Urban Flash Flooding in Downtown Madison, WI and Southern Wisconsin, 27 July 2006

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Abstract

The afternoon hours of 27 July 2006 proved to be quite an eventful one as torrential rains drenched the downtown area of Madison, WI with 3 to 5 inches of rain within a 90-minute time frame, causing damage to almost every building on the University of Wisconsin-Madison campus. This case study sought to determine the synoptic and mesoscale forcings that set up and sustained the heavy rainfall that led to flash flood conditions. It was hypothesized that the flash flooding was caused by multicellular convective cells that moved roughly parallel to a slow-moving or stationary surface frontal boundary and was sustained by a warm, moist low-level southerly flow, allowing the rainfall to be focused over one particular area and causing localized flash flooding. Additionally, it was suspected that the forcing mechanisms primarily responsible were surface and low-level forcings, including daytime heating as a mesoscale forcing, because upper-level forcings such as jet maximums are typically rare during the summer months when the jet stream retracts further north. In the end, this hypothesis was supported by the data provided in the synoptic and mesoscale analyses. The storm system of interest did consist of multicellular convective cells that traversed along a stationary frontal boundary and was sustained by warm, moist low-level southerly flow. It was also determined that the synoptic convective forcings were provided by the stationary surface frontal boundary in addition to cooling in the mid-levels of the atmosphere, while the mesoscale forcing was provided by daytime heating. As expected, there was also no upper level forcing due to the lack of presence of a jet maximum. The combination of these forcings along with the moist, southerly flow allowed for deep, moist convection to occur along the surface frontal boundary and led to the observed flash flood conditions

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I. Introduction

The afternoon hours of 27 July 2006 proved to be quite an eventful one, as torrential rains drenched the downtown area of Madison, WI with 3 to 5 inches of rain within a 90-minute time frame. Areas most affected by these heavy rains reached from the west side of Madison to the Capital Square, and almost every building on the University of Wisconsin-Madison campus sustained flood damage[1]. This particular flooding event was later categorized as a "100-year flood." The term "100-year flood" is a statistical designation indicating that a flood of this magnitude has a 1-in-100, or one percent chance, of occurring in any given year.[2] The probability occurrence for such floods is estimated with the use of statistical techniques, through a process called frequency analysis, and is based on the probability that the given event will be equaled or exceeded in any given year.[3]

The cause of flooding is often, if not always, associated with the interaction

[1] NOAA Satellite and Information Service. [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~640572]

[2] USGS. *The "100-Year Flood."* Fact Sheet 229-96. [http://pubs.usgs.gov/fs/FS-229-96/]

[3] USGS. Water Science for Schools. *Floods: Recurrence Intervals and 100-Year Floods.* [http://ga.water.usgs.gov/edu/100yearflood.html]

between meteorological conditions and hydrological conditions.[4] In terms of the meteorological conditions, there are two primary types of flooding that are characteristic of the upper-Midwest region: flash floods and river floods. Flash floods are caused by intense, high to extremely high rainfall rates over a relatively short period of time,[5] while river floods are associated with moderate to high rainfall rates spread over days and sometimes even months.[6] Nonetheless, meteorological conditions play an important, if not primary, role in flood occurrence because they provide the most necessary ingredient: rainfall. As for the hydrological conditions, a given event's chances to produce a flood are dramatically affected by factors such as antecedent precipitation, the size of the drainage basin, the topography of the basin, and the amount of urban use within the basin, to name a few. As land is converted from fields and forested land to roads and parking lots, it loses the majority of its ability to absorb rainfall.[7] Thus, urban areas are more susceptible to floods, particularly flash floods, because a high percentage of the surface area is composed of streets, roofs, parking lots, and other materials that cause runoff to occur very rapidly.[8]

With the given information in the previous paragraphs, the flooding event of 27 July 2006 can easily be categorized as a flash flood. The first indication is the high rainfall amounts in a 90-minute window. This implies a high rainfall rate over a relatively short period of time, a characteristic typical of flash floods as described above. In addition, the hydrological conditions of the Madison area exacerbated the situation and helped lead to flash flood conditions. The hilly terrain and the urban settings of the downtown area and the University of Wisconsin-Madison campus, which contain high amounts of non-absorbing materials such as concrete and asphalt, acted to enable the runoff water to quickly overwhelm the storm sewers and concentrate in the low-lying areas.[9] Thus, both meteorological and hydrological conditions played a role. However, only the meteorological conditions will be explored in depth in this case study.

Interestingly, most flash flood-producing convection is from more or less unremarkable thunderstorms, where multiple convective cells pass over a specific area, with successive cells forming, maturing, and dissipating at about the same location. The result of this process is a quasi-stationary convective rain system. Events such as these have the potential to produce flash flood conditions in two hours or less. However, the typical convective cell only has a lifetime approximately 20 minutes long. It follows then, that any convective storm lasting more than 20 minutes is made up of more than one cell. Thus, if rainfall is able to persist long enough to create flash flood conditions, then the convective storms must be multicellular in character.[10] In this way, a

[4] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.
[5] USGS. Water Science for Schools. *Questions and Answers about Floods*. [http://ga.water.usgs.gov/edu/qafloods.html]
[6] NOAA Satellite and Information Service. [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~640572]
[7] USGS. Water Science for Schools. *Questions and Answers about Floods*. [http://ga.water.usgs.gov/edu/qafloods.html]
[8] USGS. U.S. Department of the Interior. *Significant Floods in the United States During the 20th Century – USGS Measures a Century of Floods.* USGS Fact Sheet 024-00. March 2000. [http://ks.water.usgs.gov/pubs/fact-sheets/fs.024-00.pdf]
[9] NOAA Satellite and Information Service. [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~640572]
[10] Doswell, C.A. June 1993. *Flash Flood-Producing Convective Storms: Current Understanding and*

convective event achieves a relatively long duration, since individual convective cells have lifetimes that are generally too short to produce heavy rainfall even though the individual convective cell rainfall rates can be high.[11] What makes an ordinary thunderstorm dangerous from the standpoint of flash flood potential is when they become quasi-stationary systems. This can arise in several different ways, but the basic elements of the process are the always the same: convective storms form repeatedly in about the same location, following each other in succession, reaching maturity and maximum rainfall rate at about the same location. This series of convective cells results in the so-called "training" effect, which appears as a continuous wave of convective storms as new cells form on the flank of preceding cells, eventually becoming "the storm" as the older cells dissipate.[12] The propagation speed and direction of the convective cells is dependent upon the movement of the individual updrafts themselves. Individual convective updrafts tend to move with a speed and direction roughly comparable to the mean wind in the tropospheric layer containing the updraft; thus, the cells are simply advected along the mean wind flow.[13] Figure 1 shows a schematic that clearly demonstrates this process.

