Influences of Land Surface Characteristics on Precipitation over the Lower Mississippi Alluvial Plain

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The lower Mississippi River alluvial valley, covering sections of Mississippi, Arkansas, and Louisiana, is well recognized as a major agricultural center of the US. Since roughly 1940, land use, vegetation, and soil characteristics have remained relatively consistent over the area, with irrigation levels increasing in association with crop density. Research has shown that agriculture can have an influence on regional weather variability through land use, soil type, and vegetation patterns by influencing energy and moisture transport into the atmospheric boundary layer. Due to the relatively sharp contrasts in these surface characteristics between the alluvial valley and surrounding regions, it is suspected that anthropogenic weather modification may be occurring in the form of enhanced mesoscale convective circulations. These circulations are most evident during the warm season when radiational surface heating is greatest and synoptic-scale forcings are minimal, and can have a direct influence on agriculture by varying the intensity and distribution of convective precipitation. The purpose of this project is to define the existence and location of convective boundaries and associated precipitation over the lower Mississippi River alluvial valley. This will aid water resource managers and meteorological forecasters in recognizing the relative climatological patterns of rainfall during the growing season, and will provide information on the influence of anthropogenic land use and soil moisture boundaries on precipitation distribution. Initial results from the study indicate an eastward shift in warm-season precipitation relative to predominantly agricultural areas, such that rainfall is minimized over the lower Mississippi River alluvial valley and maximized directly eastward along the Hwy. 45 corridor. Although there are a number of factors that combine to generate this pattern, it is expected that enhanced soil moisture and latent heat flux due to heavy irrigation over the alluvial plain may play an important role in generating more intense convective boundaries over the region, leading to increased downstream transport of atmospheric moisture and subsequent precipitation.

Key words: Climatological Processes, Water Quantity, Hydrology

Introduction

The lower Mississippi River alluvial valley (LMRAV), covering sections of Mississippi, Arkansas, and Louisiana, is well recognized as a major agricultural center of the US. In Mississippi alone, the alluvial valley boasts 80% of the states total agricultural production (Delta Council, 2008), which is substantial given that Mississippi is the fourth largest producer of cotton and rice in the United States (USDA, 2008). Often given the misnomer the “Mississippi Delta” due to its distinctive shape, the alluvial region is characterized by extremely fertile soils deposited through repeated flooding of the Mississippi River. Before 1940, roughly 96% of the existing hardwood forest in the floodplain was converted to cultivated land (MacDonald et al., 1979), and subsequent land use, vegetation, and soil characteristics have remained relatively consistent since that time.

Agriculture is known to be highly dependent on climatological variables related to the surface energy and water budgets; however, research has shown that agriculture can have an influence on regional weather variability through land use and vegetation patterns (Brown and Arnold, 1998). Specifically, soil type and vegetation play a key role in determining the dynamics of energy and moisture transport into the atmospheric boundary layer through spatial variations in evapotranspiration, albedo, and surface heat fluxes (Hong et al., 1995; Segal et al., 1988; Ookouchi et al., 1984; Rabin et al., 1990; Mahfouf et al., 1987; Boyles et al., 2007). These effects are well documented, and can occur in various climate zones given weak synoptic forcing. Additionally, agricultural land use can influence the dynamics of the boundary layer through variations in surface roughness over the growing season, effectively modifying existing sub-synoptic and mesoscale flow regimes by varying the intensity of turbulent mixing through the radix layer.

The energy, moisture, and turbulent fluxes all have strong influences on the generation and strength of mesoscale circulations, and therefore precipitation. As a result, variations in land use and/or soil type can lead to changes in regional precipitation patterns (Anthes, 1984). Several studies have demonstrated the role of the sand-clay soil boundary in eastern North Carolina (a.k.a., the "Sandhill Effect") on mesoscale surface convergence and convective precipitation (Boyles et al., 2007; Koch and Ray, 1997). Similar soil contrasts exist within the LMRAV, although no studies have been done to indicate that regional precipitation patterns are affected; however, research has shown that abnormal temperature variations in the floodplain do exist as a result of spatial variations in soil and vegetation (Raymond et al., 1994; Brown and Wax, 2007). These temperature effects could be an indicator of possible boundary layer modification through surface influences, resulting in the generation of mesoscale circulations and localized convective precipitation.

It is the purpose of this research to determine if mesoscale convective boundaries occur along the LMRAV as a result of surface heterogeneities, and to establish how local precipitation patterns are influenced by such features. This will be done using high-resolution radar precipitation estimates and satellite imagery, the former of which is available since 1996. Although modeling studies have been carried out in other locations to examine the sensitivity of mesoscale circulations to surface characteristics (Mahfouf et al., 1987; Boyles et al., 2007; Hong et al., 1995), it is necessary to first study observed data to determine if a relationship is visible. Results of this research can be used to establish the existence of interbasin water transport through atmospheric processes, and will provide information regarding localized weather modification through anthropogenic land cover changes.

Data and Methods

Study Area

The study area for this research is roughly defined as northern Mississippi, southeastern Arkansas and northeastern Louisiana, which contains within it the LMRAV (a.k.a., Mississippi Delta). This region is heavily agricultural, and is most recognizable in northwestern Mississippi by a sharp change in vegetation, soil type, and elevation. No specific outlines are used to define an area of interest in or around the LMRAV to minimize subjective interpretation of atmospheric patterns; however, the study region is expanded east through Tennessee and Alabama to take into account advection of convective features originating over the Mississippi Delta (Figure 1).

