1.2 Multiscale Evolution and Predictability of a Warm Season Climate Anomaly in the U.S. Southern Great Plains

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1. Introduction

Intraseasonal changes in regional climate are difficult to predict because they often are caused by a combination of regime shifts in the large scale circulation and the development of poorly understood land-atmosphere feedback mechanisms. Improved prediction of regional climate anomalies such as heatwave, drought or flood is important to help reduce loss of life, property, and agriculture. In this paper, we examine the onset and maintenance of a seasonal climate anomaly that developed over the U.S. Southern Great Plains during summer 2002. A six-week period of cooler and wetter than average weather began with flooding rains in the vicinity of San Antonio, Texas on 1-2 July 2002. It appears that the origins of this flooding event can be traced back through a multiscale sequence of weather events to a mesoscale convective vortex that formed over Kansas and Oklahoma on 15 June 2002. The Texas flood caused saturated soil conditions which, in turn, initiated a regional soil moisture feedback process that helped maintain the cool anomaly into mid-August.

This preprint article is a descriptive summary of a work in progress. Model analyses identified in section 2 are used to diagnose the life cycle of the U.S. Southern Great Plains during summer 2002. We continue to more comprehensively analyze the dynamical relationships suggested by the multiscale sequence of weather events highlighted in section 3. While the individual weather events are related to the genesis of the regional climate anomaly, we also highlight in section 4 the possible land-atmosphere feedback mechanisms that helped maintain the anomaly. Note that some figures were omitted due to file size limitations. Interested readers are encouraged to contact the author for complete and updated reports on this work.

2. Model Analyses and Forecasts

Model analyses from the 20-km Rapid Update Cycle (RUC) are presented in section 3 to highlight a sequence of weather events occurring at multiple time and space scales that contributed to the onset and maintenance of the regional cool anomaly over the U.S. Southern Great Plains during summer 2002. The RUC analyses were produced by the NOAA Forecast Systems Laboratory and obtained from an online archive maintained by the Atmospheric Radiation Measurement (ARM) Program (http://www.archive.arm.gov). Anomaly fields shown in section 4 are calculated relative to the 1971-2000 long term mean using the NCEP Reanalysis (Kalnay et al., 1996). The NCEP Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center (CDC), Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov/. Precipitation data were provided by the NOAA Climate Prediction Center (CPC) U.S. Unified Precipitation Dataset gridded at 0.25 degree resolution (Higgins, 2000). The Unified Precipitation Dataset for 2002 was obtained from the CPC web site (http://www.cpc.noaa.gov) while the 1948-1998 long term mean of these data was obtained from the CDC website listed above.

3. Multiscale Weather Events of Summer 2002

In this section we highlight a multiscale sequence of weather events that occurred in summer 2002, emphasizing those which appeared to contribute most directly to the onset of the regional cool anomaly over the U.S. Southern Great Plains.

a. *Mesoscale Convective Vortex*

On 15 June 2002, a large-scale upper-level ridge (trough) axis was positioned over the western (east-

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ern) United States. A mobile upper-level short-wave originated over the Pacific Northwest, passed through the ridge, and traveled across the Rocky Mountains to help initiate a lee surface cyclone in southeastern Colorado on 16 June 2002. A mesoscale convective system (MCS) formed in this environment on 15-16 June (Fig. 1) 2002 and evolved into a squall line affecting Kansas and Oklahoma. The MCS introduced a source of vorticity as seen in Fig. 1a. The resulting mesoscale convective vortex (MCV) remained coherent while tracking southeastward into southern Mississippi and Alabama by 18-19 June 2002 (not shown). At this time, the MCV and its associated convection was located near the bottom of the large-scale trough. When the large-scale trough began to fill and move downstream, the residual effects of the MCV appear to have helped induce a large upper-level cutoff cyclone over the southeastern U.S. as described in the following subsection.

b. Southeastern U.S. Cutoff Cyclone

By 21 June 2002 the large-scale wave pattern had shifted eastward so that the ridge axis was centered over the central United States (compare Fig. 1a and Fig. 2). The convective activity described previously appears to have introduced a vorticity source and enhanced diffluence upstream of where the large-scale cutoff cyclone formed. This is consistent with the findings of Bell and Bosart (1993) in a study of winter cutoff cyclone genesis in the same region. They stated in their abstract that

> “The primary large-scale features prior to cutoff cyclone formation are an amplifying ridge over the western United States and eastern North Pacific and a diffluent trough over the central United States. The primary smaller-scale feature prior to cutoff formation is a short-wave trough-jet streak system that propagates through the longer-wave-amplifying ridge, and then intensifies upon arriving in northwesterly flow downstream of the ridge axis. The intensification of this shorter-wavelength system is associated with increases in stratospheric potential vorticity at levels considered to be well within the middle and upper troposphere.”