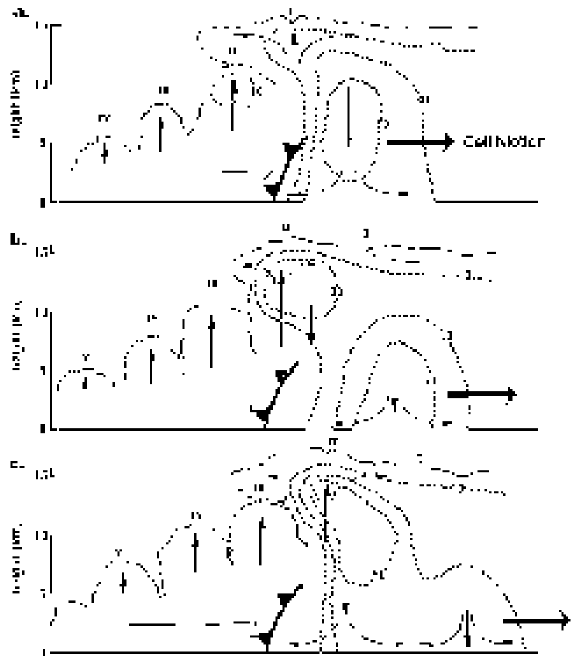

Figure 1: Schematic showing three stages in the evolution of a multicellular thunderstorm system. Cells are labeled with Roman numerals (I, II, III, etc.). The thin arrows indicate the updrafts, downdrafts, and divergence at the storm top and the surface associated with each cell. The frontal symbol indicates the low-level outflow boundary and the heavy arrow indicates the cell motion. The hatched lines show radar reflectivity and are labeled in dBZ. Note that the cells are moving left to right while the frontal boundary remains fixed in place.[14]

An ideal situation leading to flash flood conditions is when the convective cells move roughly parallel to a slow-moving frontal-type boundary, leaving a quasi-stationary segment of the boundary behind into which a substantial moist boundary-relative flow is impinging, creating new cells that repeat the motion of their predecessors and reinforce the boundary,

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Research. Proceedings, Spain-U.S. Joint Workshop on Natural Hazards, Barcelona, Spain, 8-11 June 1993.

[11] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

[12] Doswell, C.A. June 1993. *Flash Flood-Producing Convective Storms: Current Understanding and Research*. Proceedings, Spain-U.S. Joint Workshop on Natural Hazards, Barcelona, Spain, 8-11 June 1993.

[13] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

[14] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581. (Image copied from http://www.cimms.ou.edu/~doswell/Methodology/Methods07.GIF)

maintaining its position against the flow. A system such as this can last for several hours as long as the moist, unstable flow is maintained.[15] In addition, convective storms are associated with the vast majority of flash floods simply because they process large amounts of water vapor in a short time.

Based upon the information presented above with regards to the formation of typical flash flooding events, a general hypothesis of the meteorological conditions that led to the flash flooding event on 27 July 2006 can be formed. Because this event was categorized as a "100-year flood," it is hypothesized that the conditions during this particular event closely follow the ideal conditions for flash flooding as described in the previous paragraph. Thus, it is suspected that multicellular convective cells that moved roughly parallel to a slow-moving or stationary surface frontal boundary caused the flooding event on 27 July 2006 and was sustained by a warm, moist low-level southerly flow, allowing the rainfall to be focused over one particular area and causing localized flash flooding. Additionally, it is suspected that the forcing mechanisms primarily responsible were surface and low-level forcings, including daytime heating as a mesoscale forcing, as upper-level forcings such as jet maximums are typically rare during the summer months when the jet stream retracts further north.

This paper takes an in depth look at the meteorological environment present before the flash flooding event on 27 July 2006, focusing on the setup conditions present at 12Z. In section II, the sources for the surface, upper-air and mesoscale analysis data are discussed. Sections III and IV examine and analyze the synoptic and mesoscale environments, respectively, including a discussion on the forcing mechanisms present at each scale and the implications of their presence on the flash flood event. A conclusion and summary of the findings of this case study is included in Section V.

II. Data

Several data sources were used to complete the analysis for this case study. The synoptic environmental analysis was conducted using data from the Unisys Weather Archive and the Storm Prediction Center (SPC). The Unisys Weather Archive provided a surface analysis map, an infrared satellite image with a resolution of 4 kilometers (km), and a four-panel plot that includes a temperature analysis at 850 mb, a wind analysis at 300 mb, a surface analysis and a relative humidity/lifted index analysis. SPC provided analyses of important variables at the 300, 500, and 925 mb levels of the atmosphere. The mesoscale environmental analysis was carried out using soundings and hodographs from SPC in addition to radar data that was generated by the Global Atmosphere Research Program (GARP) from the Milwaukee radar between 16:02Z and 22:48Z on 27 July 2006. The hand-drawn mesoscale diagram included in the mesoscale environmental analysis compiled important meteorological variables for this particular event, drawn from data provided by SPC. Various other sources were also used to provide supporting information to the synoptic and mesoscale analyses, including fact sheets from United States Geological Survey (USGS) and scientific papers written by C.A. Doswell.

III. Synoptic Environment

There are several key synoptic-scale ingredients for high precipitation rates that can lead to flash flooding. An in-depth look at the synoptic environment previous to the

[15] Doswell, C.A. June 1993. *Flash Flood-Producing Convective Storms: Current Understanding and Research*. Proceedings, Spain-U.S. Joint Workshop on Natural Hazards, Barcelona, Spain, 8-11 June 1993.

27 July 2006 rainfall event can provide valuable insight as to the conditions that led to flash flooding. Several valuable pieces of information can be inferred from the surface analysis plot shown in Figure 2.

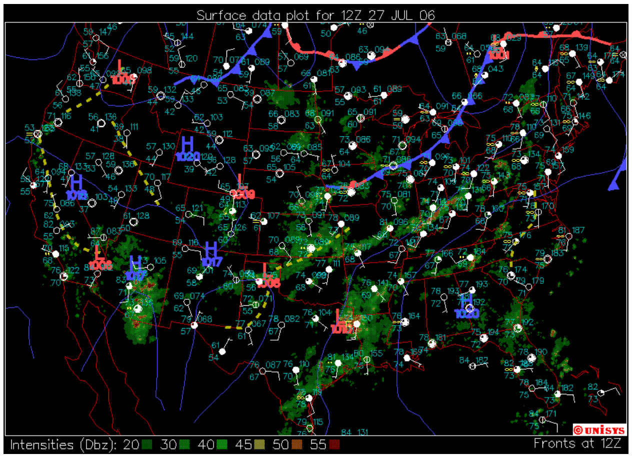

Figure 2: Surface Analysis Plot at 12Z on 27 July 2006. Note the cold frontal boundary draped across the upper Midwest, a typical setup for the summer months, and the beginning of a stationary frontal boundary over central Iowa. As the day progressed, this frontal boundary likely progressed into southern Wisconsin.

This surface plot shows the setup conditions at 12Z before the heavy rainfall event occurred. There is an area of low-pressure centered over Quebec province in Canada, which is connected to a cold front that extends southwest through the lower peninsula of Michigan, through southern Wisconsin and into central Iowa. Note how the cold front drapes directly over Madison, WI, the primary focus area of this case study, the implications of which will be discussed later on. This particular setup is typical during the summer months for the upper Midwest region due to the retraction of the jet stream further north. Often, the tail end of the cold frontal boundary tends to stall in this type of setup, creating a stationary frontal boundary. As can be seen in Figure 2, the early stages of a stationary frontal boundary can be seen over central Iowa. As the day progressed, this stationary frontal boundary extended into southern Wisconsin. As previously mentioned, a stationary frontal boundary is one condition needed for an ideal flash flood situation. This frontal boundary provided one of the dynamical forcing mechanisms that helped initiate and sustain convection over Madison. Additionally, the stationary nature of the frontal boundary helped to concentrate the convection over Madison, aiding in promoting flash flood conditions. Another important factor to note is the wind direction in the vicinity of the frontal boundary. Out ahead of the front, there was southwesterly wind flow, which helped to siphon warmer, moister Gulf-Coast originated air into the southern portions of the state. The high dew points ahead of the front provided further evidence of this moisture influx to the region. Additionally, behind the frontal boundary, westerly winds prevail. Most importantly, though, is the fact that the wind flow on either side of the frontal boundary is roughly parallel to the frontal boundary, and, as mentioned previously, is yet another factor leading to ideal flash flood conditions.