Although convective boundaries could potentially form year-round over the study area, several factors limit the time period of analysis to only the warm season (May – September). First, surface heterogeneities have the greatest atmospheric influence through the sensible and latent heat fluxes, which are driven by surface heating. As a result, only those months where surface heating is maximized will be used for analysis. Second, cool-season precipitation patterns are dominated by large-scale mid-latitude weather systems, minimizing the ability to differentiate localized convective precipitation from the heavier and more persistent stratiform and frontal convective systems.

Defining Synoptically-Benign Days

Atmospheric convection is heavily influenced by synoptic-scale circulation patterns and processes, such as surface fronts and upper-level convergence/divergence. These features effectively mask the influence of surface characteristics on localized weather patterns, making it difficult to separate the unique influence of different environmental properties. Ideally, only days with minimal synoptic forcings over the region will be included for analysis since this will give a better indication of the effect of surface features on localized convection. As a result, the first step in this project is defining a synoptically benign day over the LMRAV. These criteria will then be used to differentiate appropriate days to include in the analysis.

To quantify the synoptic conditions over the study region, 00Z and 12Z atmospheric sounding data from Jackson, MS, Shreveport, LA, and Little Rock, AR were used to quantify wind speeds at 850 hPa (~1500 m) and 500 hPa (~6000 m) for all warm-season days (May – September) from 1996 – 2008 (Figure 1). This time period was limited by the availability of high-resolution precipitation data, which first became available in 1996. By using sounding data at these locations, a day influenced by an approaching frontal system from the west can be accounted for. The 850 hPa level was used because it normally describes synoptic conditions just above the planetary boundary layer (i.e., near -surface), while the 500 hPa level describes mid-level winds that act to advect mature convective systems. No upper-level data were utilized because of common missing values, and because the convection resulting from the surface boundaries is often relatively shallow before it produces precipitation.

The median wind speed value at each level was used as the criteria to differentiate synoptically-benign days. These values were 7.7 ms^{-1} (15 knots) at 850 hPa and 14.4 ms^{-1} (28 knots) at 500 hPa. Any day where the 850 hPa and 500 hPa levels at all sounding locations showed a wind speed less than the given criteria value for the 00Z and 12Z value for the given day, as well as the 00Z value for the following day, was considered synoptically weak. This method yielded 245 synoptically weak days out of a possible 4749 days (5.2%).

Satellite Data

Available synoptic and precipitation data are not able to recognize mesoscale convective boundaries independently due to spatial and temporal resolution issues; therefore, it was necessary to incorporate satellite imagery to visualize cloud patterns associated with localized surface convection. For this project, visible (~5 μm) and near-infrared (~10 μm) images from the Geostationary Operational Environmental Satellite (GOES) 10 (i.e., GOES East) were used, which have a nominal resolution of 1 km and 4 km, respectively. Imagery was obtained from the Comprehensive Large Array-data Stewardship System (CLASS) (NOAA, 2009).

Whenever possible the higher resolution 1 km visible imagery is used to define the generation and extent of the mesoscale convective boundaries, with the 4 km near-infrared data used to estimate the depth of convection using brightness temperatures. However, when the visible data are not available or are not valid, such as during the night or at extreme low sun angles, the 4 km near-infrared data are used to define the surface boundaries.

Precipitation Data

The precipitation data used in this project are multi-sensor precipitation estimates, derived from hourly WSR-88D data (Weather Surveillance Radar – 1988 Doppler; details of the methods and limitations of the products can be found in Fulton et al. [1998]). Radar-based precipitation estimates have become a useful and valuable tool in hydrometeorological research due to their high spatial and temporal resolution. This is especially true in research related to small-scale or intense precipitation variability; however, since radar is a remotely sensed platform with inherent, though understood, limitations (i.e., beam blockage, false return signals, truncation error, etc.), the NWS has developed algorithms designed to minimize the error in associated precipitation estimates.

Multi-sensor data are produced by combining hourly radar precipitation estimates (a.k.a., Stage I data), in the form of a digital precipitation array (DPA), with hourly surface-based observations. The surface observations are used to calculate a corrective mean field gauge-radar bias using a Kalman filtering approach, providing a local adjustment to the radar-derived precipitation field (Smith and Krajewski, 1991). Stage II data are then corrected radar-based precipitation estimates for an individual radar coverage. An additional process involves combining the individual corrected radar fields into a mosaic of coverages, resulting in a continuous field of multi-sensor precipitation estimates. These data, termed the Stage III product, are manually quality controlled at NWS river forecast centers to remove areas of known contamination (Briedenbach et al., 1998; NOAA/NWS, 2007).

Since approximately 2003, the Office of Hydrologic Development (OHD) of the NWS has made a transition from the Stage III processing algorithms to the updated Multisensor Precipitation Estimator (MPE) algorithm. The MPE algorithm includes an additional weighted adjustment based on surface gauge distance from a precipitation measurement; therefore, more weight is given to the radar estimate as the precipitation event occurs further from a rain gauge, allowing for adjustment based on within-storm variability (Westcott et al., 2005; Fulton et al., 1998; Seo, 1998). Despite the fact that the algorithm used to calculate the precipitation estimates has changed during the study period for this project, no correction has been made to adjust the data since no quantification of the bias difference between MPE and Stage III is currently available.