Many of these features are seen as the flow pattern evolves between 15 and 21 June 2002. The passage of a short-wave trough through the northwesterly flow downstream of the ridge axis was seen in Fig. 1a in association with the MCS on 15-16 June 2002. Figure 2 shows intensification of the shorter-wavelength system over Alabama and Georgia on 21 June 2002 as the tropopause pressure (a proxy measure of stratospheric potential vorticity) descends below the 400 hPa level.

Unlike the case examined by Bell and Bosart (1993), the present cutoff cyclone also has characteristics of a “trough fracture” (Dean and Bosart, 1996), defined as a splitting of a single vorticity center into two or more separate vorticity centers. Indeed, Dean and Bosart (1996) state that “trough fracture occurrences are frequently associated with the formation of a cutoff cyclone equatorward of the main belt of westerlies.” We see this in Fig. 2 as the large-scale trough shifted eastward into the North Atlantic (just beyond the edge of the figure) while apparently leaving behind a secondary local vorticity maxima. For the present case, it is difficult to determine if the vorticity associated with the cutoff cyclone was provided by a trough fracture or by the intensification of the short-wave trough propagating into the area from the northwest. If the latter mechanism played a role, then it is probable that the MCS event was related to the genesis of the cutoff cyclone.

Prediction of cutoff cyclones is considered a type of flow regime change that is difficult for NWP models to handle well. With poor numerical guidance for these events, forecasters often have difficulty anticipating the formation of cutoff cyclones at long lead times. A review of extended forecast discussions from NCEP’s Hydrometeorological Prediction Center (HPC) suggests that forecasters began to anticipate the development of the cutoff cyclone and its enhanced diurnal convection over the southeastern U.S. by around 18 June 2002. This was just 2-3 days prior to when the cutoff cyclone formed. The multi-scale characteristics of features contributing to cutoff cyclone genesis raise questions about how the predictability limit of such events compares to that of convective storms described in the previous section. Furthermore, all of the features involved may depend on potential vorticity anomalies or other features that are poorly represented in observations or analyses (i.e. Roebber et al., 2002). Some of these concerns will be explored later.

c. Texas Flood

After the upper-level cutoff cyclone developed over the southeastern U.S. around 21 June 2002, it drifted slowly westward across states bordering the Gulf of Mexico. Deep layer moisture originating from the Gulf of Mexico and western Caribbean Sea was drawn into the cyclonic circulation (not shown). The enhanced instability and moisture associated with the cutoff cyclone caused increased diurnal convection and cooler temperatures across the southeastern U.S. through 1 July 2002 (see section 4b).

By 1 July 2002, the strength of the upper-level anomaly began to diminish, but its residual effects were seen as a broad inverted trough in the middle troposphere (Fig. 3a). Embedded within the inverted trough were two vorticity maxima, one located over southwest Texas and another over Kansas and Oklahoma. Strong moisture and warm temperature advection in the lower troposphere (Fig. 3b,c) provided the remaining ingredients for flooding rains to occur in south Texas. Figure 4 shows accumulated rainfall over Texas and Oklahoma from 1-7 July 2002. Federal and state disaster assistance from the flood exceeded $65 million through 19 August 2002 (FEMA, News Release 1425-74, 21 August, 2002, available online at http://www.fema.gov/diz02/d1425n74.shtm). Nine persons died in the event, and 39 counties in Texas were declared Presidential disaster areas for losses due to flooding.

Floods of this magnitude are not uncommon in south Texas. Grice and Maddox (1982) examined 31 heavy rain cases that were not of tropical origin. Among the features common for all the events they studied were a moisture ridge and strong warm advection in the lower troposphere. Furthermore, Grice and Maddox (1982) found that upper-level support was present for all events such as a traveling shortwave in nearly zonal westerly flow (their "meso-high" scenario) or a nearly stationary trough with split flow (their "frontal" scenario). The case considered here presented the common lower-tropospheric conditions needed for heavy rain events. However, upper-level features are different from either scenario described by Grice and Maddox (1982) as the subtropical high that normally suppresses convection was divided by an inverted trough that originated with the cutoff cyclone over the southeastern United States.