The dynamical forcings provided by the surface frontal boundary and the associated winds can be seen in Figure 3. The cloud cover exhibited in this image paralleled the surface features seen in Figure 2. There was some cloud cover out ahead of the frontal boundary in the Lower Peninsula of Michigan and along the stationary portion of the frontal boundary near the southwest corner of Wisconsin and central Iowa. The cloud cover was indicative of the convective

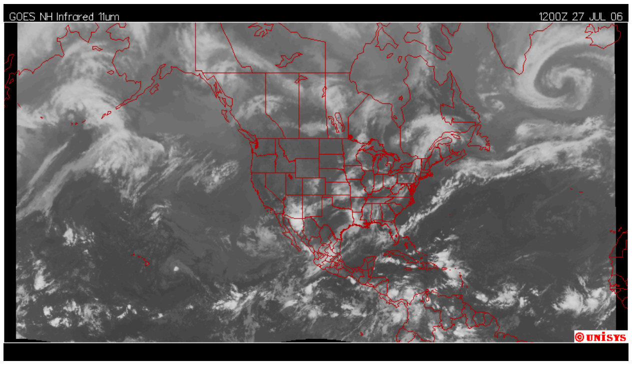

Figure 3: Infrared Satellite Image with a 4 km resolution at 12Z on 27 July 2006. Note the parallels of the features in Figure 2, particularly the cloud cover out ahead of the frontal in Lower Peninsula Michigan and southwest Wisconsin and central Iowa that later traversed over Madison and brought heavy precipitation.

dynamical forcings provided by the stationary frontal boundary, which further developed over Madison later on in the afternoon and brought along heavy rainfall. However, there may be more than surface features that provided additional forcing for convection in this case, particularly in the upper levels of the atmosphere.

Upper-level variables also have the potential to provide dynamical forcings that promote and sustain convection and help lead to flash flood conditions. Figure 4 is a four-panel plot that showcases several important upper-level variables that provide some insight to causes of the 27 July 2006 flash flood event. The upper-left image shows the 850 mb temperatures. However, it doesn't appear that temperature advection plays a major role in this particular case since the 850 mb winds are very weak. At the 300 mb level, shown in the upper-right image, there is a relatively higher region of wind speeds over the upper Midwest, but note the lack of presence of any jet maximum. This is typical for summer months, when the jet stream has retracted further north. Thus, it appears that the upper-levels of the atmosphere do not provide a direct dynamical forcing for this particular case. However, one important aspect to note about the winds at the 300 mb level is that the flow is purely zonal over the Upper Midwest. This purely zonal flow at the upper levels may help to provide

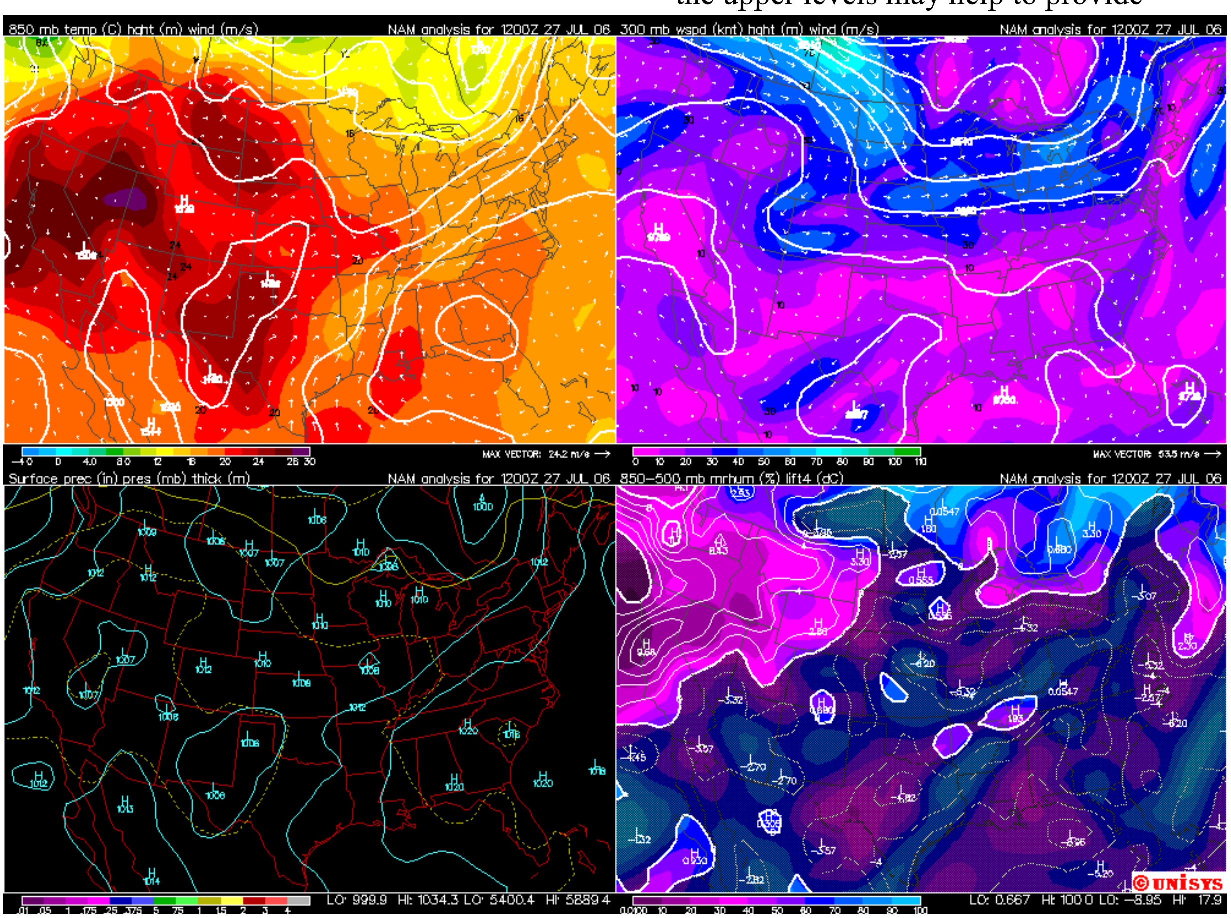

Figure 4: Four-panel plot at 12Z on 27 July 2006. The upper-left image shows the 850 mb temperatures. The upper-right image shows 300 mb winds. The lower-left image is a surface analysis. The lower-right image shows relative humidities (shaded regions) and lifted indices (negative indices are demarcated by the hatched region).

steering winds for deep convection, causing the storms to travel directly along the stationary frontal boundary that stretches from west to east across Southern Wisconsin. This detail will become important when the lower-level winds are discussed in more detail in the mesoscale environment section and the implications will be discussed then. Another interesting, and potentially important aspect to note is the positively tilted trough in the height lines in the 300 mb image. This variable is not so important here, but becomes important if this trough is found in the mid-levels of the atmosphere, particularly at the 500 mb level, which will be examined shortly. The lower-left image shows another surface analysis; however, details have already been discussed in association with Figure 2 and will not be reiterated here. The lower-right image contains two very important variables for the initiation and sustenance of convection: lifted indices and relative humidities. Lifted indices indicate the stability of the atmosphere, while relative humidity indicates the moisture content of the air. The hashed regions in the lower-right image indicate the regions of negative lifted indices, or regions of unstable air. Southern Wisconsin was covered with negative lifted indices at 12Z, thus indicating the presence of unstable air before the heavy rainfall event occurred. This unstable air helped lead to convection initiation in the presence of dynamical forcings, including the forcing provided by the surface frontal boundary, and perhaps a few more that will be discussed shortly. Additionally, there was a region of high relative humidity just to the west of Madison, WI, with relative humidities between 60%-70%. The rest of Southern Wisconsin experienced relative humidities between 50%-60%. These high relative humidities were indicative of the moist southerly airflow near the surface ahead of the stationary frontal boundary and provided the necessary moisture needed to sustain convection once it had been initiated, contributing to the heavy observed rainfall rates and relatively long duration of the convective line. Thus, it appears that the convective system had the needed moist boundary-relative flow for sustenance, yet another one of the factors present in an ideal flash flood situation.