Stage III and MPE precipitation estimates are provided by the NWS in XMRG format, and are projected in the Hydrologic Rainfall Analysis Project (HRAP) grid coordinate system. The HRAP coordinate system is a polar stereographic projection centered at 60°N / 105°W, with a nominal 4x4 km grid resolution. For the purposes of this study, the multi-sensor precipitation estimates were decoded such that the latitude and longitude of the respective HRAP grid cell center was associated with the corresponding precipitation value.

Hourly Stage III and MPE data, coded in universal time coordinated (UTC), were used to generate daily precipitation values by averaging values from 0500 – 0500 UTC. This corresponds to 2400 – 2400 local standard time (LST) over the study region, or midnight to midnight. This was done so that all precipitation occurring during the daylight hours for a given day could be accumulated together. Only days with non-missing data for all 24 hours were used for analysis.

Koch and Ray (1997) state that radar data alone cannot detect convergence zones due to inherent physical limitations in the observation process (i.e., varying beam elevation with distance); however, it should be noted that within this project, the precipitation estimates are not being used to detect mesoscale convective boundaries. To be precise, satellite imagery is the primary tool by which the boundaries are detected, at which point the multi-sensor precipitation estimates are used to verify the maturation of the associated convection and to define the rainfall associated with the events.

Results

General Patterns

Before investigating the defined synoptically-benign days for the existence and extent of mesoscale convective boundaries and the associated precipitation, it is necessary to quantify the associated synoptic conditions and precipitation distribution. The average wind and temperature conditions associated with the 245 synoptically-benign days were calculated using the 32 km NARR data for the 850 hPa and 500 hPa levels, while the precipitation data were summarized using expected value (i.e., mean) and variance assuming the rainfall at individual grid cells followed a gamma distribution (Thom, 1958).

The average conditions at the 500 hPa level for all synoptically weak days are roughly equivalent barotropic through the Ohio Valley, becoming weakly baroclinic over the study region (Figure

2a). Wind speeds are relatively low over the LMRAV (< 5 ms^{-1}), and show an anticyclonic flow pattern around an axis in northeastern Louisiana. Based on this synoptic set-up, winds generally flow from the northwest across the LMRAV. Additionally, there is a weak latitudinal temperature gradient across the area. It should be noted that the estimated temperature and height gradients are relatively weak overall, and do not show the variability associated with individual days; therefore, they are meant to show only the general conditions associated with all synoptically-weak days.

Similar patterns exist at the 850 hPa level as at the 500 hPa level with respect to both wind speed and direction (Figure 2b). There is a general anticyclonic circulation, again centered over northeast Louisiana, indicating a minimal vertical offset in synoptic conditions from the top of the planetary boundary layer to the mid-levels. Accordingly, there is weak westerly and northwesterly flow (~<2 ms^{-1}) over the study area. The temperature patterns show a weak meridional temperature gradient across the Mississippi Valley with a closed geopotential height contour over the study region. This indicates that the anticyclonic rotation centered over northeast Louisiana is a result of low-level divergence, typical of normal warm-season conditions over this area. Since the atmospheric conditions over the study region at 850 hPa on synoptically weak days are roughly barotropic, it is hypothesized that any vertical development will be a result of thermal instability originating at the surface.

The average daily precipitation for all synoptically-benign days shows localized maxima along the Gulf Coast from central Louisiana through the panhandle of Florida (Figure 3b). This coincides with the sea breeze front that dominates this area on days with minimal synoptic forcings, further verifying the criteria used in this study to define synoptically-benign days. The high precipitation depths follow a line roughly northeast through Alabama into the southern Appalachians, while there is a relatively steep gradient towards lower rainfall amounts over the LMRAV. Within the LMRAV there is a distinct area of low average rainfall in northwest Mississippi, stretching northwest into Arkansas; however, along a north-south line through northern Mississippi there is a slight increase in rainfall depth that separates rainfall minima to the east and west.

The rainfall minimum over the study area may be associated with subsidence from the synoptic high pressure that is shown to exist in the lower levels (Figure 2), which dynamically hampers thermodynamic uplift by limiting the vertical extent of the planetary boundary layer. Additionally, the mean westerly and northwesterly winds over the study area imply decreased mid-level moisture convergence by advecting cooler continental air from the Great Plains, which would further weaken any convective uplift.

The convective nature of precipitation events during synoptically weak conditions inherently suggests higher variability (high intensity, low spatial extent), such that areas with high rainfall amounts should also have high variability; therefore, combining mean and variance estimates will allow for a more detailed analysis of convective precipitation distribution across the study area. Daily precipitation variance (for only synoptically-benign days) mirrors the general rainfall distribution across the study region, including the maximum along the coast and minimum in northern Mississippi and Arkansas (Figure 3b). Additionally, the north-south line of increased rainfall is shown as limited areas of higher variance in northern Mississippi.

This line of increased precipitation is roughly centered between the Mississippi Delta bluffs to the west and the Pontotoc Ridge to the east, which might imply an orographic influence; however, the substantial variations in soil type and vegetation between the areas preclude such a general conclusion. Along this line, however, it is possible that the planetary boundary layer in this region is neutrally stable with a shallow stable layer near the surface, such that the slight increase in elevation along the Mississippi Delta bluffs upwind may provide a weak convective triggering mechanism. Likewise, an enhanced mesoscale circulation may be the cause of the precipitation, which would form as a result of the change in land cover features and an enhancement of the surface heat flux gradient. This is similar to the generation of the sea breeze circulation that is related to the precipitation maxima along the coast.