Examination of HPC forecast discussions revealed that forecasters anticipated a heavy rainfall event as early as 24 June 2002, but could not consistently identify a preferred location for where the heavy rain would occur. Furthermore, HPC forecasters maintained continuity in their belief that the upper level shortwave features embedded in the large-scale inverted trough would turn north and rejoin the westerly flow. The persistence and strength of the ridge to the west prevented this from happening. After the onset of the flooding event, HPC forecasters correctly suggested that an elevated convective threat and below normal temperatures should be expected throughout July 2002.

In sum, a shortwave of continental origin helped induce an MCS in northwesterly flow over the central Plains which, in turn, may have helped induce an upper-level cutoff circulation that ultimately led to a major flooding event in Texas. The sequence of events occurred on time scales of hours to weeks and ranged in size from convective to synoptic scales. Individually, each of these events were difficult to predict beyond a few days lead time. Thus, it would have been exceedingly difficult to anticipate the onset of a persistent regional climate anomaly that followed the Texas flood as described in the following section.

4. Regional Climate Responses to Weather

Climate is defined as the integral effect of weather occurring throughout a specified period of time. A sequence of weather events were highlighted in the previous section that occurred on multiple time and space scales during summer 2002. Consider now the intraseasonal climatic response to these weather events, with regional emphasis on the U.S. southern Great Plains.

Societal impacts of climate are experienced in terms of "sensible" weather such as temperature, humidity, and rainfall. Thus, in the present section, intraseasonal variations in 2-m temperature anomalies and fraction of normal rainfall are presented as averages over half-monthly periods (Fig. 6). Humidity anomalies are not shown because they are, as expected, negatively correlated with temperature anomalies and provide little additional information. To identify plausible mechanisms that help initiate and maintain the "sensible" characteristics of climate anomalies, we additionally show 500 hPa geopotential height anomalies (Fig. 5), fraction of normal 0-10 cm soil water content, and 700-500 hPa lapse rate anomalies (Fig. 7). The goal here is not to determine *conclusively* which processes (*e.g.*, feedback cycles) contributed most strongly to the onset and maintenance of the regional climate anomalies. To do so would require extensive and carefully controlled numerical sensitivity studies that are beyond the scope of the present paper. Instead, our contribution is to demonstrate that seasonal prediction of regional climate anomalies is limited by present capabilities of forecasting the multiscale progression of individual weather events. This is accomplished by documenting the presence of regional climate anomalies and showing that their existence is linked directly to the sequence of weather events described above.

a. 1 June to 15 June 2002

Negative 500 hPa height anomalies were present across parts of the northern U.S. and southern Canada during the first half of June 2002 (Fig. 5a). These negative anomalies were produced as a deep trough moved from west to east during the period. Enhanced rainfall and cooler than normal 2-m temperatures were collocated beneath the negative height anomalies across the northern U.S. (Fig. 6a). In contrast, heatwave and drought conditions began to develop over the western U.S. associated with positive height anomalies and dry soils (Figs. 5-7a).

The negative temperature anomalies over the northern and southern Great Plains appear highly correlated with positive 0-10 cm soil moisture anomalies and negative 500-700 hPa lapse rate anomalies (compare Figs. 6a and 7a). Although anticorrelated soil moisture and temperature anomalies can be attributed to local feedback processes, inspection of daily anomaly maps (not shown) reveals that the soil moisture and temperature anomalies were not present until rainfall occurred in these areas. The negative lapse rate anomalies found over the same regions can be attributed to midtropospheric latent heat release associated with cloud condensation. In combination, the anomaly features suggest that the reduction of 2-m temperatures was due to the enhanced clouds and rain from transient weather systems, rather than by land-surface feedback processes associated with persistent soil moisture anomalies.

The regional climate anomalies during the first half of June 2002 appear to result from rather transient weather events and have no clearly identifiable maintenance mechanisms. It is important to note the lack of such features during this period to show how less transient weather events later in the summer helped initiate persistent regional climate anomalies.

b. 16 June to 30 June 2002

Persistent regional climate anomalies began to appear in the second half of June 2002 associated with the development of a strong 500 hPa ridge over the Great Lakes and an unusually deep upper level cutoff low over the southeastern U.S. (Fig. 5b and Sec. 3b above). The cutoff low drifted westward, slowed by additional ridging over the southwestern United States. The heatwave and drought strengthened across the most of the U.S. except in the southeast where enhanced rainfall and cooling occurred in association with the drifting upper level cyclone (Fig. 6b).

