15-Year Climatology of Fronts and Convective Cold Pools in the Oklahoma Mesonet

Part II: Case Studies

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ABSTRACT

1. Introduction

Section 2 details the methodology for analyzing frontal passages and cold pools. Section 3 covers results for four cases studies: 1) 13 June 1997, 2) 15-16 June 2002, 3) 20 May 2011, and 4) 24-25 May 2011. Section 4 summarizes the conclusions.

2. Analysis Methodology

The data used in this analysis comes from the Department of Energy Atmospheric Radiation Measurement (ARM) Program's Oklahoma Mesonet dataset (Brock et al. 1995; McPherson et al. 2007). The selected data cover over 100 non-panhandle stations at 5-minute frequency covering the period 1997-2011 at roughly 40 km spacing.

The frontal passages are identified using the analysis method described in more detail in Part I. Using 30-minute differences in diurnal and elevation adjusted temperature and pressure, calculated every 5 minutes, a unitless front score (FS) can be calculated (Eq. 1).

$$FS_{\text{final}} = 1\,\text{mb}^{-1}\Delta P_{\text{diur.,elev.}} - 1\,\text{K}^{-1}\Delta T_{\text{diur.,elev.}} \tag{1}$$

Fronts occur at Mesonet stations when the FS exceeds a minimum threshold of 3, while fronts occur at Mesonet triangles if the FS exceeds the minimum threshold at all three stations within a 2-hour span.

Cold pools occur at Mesonet triangles if the triangle experiences both a frontal passage and if the strong divergence threshold ($D_i > 10^{-4}\text{s}^{-1}$) is reached within half an hour before or an hour after the front reaches halfway across the triangle. These fronts and cold pools can be tracked across the Mesonet.

3. Case Study Results

Over the course of 15 yrs of Mesonet data, tens of thousands of frontal passages at triangles were detected in the Oklahoma Mesonet. Hundreds of events involving a front that sweeps through large portions of the Mesonet can be used for case studies. Four such cases will be shown in this section: 1) 13 June 1997, 2) 15-16 June 2002, 3) 20 May 2011, and 4) 24-25 May 2011. These cases are supplemented with radar images from the UCAR image archive.

a. 13 June 1997 Case

At approximately 0000 UTC on 13 June 1997 a squall line, which initiated in southeastern Colorado and northeastern New Mexico, entered Kansas, the Oklahoma panhandle, and Texas. The disorganized line of thunderstorms reached the Mesonet grid at roughly 0300 UTC and was tracked for the next 7 hrs across the Mesonet (Fig. 1) with isolated thunderstorms popping up ahead of the main line. At 0330 UTC (Fig. 1a) the front analysis found only smaller segments of a front (yellow and magenta segments for fronts and strong fronts, respectively) in the northwest and center-west portions of Oklahoma. The radar images show a gap between two thunderstorms that coincides with the lack of strong convergence (the gap in the red dots in Fig. 1a). In the areas where a front was defined, convergence was present to the east ahead of the front and divergence to the west behind the front. At 0330 UTC there was only one triangle designated as in a cold pool, located in the northwestern corner of the Mesonet domain.

From the 0500 UTC front analysis (Fig. 1b), the stronger, more well-defined front marks the leading edge of the system which had been organizing over the previous two hours. There was some bowing of the front present with trailing stratiform precipitation. The squall line had caught up to the isolated thunderstorms that developed ahead of the line. The area ahead of the front had strong convergence while strong divergence was present behind the front. Farther behind the front, near the back edge of the stratiform precipitation, there was a second region of convergence where a one-triangle front is marked. The analysis was designed to capture the strongest fronts at each triangle and in this case this latter front was stronger than when the initial line passed through heading eastward. This was likely a result of the squall line being somewhat disorganized in that area at the time it passed that particular triangle. A large active cold pool stretched from the front of the main squall line to the back edge of the stratiform precipitation in west-central Oklahoma.