Event-specific Analysis

Using the 245 defined synoptically weak days, visual analysis of the GOES satellite data was performed to define those days when a mesoscale convective boundary occurred. A boundary was recognized as a curvilinear cloud feature that originated and decayed over a single diurnal cycle, normally through the course of one afternoon. The multi-sensor precipitation and associated synoptic data were then utilized to extract only those days where rainfall amounts and/or distribution were associated with convection over the LMRAV. Several techniques were used to minimize the inherent subjectivity in the analysis, which is often a substantial source of error in any manual visual interpretation. The following criteria were used to define a day where a regional surface influence was apparent:

I. Satellite imagery must show a distinct curvilinear mesoscale cloud feature with a diurnal temporal extent over the study area.
II. Multi-sensor precipitation estimates must show a distinct area or areas of scattered rainfall within or in close proximity (~<20 km) to the defined mesoscale convective boundary.
III. The areas of rainfall must not be part of an existing larger-scale mesoscale boundary, defined by a clear enhancement of precipitation beyond the study area.
IV. Flow at 500 hPa must show that the rainfall is downwind of the lower Mississippi River alluvial plain.

Although a strictly visual analysis is not the ideal method of defining and studying mesoscale convective boundaries, it is the objective of this paper to only define their existence over the LMRAV. Quantification of the boundaries over time and space, as well as examination of the surface features associated with the boundaries, is beyond the scope of this paper and is therefore held as a topic for future research.

Evaluation of all synoptically-benign days revealed that mesoscale convective boundaries do develop over the LMRAV, namely along the eastern edge of the Mississippi Delta during days with weak westerly flow at 850 hPa. In general, less than 10% of the synoptically-benign days were characterized as having mesoscale convective development over the study region. Additionally, the strength and spatiotemporal extent of these boundaries varied widely, making it difficult to accurately determine the associated surface influences. The boundaries that did occur produced initial development in the late morning (10:00 – 11:00 LST) and lasted through the late afternoon / early evening (17:00 – 18:00 LST). When precipitation did occur, substantial increases in intensity and/or extent occurred in the early afternoon (13:00 – 14:00 LST) with a temporal extent of several hours.

For most synoptically-benign days with recorded precipitation, a stronger boundary or circulation not associated with the study area overwhelmed localized convection, degrading or preventing any noticeable convective boundaries. For days with no precipitation or convective boundary over the study area, the dominant wind direction was from the east or north. This indicates that the dominate area for the development of a mesoscale convective boundary is along the eastern edge of the Mississippi Delta when westerly near-surface winds are dominate.

To provide a more detailed understanding of the cloud and precipitation patterns associated with a mesoscale convective boundary over the LMRAV, two days in which a distinct boundary developed are looked at in detail. The first occurred on July 12, 1997, and was characterized by a relatively disorganized boundary with localized convection along a north-south line that originally developed in northeast Mississippi (Figure 4). Initial surface conditions showed cellular convection over the region, indicating low-level instability and turbulence within the planetary boundary layer. Additionally, low-level winds were weak and westerly while mid-level winds were somewhat stronger and from the northeast, leading to substantial directional shear over the study area. The convective storms that developed along the boundary showed good vertical development, as can be seen by the bright appearance on the visible satellite imagery; however, precipitation amounts were relatively low and spatially limited since the individual storms were short-lived, most likely due to a lack of low-level moisture.

The conditions on September 9, 2006 were more favorable for the development of a mesoscale convective boundary across the study area in that the 850 hPa flow had a southerly component, increasing the surface moisture convergence over the Mississippi Delta. This can be readily seen by the generation of a sea breeze front along the Gulf Coast during the morning and early afternoon (Figure 5), which are normally associated with weak synoptic forcings. The study area was initially clear with scattered cirrus clouds until roughly 11:00 LST, at which point a distinct convective boundary began to develop along the Mississippi Delta bluff line from Vicksburg, MS northwards (Figure 5). This line continued to develop before producing a linear precipitation pattern at 14:00 LST, which maintained its spatial structure and position for the next few hours. This suggests that some surface feature related to the Mississippi Delta (i.e., elevation, soil and/or vegetation heterogeneity) was the primary cause of the convection.

Discussion

The objectives of this research were to identify the generation of mesoscale convective boundaries within or along the borders of the LMRAV, which would likely form due to rapid changes in soil type, vegetation, and elevation. When convective boundaries do form, it was also the intent of this project to ascertain the spatial and temporal extent of the related precipitation. This is an important aspect of the research because downstream advection of precipitation could lead to interbasin transport of water, which is a key aspect in sustainable agriculture within the Mississippi Delta.

Mesoscale convective boundaries normally occur when regional synoptic forcings are weak and surface heating is strong; therefore, only days defined as synoptically benign (wind speeds less than 7.7 ms^{-1} and 14.4 ms^{-1} at 850 hPa and 500 hPa, respectively) during the warm season (May – September) were included in the analysis. This narrowed the days available for study to 245 (5.2% of the total number of days).

Analysis of 1 km visible GOES satellite data revealed that less than 10% of all synoptically-benign days during the study period were associated with distinct mesoscale convective boundaries. Additionally, of those that did form, most were relatively disorganized and short-lived, rapidly deteriorating and merging with the dominate regional circulation. When strong boundaries were generated within the study area, they were nearly always aligned with the eastern boundary of the Mississippi Delta where the strongest gradients of soil type, vegetation, and elevation exist, and usually formed under dominate westerly flow in the lower atmospheric levels. This immediately raises the question as to what specific surface characteristic leads to the convective development.