For the same reasons outlined in the previous period, the cool temperatures over the southeastern U.S. do not appear physically linked to the collocated positive soil moisture anomaly. As the upper level cyclone drifted slowly westward, convective rainfall increased in frequency and coverage causing a non-monotonic increase in soil moisture over Louisiana and eastern Texas. The initial formation of this soil moisture anomaly is highlighted because it persists through August and arguably contributes to the maintenance of an important regional climate anomaly. From this viewpoint, it is clear that cut-off cyclones must be predicted accurately to help anticipate the onset of intraseasonal regional climate changes. Unfortunately, cut-off cyclone development usually is not forecast well by numerical weather prediction models during summer.

c. 1 July to 15 July 2002

Heatwave and drought conditions continued into July across the western U.S. as the 500 hPa ridge amplified further over the region. The amplifying ridge blocked the westward progression of the upper level cutoff cyclone that had formed over the southeastern U.S. in the previous period (Fig. 5c). This large scale circulation pattern contributed to an historic flooding event in Texas during the first few days of July 2002 (see Sec. 3c). The excessive rains led to saturation of the 0-10 cm soil layer across Texas and Oklahoma (Fig. 7c). As before, it does not appear that the soil moisture anomaly contributed to negative 2-m temperature anomalies during this period. It is more likely that the cooler weather was caused by reduced solar radiation passing through the cloud cover associated with such unstable atmospheric conditions.

The large-scale circulation established favorable conditions for the flood to occur in Texas. However, the smaller scale details such as vorticity and moisture convergence embedded within the broader cyclonic circulation determined more precisely where the flooding rains occurred (see section 3b). Our ability to forecast the flood and, hence, the formation of a regional climate anomaly, is crucially dependent on the skill in predicting the timing and placement of the smaller scale features. This example illustrates again that skillful prediction of intraseasonal climate changes requires accuracy at all scales.

d. 16 July to 31 July 2002

The positive 500 hPa height anomaly relaxed during the second half of July 2002, returning to near normal except over the Great Lakes (Fig. 5d). The western U.S. heat wave weakened and shifted eastward to the central plains and Great Lakes regions where

2-m temperatures were more than 2 degrees above average (Fig. 6d). The southern plains soil moisture anomaly associated with the Texas flood persisted through the entire month (Fig. 7d).

An anomaly couplet of 2-m temperatures formed over the central and southern plains during this period (Fig. 6d). The couplet appears to lack upper-level support, but does seem related to soil moisture and 700-500 hPa lapse rate anomalies. This is a change from earlier periods wherein the 2-m temperature and lapse rate anomalies were more closely tied to those of the 500 hPa height field. Warm 2-m temperatures and positive lapse rate anomalies over the central plains suggest that the boundary layer mixed deeply with strong heating and low humidity. In contrast, the persistently cool 2-m temperatures over the southern plains were collocated with positive soil moisture anomalies and nearly normal lapse rate anomalies. These characteristics suggest that the enhanced soil moisture caused a repartitioning of the surface energy balance, thereby enforcing a commonly understood feedback cycle between soil moisture, temperature and humidity. Since the formation of this feedback cycle is linked to the Texas flood in early July, it is clear that accurate prediction of a persistent regional climate anomaly depends on skillful prediction at all scales of motion.

e. 1 August to 15 August 2002

Positive 500 hPa height anomalies remained over the Great Lakes during early August, but negative anomalies appeared over the northwestern U.S. as the flow became more transient (Fig. 5e). Consequently, the heatwave ended over the western U.S. (Fig. 6e) and 700-500 hPa lapse rate anomalies had little in common with those of earlier periods (Fig. 7e). Only the 2-m temperature and soil moisture anomalies over the southern plains continued to persist into August. Hence, having persisted for about six weeks, these were the longest lasting anomalies of the summer season and highlight the multiscale evolution of individual weather events into regional climate.

f. 16 August to 30 August 2002

During the second half of August 2002, 500 hPa height fields returned to near normal as the flow became more northwesterly (Fig. 5f). Rainfall associated with transient waves enhanced soil moisture levels over much of the United States (compare Figs. 6f and 7f). The southern plains climate anomaly had finally dissipated, indicating that residual effects of the July flood no longer influenced the region. This concludes our description of the southern plains climate anomaly, although other features began to develop in manner that is consistent with the arguments herein.

