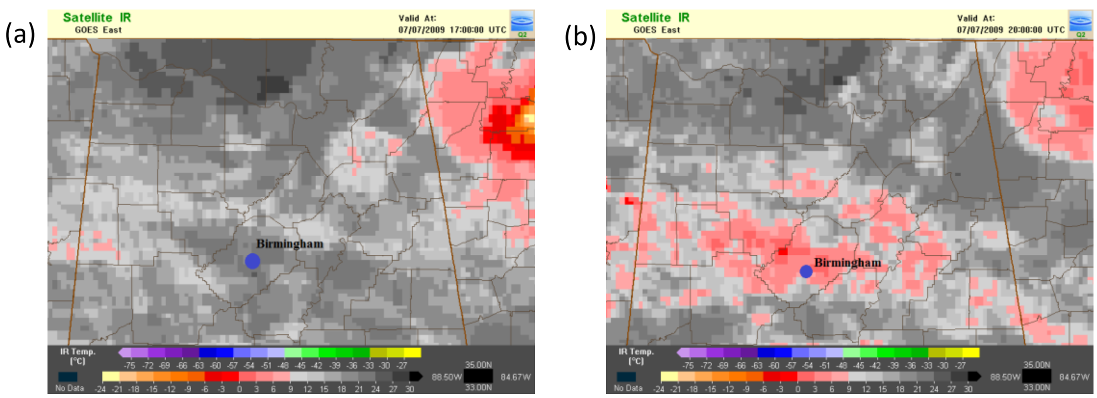

Figure 10. Satellite IR at (a) 1700 and (b) 2000 UTC 7 July 2009, depicting scattered clouds during the day leading to convection developing in a west to east orientation in central Alabama (denoted by the colder cloud tops in color shading). (Image taken from the National Mosaic & Multi-sensor QPE Satellite Infrared)

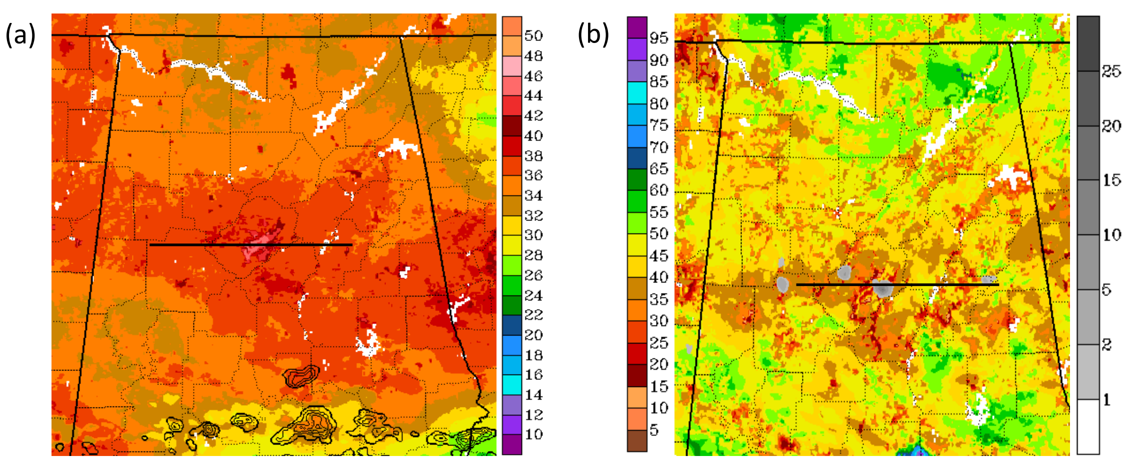

Figure 11. Comparison of (a) TSKIN (°C) at 1900 UTC and (b) 0-10 cm layer RSM (colored units in percent saturated, gray-scaled units of precipitation in mm h^{-1}) at 2000 UTC 7 July 2009 in central and northern Alabama. Black line depicts approximate location of unknown boundary identified at 2000 UTC by NWS BMX.

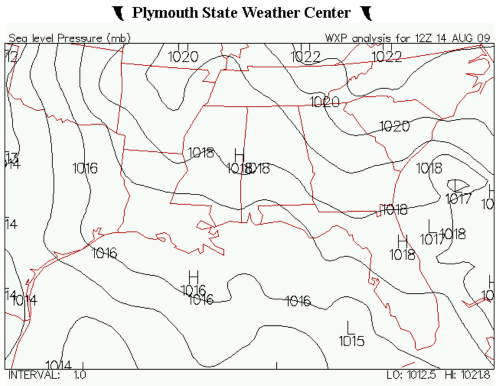

Figure 12. Mean sea level pressure (contours of 1 mb) at 1200 UTC 14 August 2009. (Image taken from the Plymouth State Weather Center)

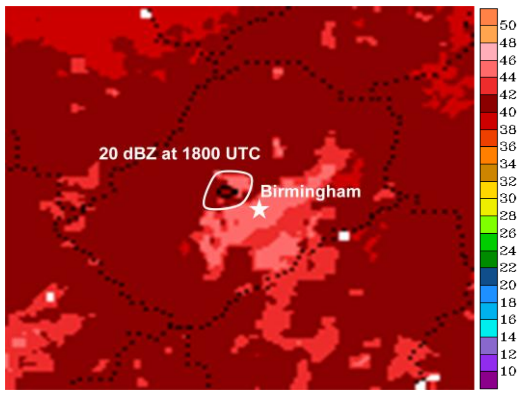

Figure 13. TSKIN (°C) near Birmingham, AL at 1800 UTC 14 August 2009. White outline shows approximate location of CI at 1800 UTC.