Conditions over the LMRAV during the warm season are generally warm and relatively humid; however, surface moisture convergence is usually limited on days with dominate westerly flow at the surface. Taking into account the available soil moisture and high rates of evapotranspiration over the cultivated cropland within the Mississippi Delta, it is possible that the surface latent heat flux could intensify at a local scale, destabilizing the boundary layer. At this point a weak triggering mechanism is all that is needed to generate convection, such as low-level winds flowing perpendicular to the Mississippi Delta bluff line. In such a case it is reasonable to assume that the low-level atmospheric conditions are not strong enough to produce deep convection due to the overall thermodynamic conditions of the region in the warm season, but can enhance the formation of a boundary if it were to form due to dynamic mechanisms.

Regarding the precipitation associated with mesoscale convective boundary development over the Mississippi Delta, the large number of surface and atmospheric variables related to the intensity and distribution of precipitation makes it extremely difficult to quantify the conditions necessary for precipitation formation. However, in general it was found that upon boundary formation in the late morning (10:00 – 11:00 LST), the related precipitation began to form in the early afternoon (13:00 – 14:00 LST) and continued for several hours before the boundary weakened and dissipated. The precipitation rates were relatively low and the spatial extent of the convective storms was limited, although localized heavy rains were possible,.

Future Work

This project successfully showed that under specific atmospheric conditions during the warm season over the LMRAV, it is possible for mesoscale convective boundaries to form and modify the precipitation distribution across the region. The causes and driving mechanisms related to their development are not well known; therefore, the next logical step in this research is to quantify the influence of surface characteristics on the development of the convective boundaries and the related precipitation. This is a difficult undertaking due to the limited number of observations over the region and the large number of independent variables related to convective development and rainfall generation (i.e., topography, 4D atmospheric flow, surface moisture and heat fluxes, stability in the planetary boundary layer, etc.).

Mesoscale convective boundaries form due to a combination of mesoscale and synoptic atmospheric conditions, which are directly influenced by thermodynamic and kinematic processes associated with surface-atmosphere interactions. As a result, it is possible to augment observational studies of these phenomena using physics-based mesoscale numerical weather models. Accordingly, future research will employ the Weather Research and Forecasting (WRF) model for detailed analysis of the sensitivity of surface convergence zones to soil and vegetation patterns over the LMRAV. WRF is suited for this role since it is a non-hydrostatic mesoscale model with various convective, planetary boundary layer, and cloud physics parameterizations. Initial work with the model over the study area has led to the development of a domain at a nominal 1x1 km spatial resolution with 40 vertical levels. Plans include assimilation of soil moisture data from Soil Climate Analysis Network (SCAN) surface observing stations, which have a relatively high resolution over the study area, which would help resolve the moisture flux in the surface layers of the model.

Additionally, the results from this study can be augmented by employing an objective pattern recognition algorithm on the satellite data to more effectively recognize the development of mesoscale convective boundaries over the LMRAV. This will provide a more robust mechanism for quantifying the frequency, evolution, and intensity of these events. Also, my more accurately defining the occurrence of the convective events, a quantification of the associated rainfall depth and distribution can be obtained, which would provide valuable information to water resource managers and operational weather forecasters regarding local-scale precipitation modification.

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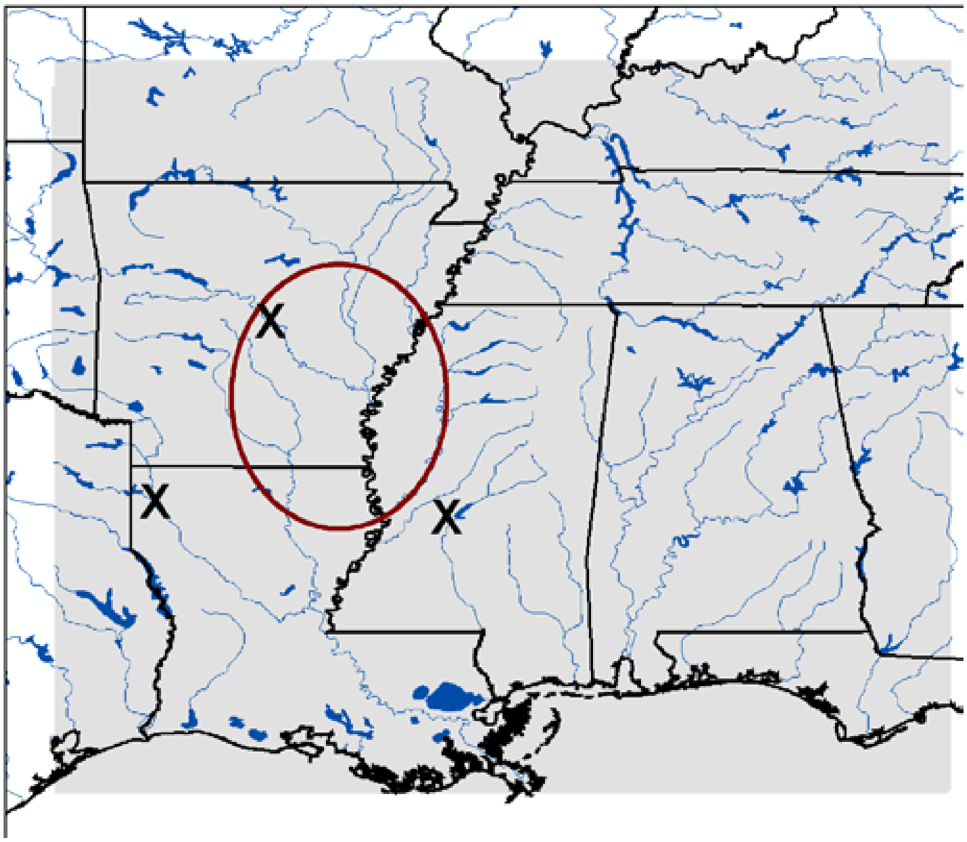


Figure 1. Study area outlined by the shaded area with the general location of the lower Mississippi River alluvial valley shown by the red oval. "X"s mark the location of the atmospheric sounding sites at Little Rock, AR, Jackson, MS, and Shreveport, LA.