5. Conclusions

This paper has demonstrated that a multiscale sequence of individual events collectively acted to help initiate a persistent regional climate anomaly over the U.S. Southern Great Plains during summer 2002. Each of these events has limited predictability, so it would have been difficult to anticipate their combined contribution toward the onset of the regional climate anomaly. In continuing work, the dynamical relationships among the events described herein will be explored in greater detail. Furthermore, the value of forecast guidance provided for these events by operational and research global forecast models will be evaluated. It is hoped that lessons learned from this research will ultimately help improve forecasts of future regional climate anomalies, either by contributing to forecaster knowledge or by motivating specific improvements in NWP models.

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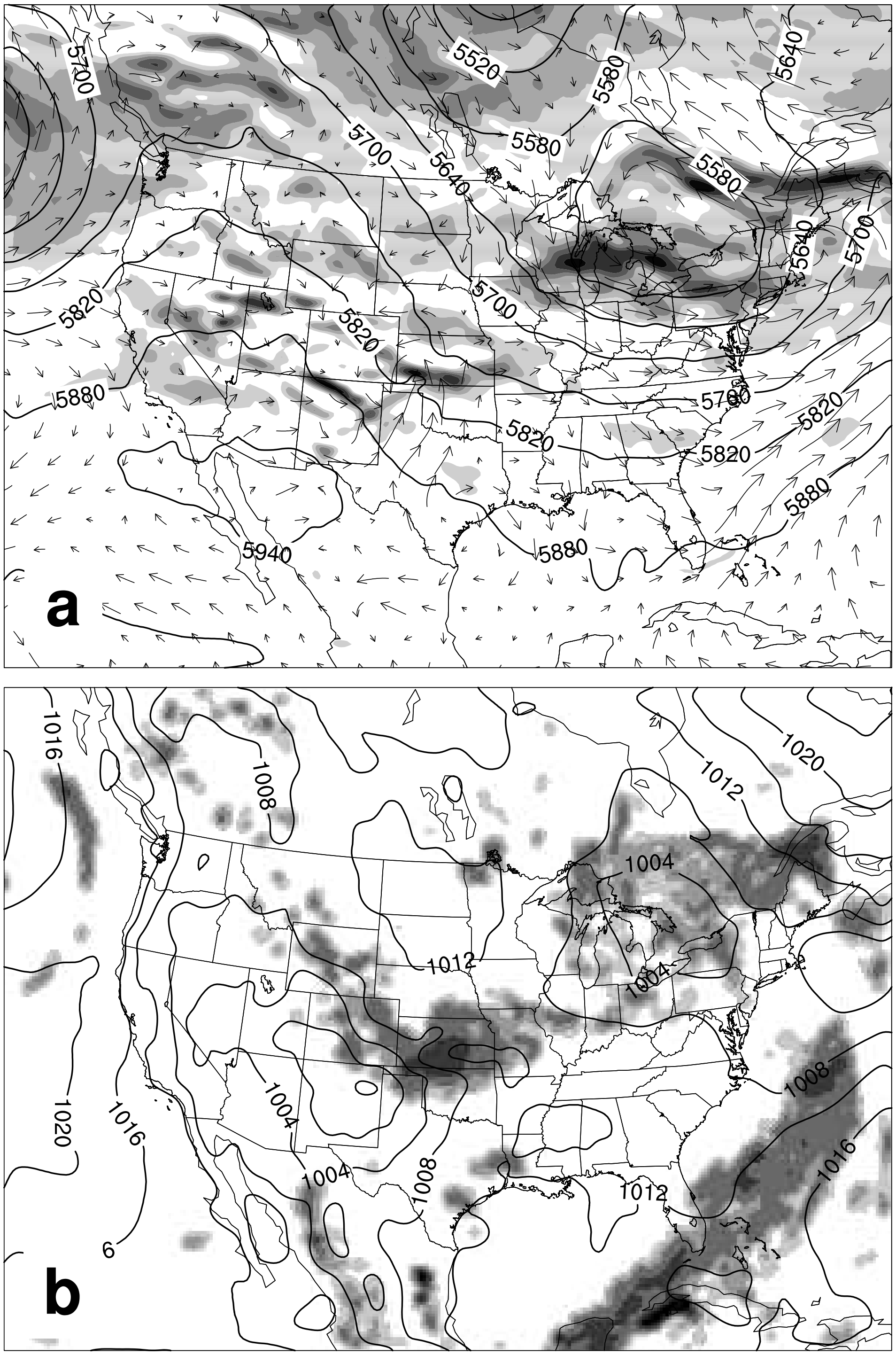