Another dynamical forcing that led to the convection that spawned high rainfall rates over Madison, WI on 27 July 2006 was found at the 500 mb level of the atmosphere (Figure 5). The primary feature of interest at

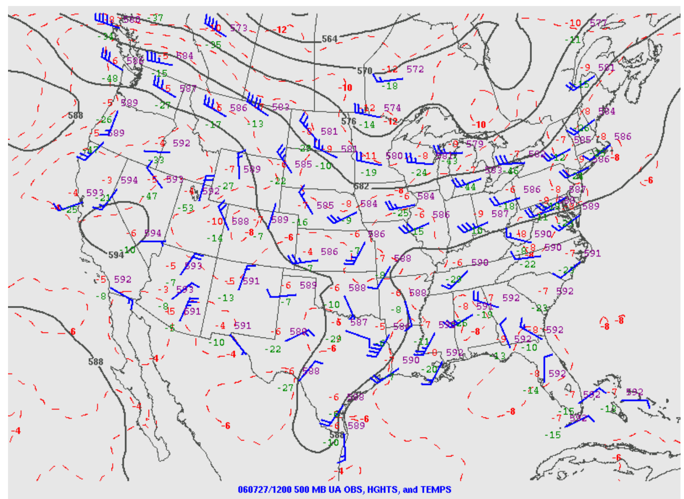

Figure 5: 500 mb synoptic map at 12Z on 27 July 2006. The primary feature of interest is the positively tilted trough just west of Wisconsin that is associated with cooling in the mid-levels of the atmosphere, a destabilization mechanism that helped initiate convection during this event.

the 500 mb level is the positively tilted trough in the height lines just to the west of Wisconsin, similar to that found at the 300 mb level. This shortwave trough indicated the possibility of some positive vorticity advection, which could have provided another dynamical forcing that initiated convection over Southern Wisconsin. More importantly, however, is that this trough in the height lines indicated cooling in the mid-levels of the atmosphere, which can also be seen by the red dashed lines in Figure 5. The cooling in the mid-levels of the atmosphere acted as a destabilization mechanism, which shifted the environment temperature profile to the left, towards colder temperatures, and subsequently increased the amount of CAPE, and thus created additional instability. Further destabilization of the atmosphere also occurred while daytime heating warmed the surface at the same time cooling occurred in the mid-levels. This higher instability increased the likelihood of convection initiation, and the increased amount of CAPE may have also helped to increase the depth of the convection and subsequently to increase the rate of rainfall.

A few other important factors that led to the flash flooding event on 27 July 2006 were present at the 925 mb level of the atmosphere (Figure 6). One of the most notable aspects of Figure 6 is the presence of a strong southerly return-flow from the Gulf of Mexico into the Upper Midwest. This southerly flow is advecting moister air northward, increasing the dew points out ahead of the frontal boundary. The green lines in Figure 6 indicate dew points, and over Southern Wisconsin, dew points are approximately 18 degrees Celsius (65 degrees Fahrenheit). The additional moisture added to the dynamical forcing provided by the surface frontal boundary and mid-level instability, led to higher rainfall amounts and contributed greatly to the flooding conditions that occurred later on in the afternoon. Also note how the 18 degrees Celsius dew point line overlaps with the placement of the stationary surface frontal boundary. This was not necessarily coincidental, however, since it is expected that drier air conditions reside behind (to the north of) the surface frontal boundary while moister air conditions prevail ahead (to the south) of the surface frontal boundary. Overall, the southerly flow allowed for high moisture content air to reach the Upper Midwest, which helped to promote deep, moist convection in the presence of the lifting mechanisms.

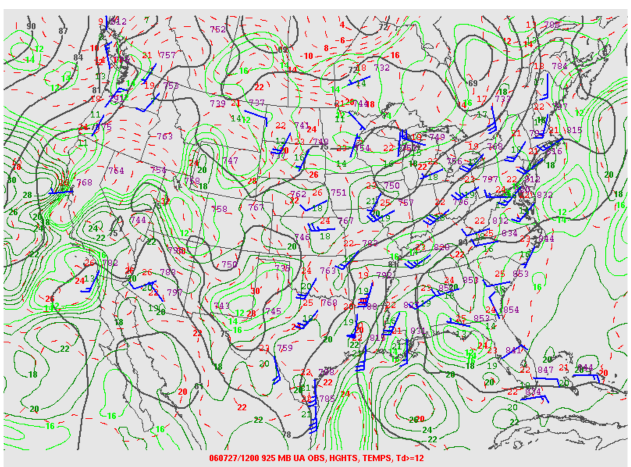

Figure 6: 925 mb synoptic map at 12Z on 27 July 2006. Note the strong southerly return-flow from the Gulf of Mexico that supplied moist air to the Upper Midwest region. The additional moisture in combination with the dynamical forcing described previously helped enhance the rainfall rates that led to flash flood conditions.

Now that the basic synoptic analysis has been carried out, the implications of the synoptic setup in relation to heavy rainfall rates can be discussed. When analyzing synoptic environmental conditions for a flash flood event, one key issue to consider is how heavy precipitation rates occur. From a synoptic viewpoint, lifting moist air to condensation is what produces precipitation. As a result, the instantaneous rainfall rate at a particular point is assumed to be proportional to the magnitude of the vertical moisture flux. This implies that rising air should have a substantial water vapor content and a rapid ascent rate, which in turn is the ultimate source for precipitation.[16] Upon analyzing the synoptic environmental

[16] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

conditions prior to the flash flooding event on 27 July 2006, both of these necessary conditions were present. Figure 6 at the 925 mb level proved the existence of consistent moisture inflow while Figure 4 supported this fact with high relative humidities over the Upper Midwest, particularly over Southern Wisconsin. The rapid ascent rate was provided primarily by the high instability of the atmosphere, as indicated by the lifted indices in Figure 4 and the mid-level cooling at the 500 mb level in Figure 5, but helped along as well by the stationary surface frontal boundary. Thus, both factors necessary for heavy precipitation rates were present. However, not all the water vapor flowing into a cloud falls out as precipitation, which brings up the topic of precipitation efficiency,[17] the ratio of the water vapor ingested into the storm to the water deposited as precipitation.[18] On the other hand, though, of the input water vapor in a convective storm, virtually all of it will condense due to the fact that a convective updraft is typically tall enough that the Bergeron process can be carried out efficiently and produce heavy rainfall that is associated with flash flooding.[19]

Another factor with regards to precipitation efficiency is the entrainment rate, since brining in unsaturated, environmental air into a storm tends to promote evaporation and consequently dissipation. An isolated storm is more likely to suffer substantial entrainment than a storm embedded within a larger storm system, since the environment associated with the system of storms is typically much more saturated than that in the vicinity of an isolated storm. Thus, a key observable factor related to evaporation is the environmental relative humidity. As the relative humidity increases, the evaporation rate decreases and the precipitation efficiency increases.[20] In terms of the flash flood event on the afternoon of 27 July 2006, it can be seen that lack of precipitation efficiency was not an issue. Despite the fact that rainfall amounts are known after-the-fact, the relative humidities prior to the event, as shown in Figure 4, were quite high and helped to indicate the potential for high precipitation efficiency and subsequently, high rainfall rates that led to flash flood conditions.