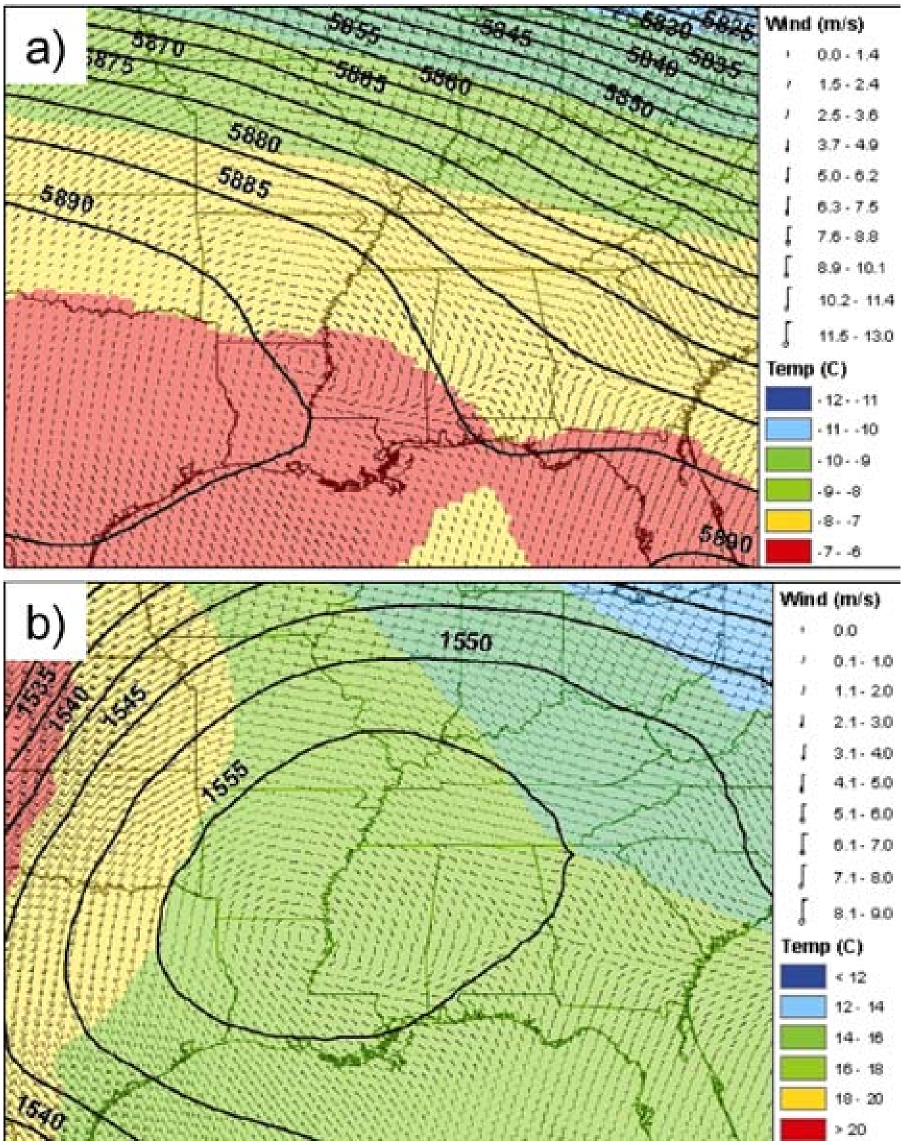


Figure 2. Mean synoptic features (wind speed, direction, temperature, and geopotential height) at (a) 500 hPa and (b) 850 hPa for all synoptically-benign days.