Figure 1: Analysis fields obtained from the 20-km RUC model valid 0000 UTC 16 June 2002. Panel (a) shows 500 hPa geopotential height, 500-600 hPa layer mean absolute vorticity (shaded), and 850 hPa wind vectors. Vorticity shading levels are (10,12,14,16,18,20)$\times 10^{-5}$ s^{-1}. Panel (b) shows mean sea-level pressure and 3-hr total model rainfall with shading at (0.01, 0.10, 0.25, 0.5, 1.0) inches.

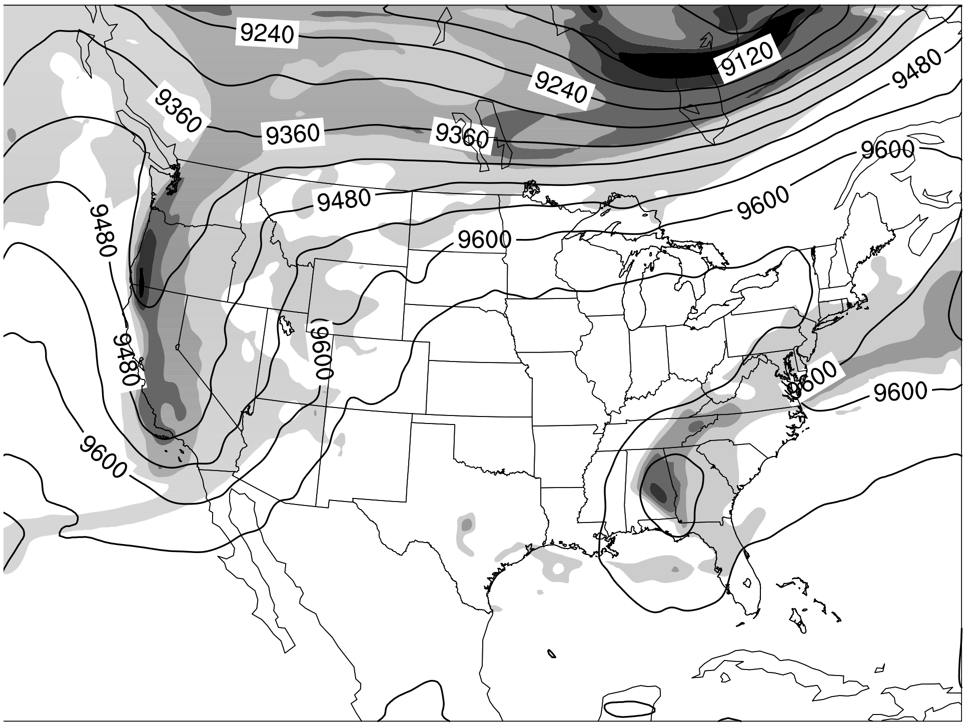
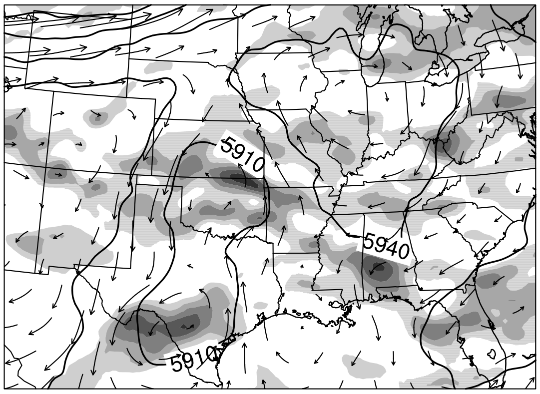
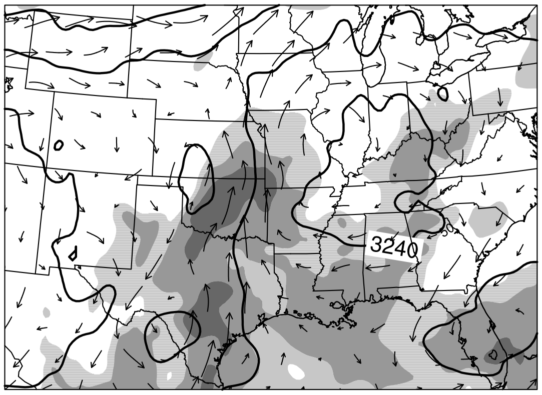