Thus, overall, the synoptic environment prior to the flash flood event on 27 July 2006 indicated a high probability for heavy rainfall rates based upon the presence of dynamical forcings provided by a stationary surface frontal boundary and atmospheric destabilization due to cooling at the mid-levels with heating at low-levels. In addition, ripe environmental surface and low-level conditions also played a role, such as high relative humidities sustained by a moist, southerly flow. Thus, the synoptic conditions were prime for flash flooding to occur. However, not only are synoptic environmental conditions important in determining flash flood potential, but so are mesoscale environmental conditions, which can provide further insight as to small-scale forcings that enhanced the dynamical forcings found at the synoptic level and likely has further implications regarding how the flash flood event played out.

[17] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

[18] Doswell, C.A. June 1993. *Flash Flood-Producing Convective Storms: Current Understanding and Research*. Proceedings, Spain-U.S. Joint Workshop on Natural Hazards, Barcelona, Spain, 8-11 June 1993.

[19] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

[20] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

IV. Mesoscale Environment

Although it is important to have synoptic-scale forcings to help initiate convection, these forcings are often on too long of a timescale to effectively initiate convection solely on their own. This fact highlights the importance of mesoscale forcings, which operate on much shorter timescales than their synoptic counterparts and can effectively set off loaded gun soundings. Thus, the major role for mesoscale processes is to provide the initial lifting mechanisms needed for convection initiation.[21]

a. Soundings and Hodographs

This first portion of the mesoscale environment will be analyzed using soundings and hodographs from Davenport, Iowa at 12Z on 27 July 2006 and 00Z on 28 July 2006. This site was chosen due to lack of sounding data available over Southern Wisconsin and because the 12Z sounding provided sufficient data regarding the setup conditions that supported the heavy rainfall event over Madison, WI during the afternoon of 27 July. The 00Z sounding is also included for completeness and to show the role of daytime heating via destabilization.

Several important variables and features that helped lead to convection on the afternoon of 27 July 2006 can be seen in the 12Z sounding from Davenport, Iowa, as shown in Figure 7. The first, and probably the most important, feature to note is the characteristic loaded-gun sounding, which indicates a deep conditionally unstable environment from approximately 950 mb up to just below 200 mb. The radiation inversion at the surface, a feature that is typically present at this time of day, provided a cap that inhibited convection initially and helped to create a layer of CIN between the surface and the 900 mb level. However, sitting above this layer of CIN is a large region of CAPE, energy that can be used by a parcel to reach high into the atmosphere. Convection is able to occur efficiently (i.e. produce convective rain clouds instead of non-precipitating stratus) when there is a relatively small amount of CIN in comparison to a larger amount of CAPE. The small amount of CIN helps to focus the convection in a particular region while the large amount of CAPE allows deep convection to occur. As can be seen in Figure 7, the ML CIN is only 233 J/kg while the ML CAPE is much larger at 3199 J/kg. Thus, the CIN to CAPE ratio at 12Z matched the ideal CIN to CAPE ratio in a typical convective setup and indicated a high likelihood for convective storms in the presence of a lifting mechanism that could lift the air parcels above the small layer of CIN. There are several ways that lifting can occur in a situation such as this. First, dynamical forcing can play a role, of which there are several for this particular case.

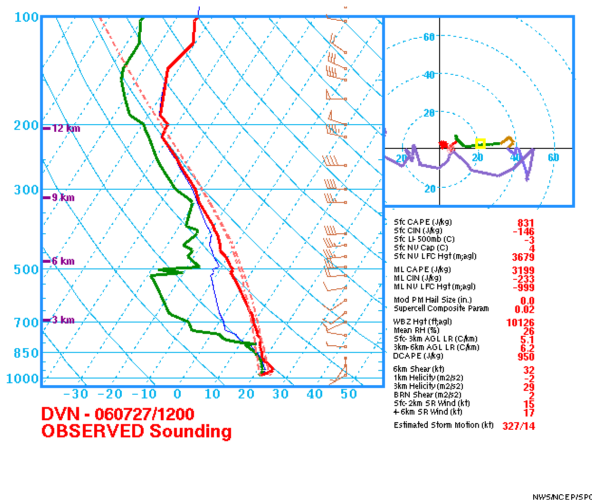

Figure 7: Sounding and hodograph from Davenport, Iowa on 27 July 2006 at 12Z. Note the loaded gun sounding that helped provide a setup conducive to convection when a lifting mechanism was present to set it off.

[21] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

However, as mentioned in the introductory paragraph of this section, dynamical forcings often act too slowly to set off convection in the first place and only act to enhance convection initiated by some other forcing, primarily at the mesoscale level. One of the primary mesoscale forcings is surface heating, which creates buoyant instability. Buoyant instability promotes strong upward vertical motions, and in the presence of adequate and high moisture contents, deep, moist convection can occur, bringing with it associated high rainfall rates that can lead to flooding. Thus, surface heating is a very important factor in determining the likelihood of convection. In essence, surface heating shifts the environmental temperature profile to the right, acting as a destabilization mechanism. This mechanism, which is often also combined with a synoptic-scale forcing, is usually what is able to set off a loaded gun sounding, as long as the cap is not too strong. Reverting back to the case at hand, the radiation inversion at the surface in Davenport, Iowa is quite shallow, and only extends up to about 950 mb from the surface. Thus, surface heating was able to cause the temperature profile to swing to the right and create buoyant instability, providing enough energy for the air parcels to be lifted from the surface, through the layer of CIN to the LFC, where the parcels were then able to rise freely. Thus, the surface heating was able to promote instability and increased the chances of convection occurrence. The resulting effect of the surface heating can be examined in Figure 8, a sounding at 00Z on 28 July 2006. Note how the temperature profile differs from that in Figure 7. The temperature profile no longer contains a radiation inversion at the surface, but also note that the value of CAPE has increased from 3199 J/kg to 3725 J/kg. Thus, the daytime heating helped to initiate convection and also increased the amount of CAPE, which allowed deeper convection to occur.

However, it is highly likely that the surface heating was not acting solo in this case; it is very likely that the synoptic-scale forcings described in the previous section helped to enhance the convection initiated by the buoyant instability created by surface heating.

Not only do mesoscale features show up on skew-t diagrams, but synoptic features can show up as well, including frontal boundaries and moisture flow. Frontal boundaries indicate an additional convective forcing for convection production while the moisture flow indicates a fuel source for sustaining the convection that does occur. The frontal boundary can be determined by examining the wind directions, particularly at the lower levels. As was indicated previously by the synoptic analysis, there was a stationary surface frontal boundary present at the time of the flash flooding event. This, in fact, can be seen in Figure 7. Note how the winds in the lower levels of

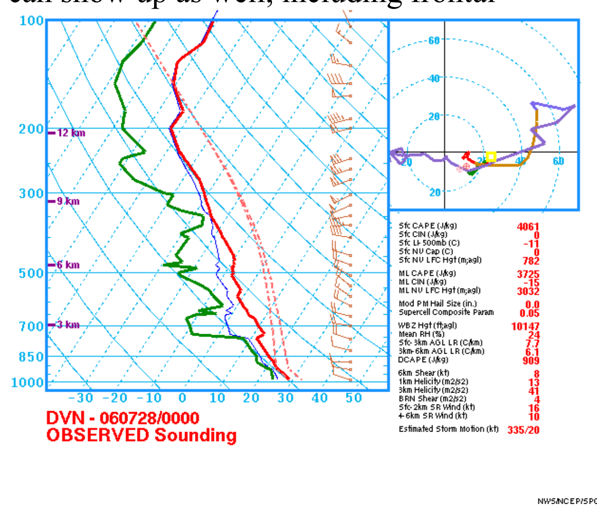

Figure 8: Sounding and hodograph from Davenport, Iowa on 28 July 2006 at 00Z. Note the difference between this temperature profile and that found in Figure 7. The daytime surface heating acted to destabilize the atmosphere and increased the amount of CAPE, allowing for deeper convection to occur.

the atmosphere begin out of the south and then turn westerly as height increases. This wind shift is typical of cold and stationary frontal boundaries. This presence of the frontal boundary at the mesoscale level highlights its importance as an additional dynamical forcing helping to create convection. As a side note, Figure 8 indicates that the frontal boundary has passed through the area, as is indicated by the westerly flow at all levels. Additionally, moisture flow can be determined by examining a skew-t diagram. The southerly flow at the low levels of the atmosphere, in addition to the close proximity of the temperature and dew point temperature profiles at the lower levels, is generally a good indicator of moisture advection. These conditions were seen with this particular case, which can be seen in Figure 7, and ulitmately helped to provide the necessary moisture needed to sustain the convective storms and allowed flash flood conditions to form. Thus, several important pieces of information can be inferred from skew-t diagrams at the mesoscale level, including both mesoscale and synoptic features.