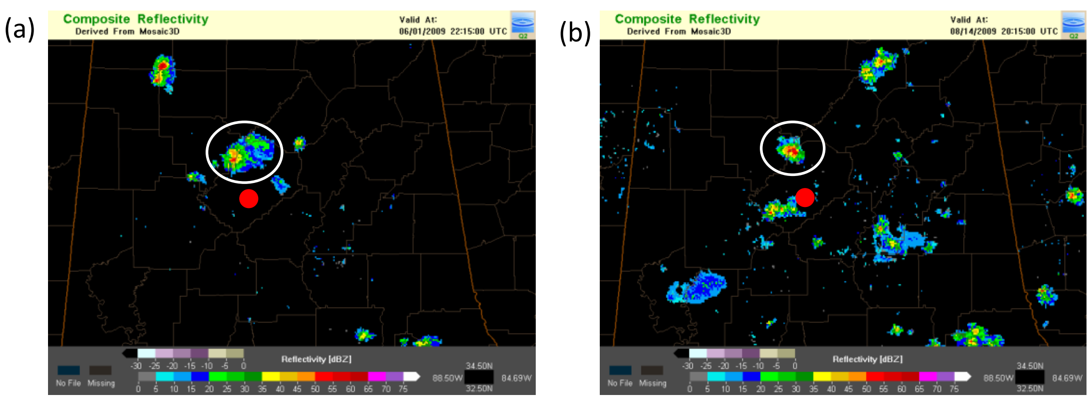

Figure 14. Comparison of composite radar at (a) 2215 UTC 1 June 2009 and (b) 2015 UTC 14 August 2009. Birmingham, AL is denoted by red dot. (Image taken from the National Mosaic & Multi-sensor QPE Composite Radar Reflectivity.)

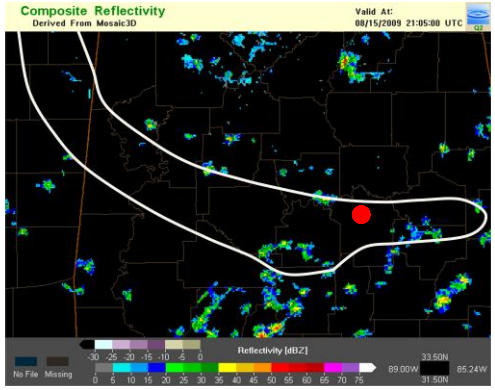

Figure 15. Composite radar at 2105 UTC 15 August 2009. White outline depicts approximate area of the Black Belt. Montgomery, AL denoted by red dot. (Image taken from the National Mosaic & Multi-sensor QPE Composite Radar Reflectivity.)

(a) (b)

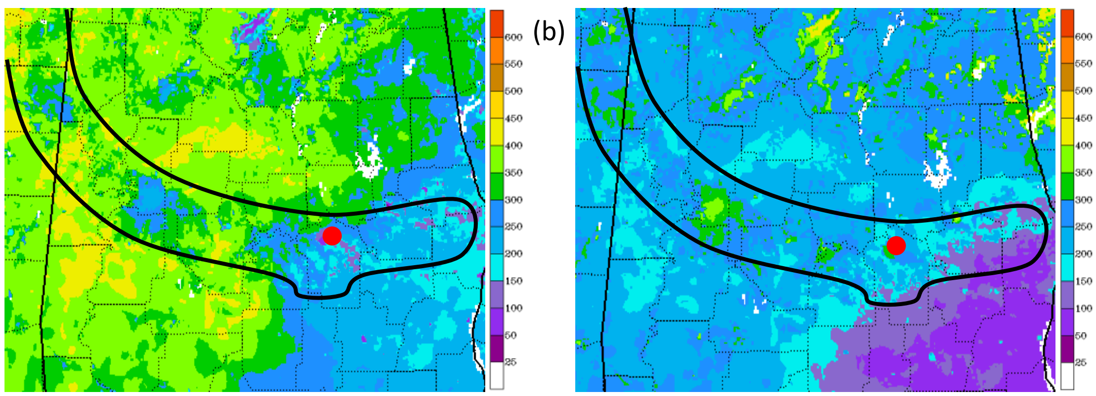

Figure 16. Comparison of (a) LHFX and (b) SHFX in central AL at 1800 UTC 15 August 2009. (Units of W m^{-2}) Montgomery is denoted by the red dot. Black outline indicates approximate location of the Black Belt.

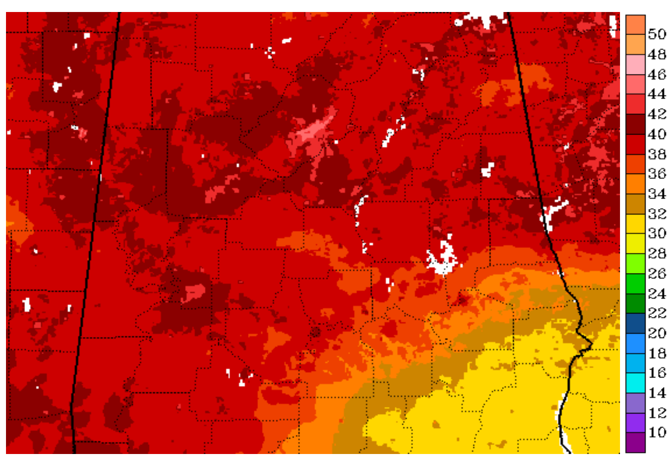

Figure 17. TSKIN (°C) in central Alabama at 1800 UTC 15 August 2009.