Figure 2: Analyses of tropopause pressure (shaded) and 300 hPa geopotential height from the 20-km RUC model valid 1200 UTC 21 June 2002. Tropopause pressure shading levels, from light to dark, are (200, 250, 300, 350, 400) hPa.

a) 500 hPa Geopotential Height, Vorticity, Vectors



b) 700 hPa Geopotential Height, Relative Humidity, Vectors



c) 850 hPa Geopotential Hgt, Isotherms, Vectors

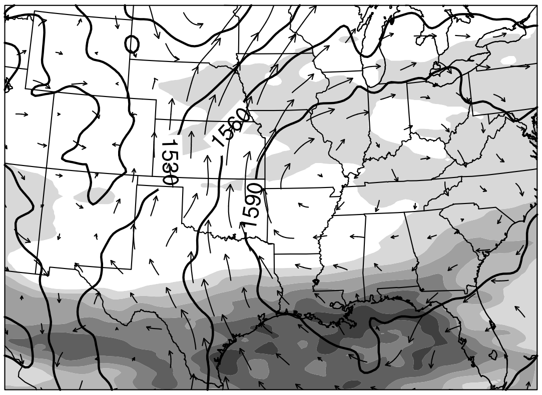


Figure 3: Analysis fields obtained from the 20-km RUC model valid 1800 UTC 1 July 2002. Geopotential height and wind vectors are shown for each panel at (a) 500, (b) 700, and (c) 850 hPa pressure levels. In (a), 500 hPa absolute vorticity shading levels are $(8,10,12,14,16,18)\times10^{-5}\ \mathrm{s}^{-1}$. In (b), 700 hPa relative humidity shading levels are (50,70,90) percent. In (c), 850 hPa temperature shading levels are (18,21,24,27,30,33) °C. In each panel, shading darkens toward higher values.