One other important piece of information that can be inferred from a sounding and its associated hodograph is the severity of the storm system. As was mentioned previously with regards to flooding events, they usually occur along with typical, non-remarkable thunderstorms. As can be seen in the hodograph portion of Figure 7, the hodograph more or less follows a straight line, thus indicating a non-severe thunderstorm, as expected. The severity, or perhaps non-severity, can also be determined by looking at the Storm Report maps produced by SPC (Figure 9). The lack of storm report data on this day highlights the fact that the flash flood event was caused by typical, non-severe convective storms and was not associated with severe storms. Further categorization of the storms, such as whether the storms were mulicellular in nature or part of a squall line, unfortunately, cannot be determined with a skew-t and associated hodograph. However, it can be determined with radar imagery, which will be discussed later on in this section.

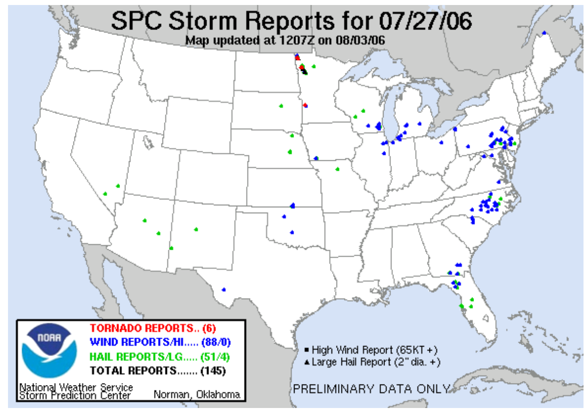

Figure 9: SPC Storm Reports for 27 July 2006. Note the lack of severe storm reports in the Upper Midwest, near the vicinity of the flash flood occurrences. Thus, it can be concluded that the storms associated with the flash flood event are typical, non-severe convective storms, not supercells.

Now that several important pieces of information have been derived from a skew-t diagram, their implications with regards to buoyancy and deep convection can be discussed. In order to produce buoyancy and deep convection, there must be three things that occur: 1) the environmental lapse rate must be conditionally unstable, 2) there must be sufficient moisture that some rising parcel associated with a moist adiabat has a level of free convection (LFC), and 3) there must be some process by which a parcel is lifted to its LFC.[22] As previously discussed, the conditionally unstable environment can be seen in Figure 7, from about 950 mb up to just below 200 mb, and is represented by

[22] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

the regions of CAPE and CIN. Sufficient moisture, the second necessity for buoyancy and deep convection, was indicated by the close proximity of the temperature and dew point profiles in the low levels of the atmosphere in Figure 7. The southerly winds near the surface also support this notion. Not only was there sufficient moisture present, but an LFC was also present in the 12Z sounding, near 925 mb. Also note the low level at which the LFC is located, which increased the likelihood that any convection that occurred could have reached this height and set off deeper convection that was supported by the relatively high levels of CAPE. The third necessary condition for buoyancy and deep convection was composed of two parts and is supported by the synoptic-scale and mesoscale environmental analyses in this case study. The primary convection initiation forcing was found at the mesoscale level, via surface daytime heating, which was then supported by synoptic-scale forcings, such as the stationary surface frontal boundary and the cooling in the mid-levels of the atmosphere. Thus, because each of the three necessary conditions were present in this particular case, buoyancy and deep, moist convection was able to occur and produced flash flood conditions over Madison, WI. However, despite the fact that this skew-t analysis supported the events that actually occurred quite well, one issue that some may have with this method of determining convective potential is the belief that it might too simple to produce highly accurate results. That may be true, but nonetheless, even though this method of determining the likelihood of convection using a skew-t diagram is simple parcel theory, it is still a powerful tool for anticipating deep, moist convection that is likely responsible for high rainfall rates associated with flooding.[23]

b. Radar Imagery

Radar imagery can provide valuable insight as to how the setup conditions evolved throughout the lifecycle of the storm and can indicate the categorization of the storm system as convective cells, squall lines or supercells. In some cases, even frontal and frontal-type boundaries can be inferred from radar imagery. The radar imagery generated for this particular case was compiled using GARP, and ran from 16:02Z to 22:48Z. Figure 10 shows a series of snapshots from the radar loop that showcases the 90-minute period of heaviest rainfall, from 17:02Z to 18:27Z, and highlights the stationary nature of the convective storms along the stationary surface frontal boundary.

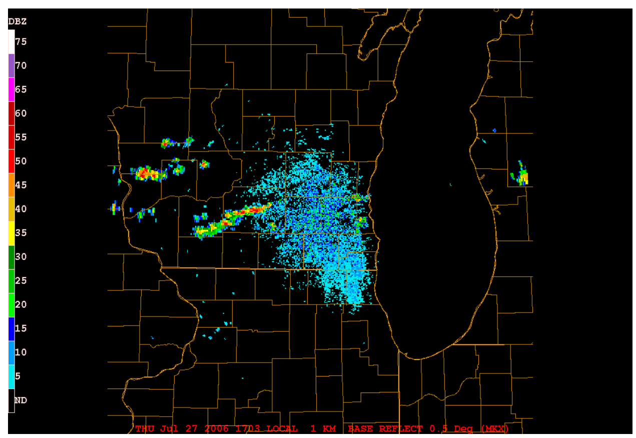

Figure 10a: Radar imagery snapshot at 17:02Z on 27 July 2006. Note the linear formation of convective cells across Southern Wisconsin, along the stationary surface frontal boundary.

[23] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

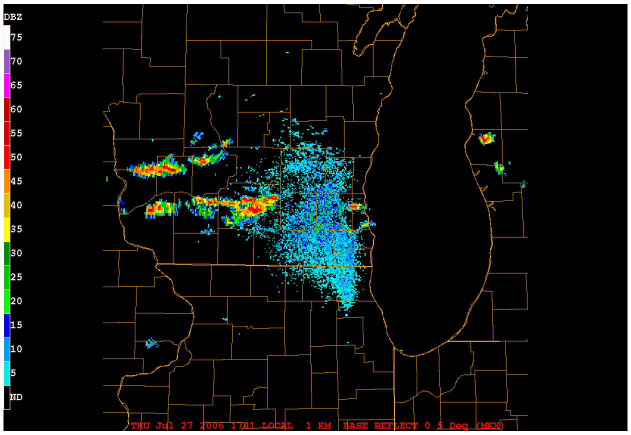

Figure 10b: Radar imagery snapshot at 17:41Z on 27 July 2006. Again, note the formation of convective cells along the stationary frontal boundary. Also note the increased intensity of the storms, indicative of a convective cells reaching maturity.