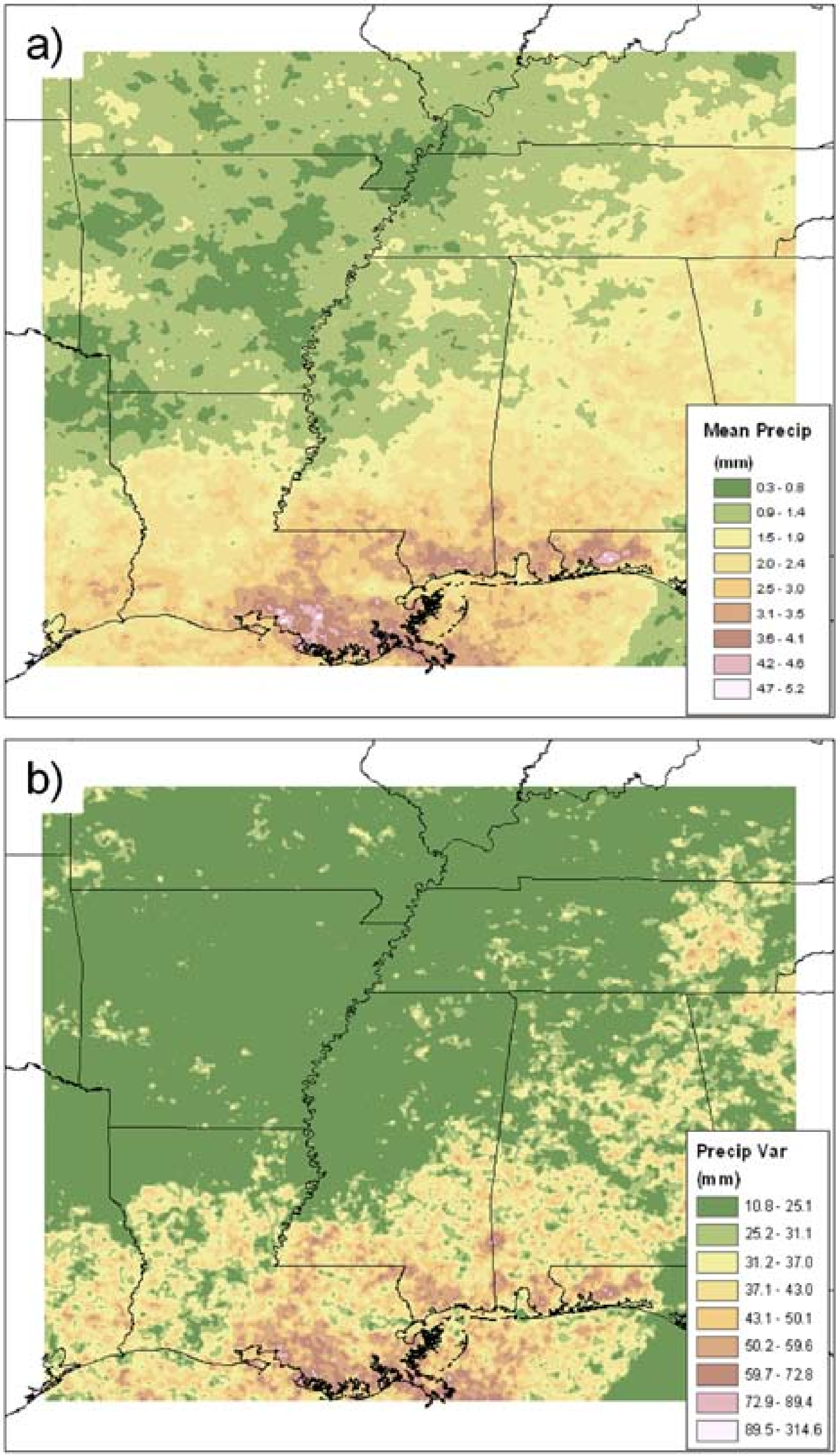
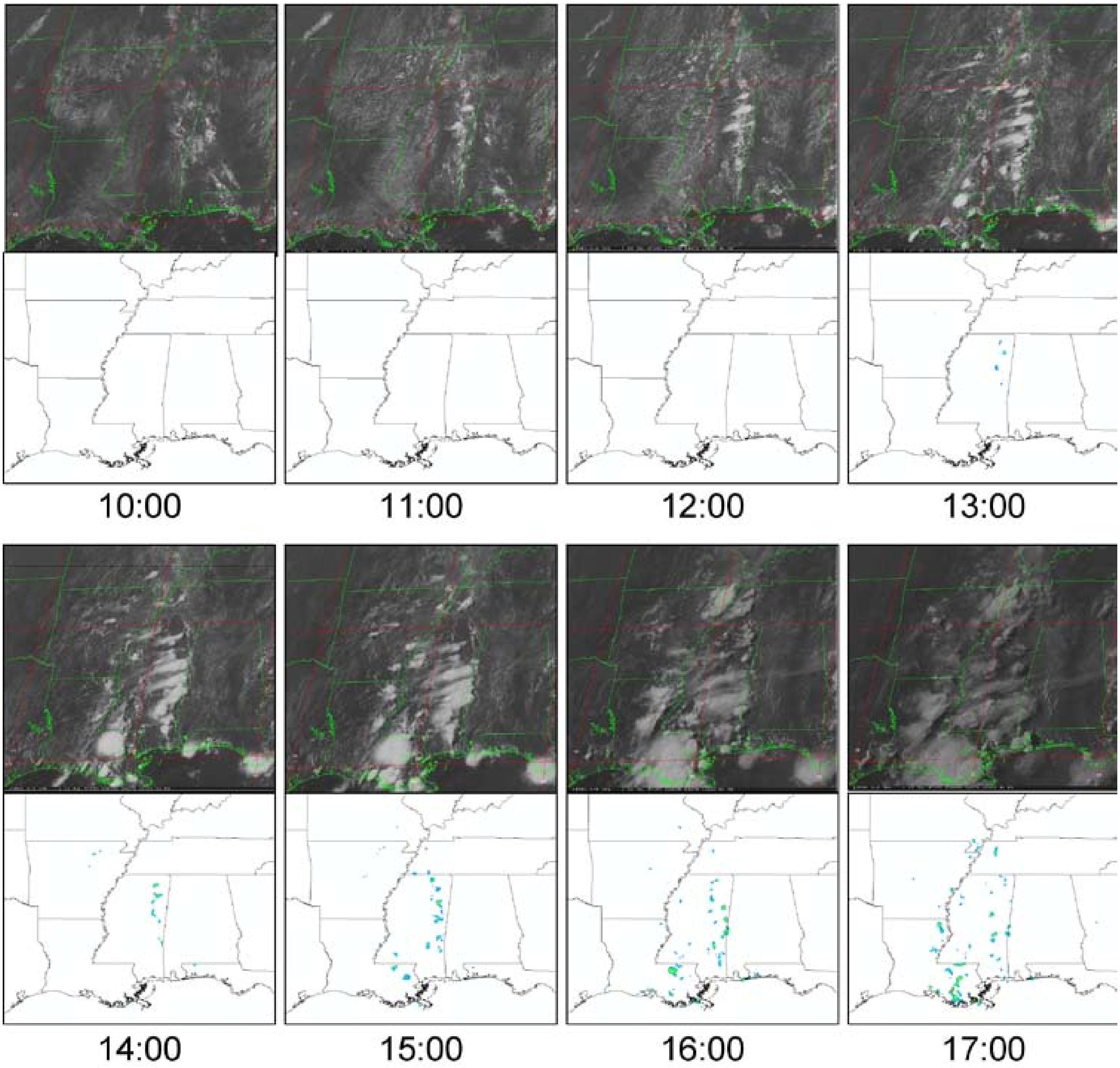