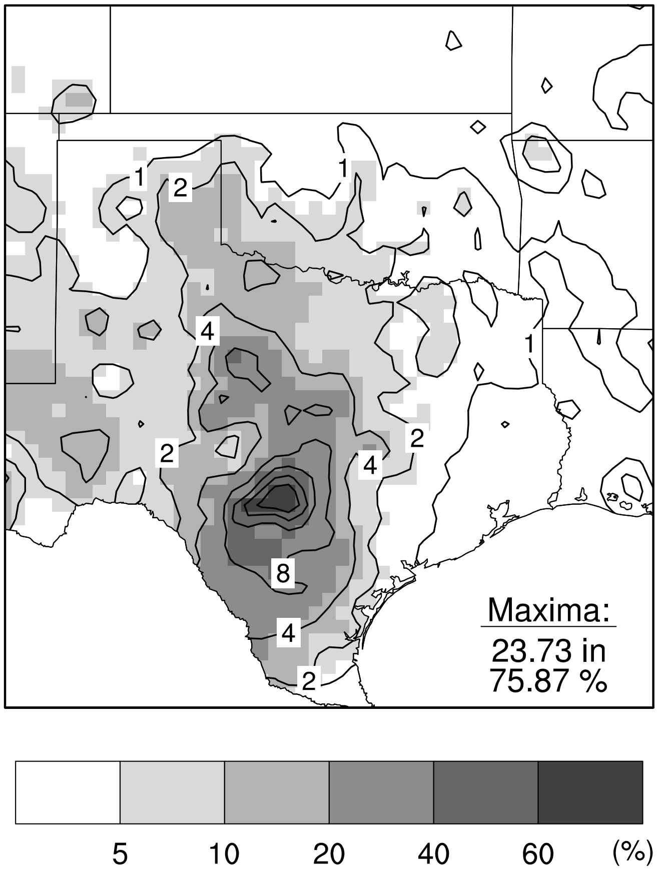
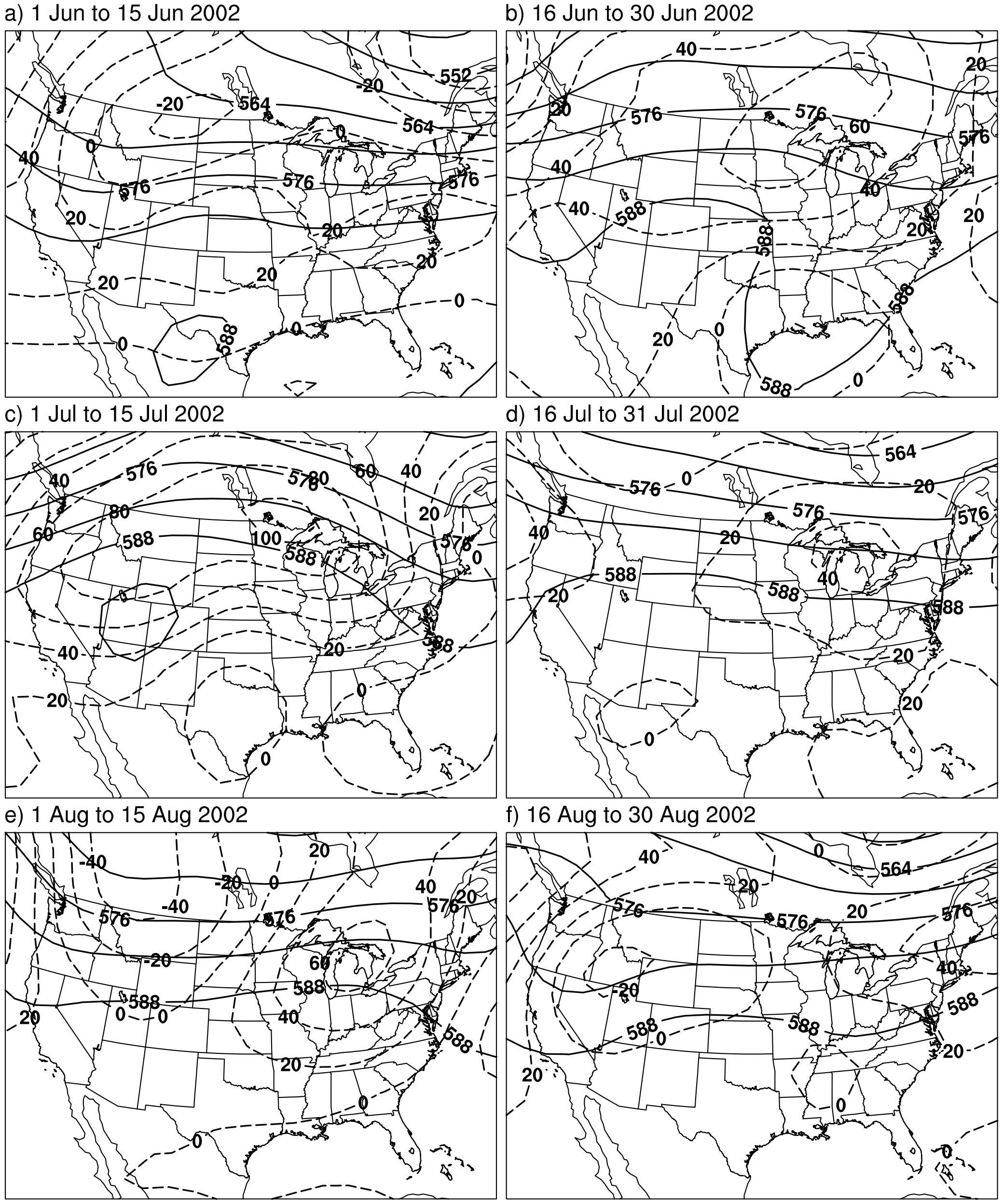


Figure 4: 1-7 July 2002 accumulated rainfall ([1,2,4,8,12,16,20] inch isohyets) and its percentage of the 1948-1998 annual average (shaded).



a) 1 Jun to 15 Jun 2002

b) 16 Jun to 30 Jun 2002

c) 1 Jul to 15 Jul 2002

d) 16 Jul to 31 Jul 2002

e) 1 Aug to 15 Aug 2002

f) 16 Aug to 30 Aug 2002

Figure 5: Mean 500 hPa height fields (solid, dm) and anomalies (dashed, m) during indicated half-monthly periods.

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Figure 6: 2-meter temperature anomalies (°C) and fraction of normal rainfall (shaded) during indicated half-monthly periods.

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Figure 7: Fraction of normal 0-10 cm soil moisture (shaded) and 500-700 hPa lapse rate anomalies (°C/km) during indicated half-monthly periods.