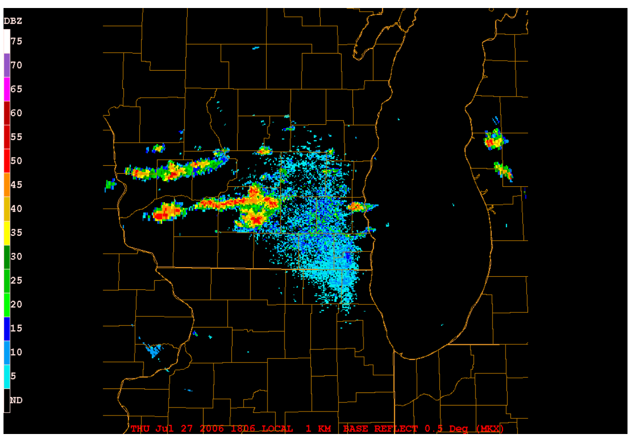

Figure 10c: Radar imagery snapshot at 18:06Z on 27 July 2006. Again, note the convective cells that formed along the stationary frontal boundary. Note how the most intense storms seem to have remained over the same areas, helping to create flash flood conditions.

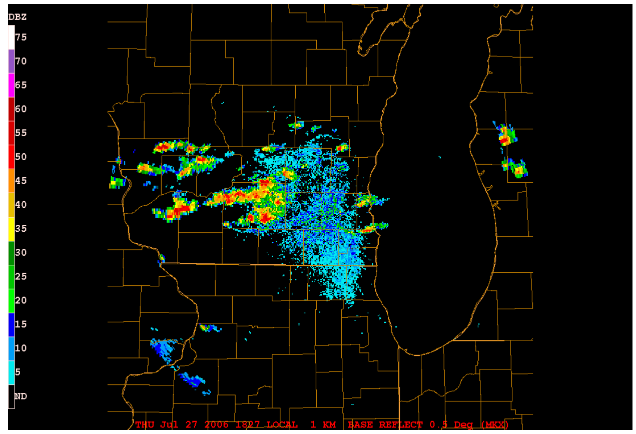

Figure 10d: Radar imagery snapshot at 18:27Z on 27 July 2006. Again, note how the position of the convective cell line is still along the surface frontal boundary, with the most intense storms still appearing to remain stationary.

A great deal of information about the evolution and forcings present during the flood event on 27 July 2006 can be inferred from the radar loop, particularly from the series of images in Figure 10 when the heaviest rainfall occurred. In the radar loop, the convective storms formed in a linear fashion stretching from west to east, and then slowly propagated to the east. This orientation of the convective cells indicated the presence of the stationary surface frontal boundary that draped across Southern Wisconsin, as was seen in the synoptic environment analysis. Based upon the radar loop, it appeared that the heavy rainfall over Southern Wisconsin, particularly over the Madison downtown area, occurred as a result of training, a successive series of showers and thunderstorms that moved repeatedly over the same area, along this stationary frontal boundary and produced flash flood conditions. Once the cells were able to initially form, they traversed east along this frontal boundary, but tended to mature and dissipate over the same areas, appearing as stationary convective cells in the radar loop. This process is observed quite well in the radar imagery in Figure 10 and is detailed in the conceptual model in

Figure 1. In the maturation stage of the storms, the highest rainfall rates are typically observed. Thus, the areas that tended to be at a maturation site saw flash flood conditions. Madison, WI was one of these maturation sites, which can be proved by the series of images in Figure 10. The strongest storms, or the storms that have reached their peak maturity, are indicated by the red reflectivities in the radar snapshots. As can be seen in Figure 10, a convective cell with a red reflectivity center remained over Madison, WI for the duration of the rainfall event. Thus, Madison saw some of the heaviest rainfalls associated with this line of storms and ultimately saw flash flood conditions as a result.

In addition to storm evolution, radar imagery can also help determine the categorization of the storm as convective cells, squall lines or supercells. However, it has already been determined that this storm system was non-severe, thus removing the possibility for categorization as a supercell. The categorization for multicellular convection or squall lines can be determined simply by observing the patterns of reflectivity in the radar imagery. For this particular case, as shown in Figure 10, the storm system showed up as a line of individual storm cells. Thus, this particular event can be categorized as a multicellular convective event. In sum, radar reflectivity imagery can provide valuable information regarding the evolution of the setup conditions and can also indicate the categorization of the storm.

c. Mesoscale Diagram

Miller diagrams are typically used to analyze the many synoptic and mesoscale features present in the atmosphere leading up to a severe weather outbreak. However, because Miller diagrams are specific to severe weather, they do not typically relate well to flash flooding events. Thus, a more general mesoscale diagram has been drawn for this particular case study that highlights important environmental factors for flash flood conditions: moisture tongues at the lower levels of the atmosphere, surface frontal boundaries, general flow at the lower levels of the atmosphere and the 300 mb level and generalized CAPE and CIN values. This diagram, showcased in Figure 11, provides a composite of several of the mesoscale and synoptic features described previously in this case study. The first important feature of this mesoscale diagram is the stationary surface frontal boundary, which provided a lifting mechanism that helped enhance mesoscale lifting created by daytime heating, and allowed convection to occur. However, in order to incur flash flooding conditions, moist, deep convection must be able to occur. Thus, moisture is a necessary component. There are moisture tongues at both the 925 and 850 mb levels, and pool of moist air at the 700 mb level, which shoved moist air up against the frontal boundary via southwesterly surface winds and provided additional fuel for the convective storms that had formed along the frontal boundary. Thus, the deep, moist convection was able to occur as a result of lifting and sufficient moisture influx. Another important feature included on this mesoscale diagram is the general wind flow at the lower levels of the atmosphere and at the 300 mb level. Note how the wind flow at the 300 mb level is purely zonal, while the winds at the lower levels are slightly from the southwest. This distribution of winds throughout the atmosphere helped to indicate the propagation direction of the convective cells. The upper level winds traditionally act as the steering winds of the storms, and because the winds were westerly along the stationary surface frontal boundary, storm propagation along the frontal boundary was promoted. The southwesterly winds at the lower levels

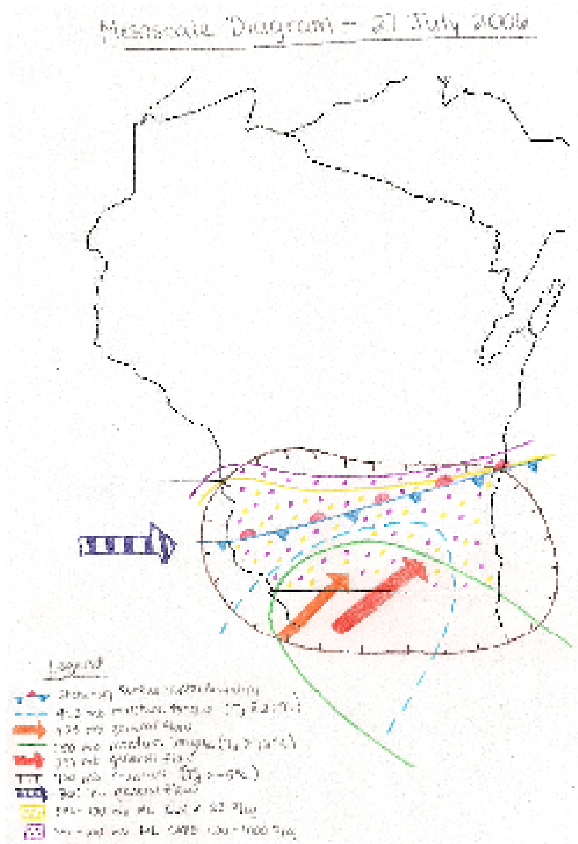

Figure 11: Mesoscale diagram for Southern Wisconsin at 12Z on 27 July 2006. Analyzed features include the surface frontal boundary, moisture tongues at the lower levels of the atmosphere, general flow at the lower levels of the atmosphere, general flow at the 300 mb level, and generalized CAPE and CIN values.

also generally helped to promote flow propagation along the surface frontal boundary. This likely aided the training process and helped to enhance the flash flood conditions. Another important aspect to note was the lack of veering or backing of winds with height. Because there was hardly any wind shift with height, no storm rotation was able to occur, and as a result, multicellular convective storms were fostered instead of supercell storms. The final features included on this diagram are the generalized CAPE and CIN values. Note how the CIN values over the southern portion of Wisconsin are much smaller than the CAPE values over the same region. As indicated in a previous section of this paper, this ratio is ideal for deep convection to occur. Thus, based on this diagram, the combination of the synoptic and mesoscale environments over Southern Wisconsin on the afternoon of 27 July 2006 were highly conducive to deep convection initiation and convection sustenance via a continuous, moist southerly flow regime and as a result, flash flood conditions were able to prevail.