Figure 3. Daily precipitation (a) average and (b) variance for all synoptically-benign days.



10:00 11:00 12:00 13:00

14:00 15:00 16:00 17:00

Figure 4. Hourly visible GOES satellite images and multi-sensor precipitation estimates over the study area for the July 12, 1997 event from 10:00 – 17:00 LST.

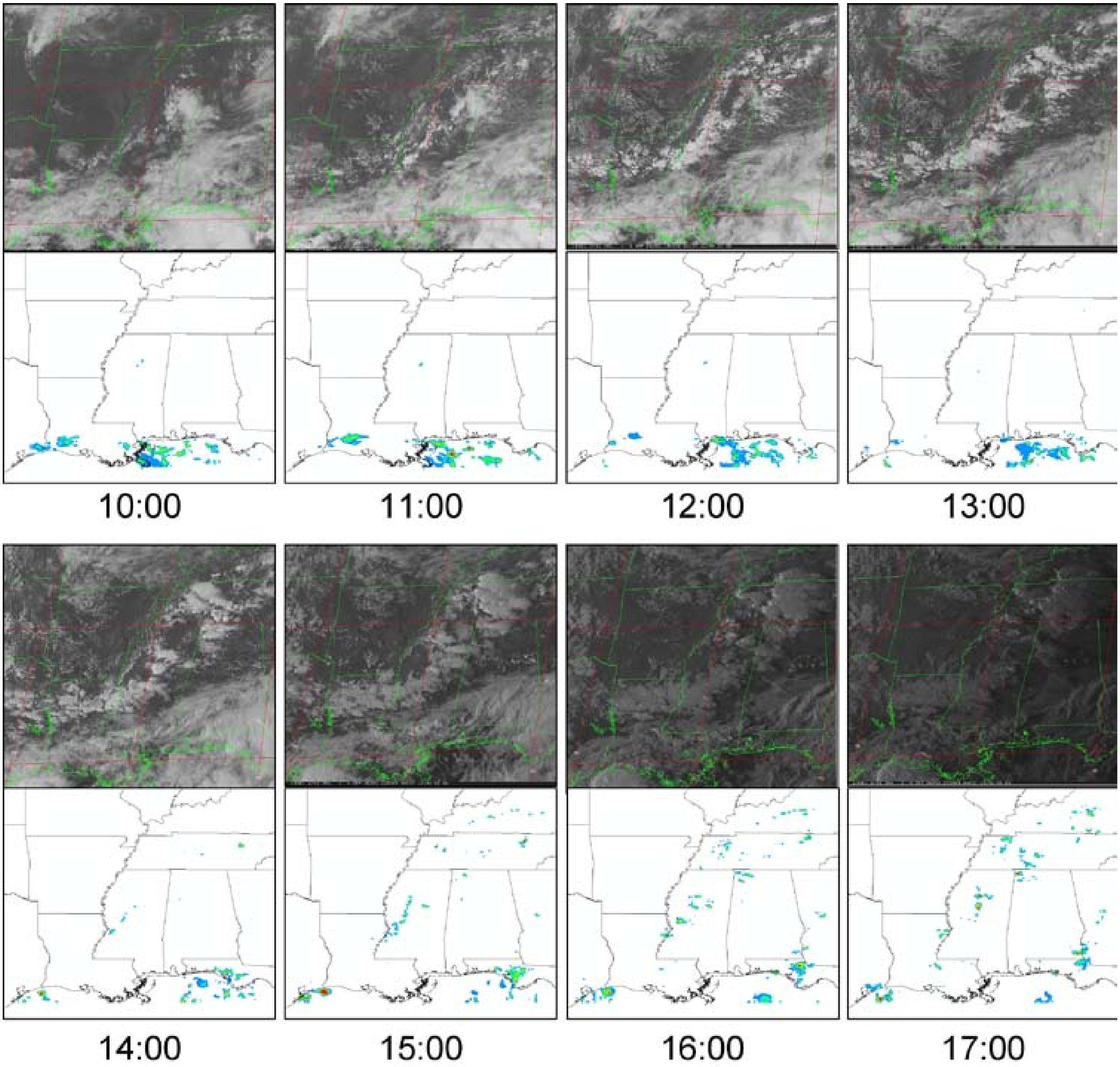


Figure 5. Hourly visible GOES satellite images and multi-sensor precipitation estimates over the study area for the September 9, 2006 event from 10:00 – 17:00 LST.