V. Conclusion

Upon analysis of the synoptic and mesoscale environments, the causes of convection initiation and sustenance leading to the flash flooding conditions that occurred on 27 July 2006 were determined. It was originally hypothesized that the conditions during this particular event would closely follow the ideal conditions for flash flooding. It was suspected that multicellular convective cells that moved roughly parallel to a slow-moving or stationary surface frontal boundary caused the flooding event and was sustained by a warm, moist low-level southerly flow, allowing the rainfall to be focused over one particular area and causing localized flash flooding. Additionally, it was suspected that the forcing mechanisms primarily responsible were surface and low-level forcings, including daytime heating as a mesoscale forcing, because upper-level forcings such as jet maximums are typically rare during the summer months when the jet stream retracts further north. In the end, this hypothesis was supported by the data provided in the synoptic and mesoscale analyses. The storm system consisted of multicellular convective cells that traversed along a stationary frontal boundary and was sustained by warm, moist low-level southerly flow. It was also determined that the synoptic forcings were provided by the stationary surface frontal boundary in addition to cooling in the mid-levels of the atmosphere, while the mesoscale forcings was provided by daytime heating. As expected, there was also no upper level forcing due to the lack of presence of a jet maximum. The combination of these forcings along with the moist, southerly flow allowed for deep, moist convection to occur along the surface frontal boundary and led to the observed flash flood conditions.

Several other factors associated with heavy rainfall rates were discussed as well, such as high rainfall rates and precipitation efficiency. Heavy precipitation is the result of high rainfall rates, which involves the rapid ascent of air containing substantial water vapor and also depends on the precipitation efficiency.[24] In this particular case, rapid ascent of air was provided by the combination of synoptic and mesoscale forcings while the substantial moisture content was provided by the southerly flow at lower levels of the atmosphere. Additionally, due to the convective nature of these storms, lack of precipitation efficiency was not an issue. Thus, the heavy rainfalls that produce flash floods are typically the result of persistent high rainfall rates and are caused by high water vapor mass flux through convection coupled with high precipitation efficiency.[25] As a result, rainfall rates associated with convection tend to be higher than with other rain-producing weather systems.[26] In addition, deep, moist convection normally occurs during the warm season when high moisture content is possible and buoyant instability promotes strong upward vertical motions. Thus, from the preceding data presentation, it should be clear that flash flood-producing storms are usually convective in nature and occur during the summer months.

Not only is it important to understand how and why certain events occurred after the fact, particularly for dangerous and costly events such as flash flooding, but it is also important to take that information that was learned from historic cases such as this and apply it to forecasting future events. A forewarning of potential flood conditions would allow for better flood preparation actions in an attempt to minimize damages as much as possible. However, flash flooding still often comes as a surprise, leaving little time for advanced warning. The flash flooding event on 27 July 2006 was one such event with little lead time warning of potential flash flood conditions. As a result of the deep, moist convection that caused slow-moving thunderstorms over Southern Wisconsin, flash flooding conditions occurred in association with torrential rainfall and caused an estimated $10 million in damages.[27] Hourly rainfall rates of 1 to 3 inches per hour persisted over a few locations for a prolonged period of time, including Madison, and allowed for rapid accumulation of rainwater.[28] Unofficial rain gauges spread throughout the affected area measured 4.5 to 5 inches of precipitation in the downtown area and on the University of Wisconsin-Madison campus.[29] The

[24] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

[25] Doswell, C.A. June 1993. *Flash Flood-Producing Convective Storms: Current Understanding and Research*. Proceedings, Spain-U.S. Joint Workshop on Natural Hazards, Barcelona, Spain, 8-11 June 1993.

[26] Doswell, C.A., H.E. Brooks, and R.A. Maddox. June 1996. *Flash Flood Forecasting: An Ingredients-Based Methodology.* Weather and Forecasting. Volume 11. p. 560-581.

[27] NOAA Satellite and Information Service. [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~640572]

[28] National Weather Service Weather Forecast Office. [http://www.crh.noaa.gov/mkx/?n=072706_madisonflooding]

[29] NOAA Satellite and Information Service. [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~640572]

distribution of rainfall over Southern Wisconsin can be seen in Figure 12.[30] Note the bulls-eye over Madison, WI. The

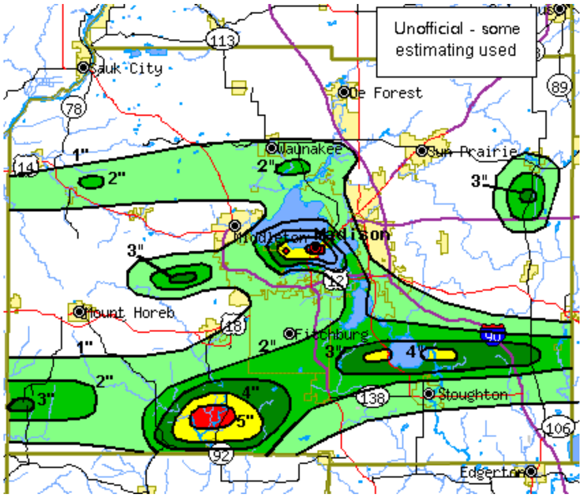

Figure 12: Estimated Rainfall for 27 July 2006. This figure shows a bull's-eye over Madison, WI where 3-5 inches of precipitation were observed, which caused flash flooding in the area.

red shading indicates areas that received between 3 and 5 inches of precipitation in association with this line of multicellular convective storms. Flash flooding conditions were exacerbated in this area due to high amounts of concrete and other non-absorbing materials. As a result, many roads became impassable and many residential homes and businesses on or near the University of Wisconsin-Madison campus had basement and first floor flooding.[31] Additionally, water depths in some areas reached to the top of small vehicles, approximately reaching a depth of 4 to 5 feet.[32] Thus, flash flooding has the potential to cause great losses due to high amounts of damage, and the damages incurred as a result of this particular flash flooding event highlight the importance of applying knowledge of the setup conditions of previous events to forecasting future events, particularly during the summer months when deep, moist convection and associated flash flood conditions are most likely to occur.

VI. Acknowledgements

There are a few people who this author would like to thank for making this case study a success. First, the author would like to thank the willing and helpful AOS 453 TA, Dan Henz, for taking the time to answer questions along the way and clarify important concepts. The author would also like to thank Professor Martin for providing the independent study experience this semester that provided inspiration for studying flooding events, including the topic of this case study. A thank you should also be extended to Pete Pokrandt for help in acquiring the necessary data to create radar imagery in GARP.

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[32] NOAA Satellite and Information Service. [http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~ShowEvent~640572]

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