From 0500 to 0700 UTC, the supercell at the south end of the squall line separated from the rest of the line. This separation appears in the form of a gap in the front indicated by lower FSs and the lack of significant radar returns (Fig. 1c). The southern cell has weaker FSs than the more well defined squall line to the northeast. The region of strong divergence was primarily concentrated in north central Oklahoma, with a smaller area of strong divergence behind the southern supercell. Cold pools are identified in both of these areas. In Western Oklahoma a few small convective cells had formed behind the secondary convergence line.

By 0900 UTC the southern supercell had progressed southeastward much farther away from the rest of the line while the main squall line continued eastward (Fig. 1d). The area of strong divergence behind the front was more concentrated on the southern half of the squall line. There was a weaker front to the east of the southern supercell. Behind the supercell to the northwest, trailing convection developed over the previous 2 hrs and eventually merges with the southern supercell (not pictured). There was clear separation between the convergence and divergence regions in the trailing convection. Overall, the front analysis performed well at representing the location of the front that would be expected based on the radar images. Despite the separation in the front, the cold pool along the front almost extends from the southern border with Texas to the northern border with Kansas. Notably, the cold pool extends back behind the front in east-central Oklahoma, suggesting a long-lived cold pool. At this time, the main cold pool has been in place for hours and has advanced eastward over time behind the squall line. However, large areas of stratiform precipitation are not classified as in a cold pool because the divergence values were not high enough at this time. Many of the triangles in northeastern Oklahoma would likely be defined as in a cold pool using a different definition relying more on sustained stratiform precipitation or lingering temperature falls.

b. 15-16 June 2002 Case

Around 1800 UTC 15 June, a line of thunderstorms oriented from northwest to southeast was located in north central Kansas and south central Nebraska moving southeastward. Over the next few hours the line merged with pop up thunderstorms in west central Kansas and spread out allowing for a much more southwest to northeast oriented storm front to develop as the combined system moved south towards the Oklahoma border. The frontal passage and cold pool (Fig. 2) analysis for this event are shown.

At 0000 UTC 16 June the squall line had just entered the northwest corner of Oklahoma. Very strong convection was present ahead of the line, including triangles over 50 km ahead of the squall line (Fig. 2a). Divergence behind the front was present as well as this line had developed into a mature system several hours earlier. The FSs exceeded the strong front threshold. A few isolated triangles along and just behind the line were designated as cold pools at this time. Presumably, the cold pool extends into Kansas.

Ninety minutes later the squall line had progressed into the state reaching from almost the southwest corner to the northeast corner of Oklahoma (Fig. 2b). The stronger radar echoes were in the western half of the squall line, matching up with the stronger FSs. Additionally, the convergence-divergence pattern ahead of and behind the front was more well-defined in the western half of the state though present throughout the squall line. A broad region of heavy stratiform precipitation was located in north central Oklahoma. In that stratiform precipitation region a cold pool was detected far behind the squall line. Additionally, along the front there was a narrow band of scattered triangles that are in cold pool status, just behind strong convective cells.

By 0300 UTC the eastern half of the squall line had lost much of its strong convection resulting in a front that does not extend all the way to the Arkansas border (Fig. 2c), or at least not a front strong enough to meet the minimum threshold in this study. The southwestern corner of Oklahoma still features strong convection, with the line extended towards north central Texas. The eastern half of the state has lost most of its divergence behind the line as the convective structure has fallen apart. However, there was still a narrow region of convergence ahead of the squall line. South central Oklahoma had a very large area of divergence behind the front. This extends up into north central Oklahoma with the trailing portion of the stratiform precipitation region. A small line of convergence was present in the stratiform precipitation region in north central Oklahoma with an additional larger line of convergence behind the stratiform precipitation. There are many triangles experiencing a cold pool in south central Oklahoma behind the squall line. Extending back several triangles deep, this cold pool covers roughly one eighth of the state. The eastern half of the state has much less cold pool coverage in this analysis though the cold pool does include a couple triangles in the northeast corner where the front had passed over an hr prior.

As the system moves farther southeast the strength of the convection in Oklahoma weakened further as the strongest cells to the west moved into Texas. The stratiform region of precipitation was well-defined and contained a large area of divergence behind the remnants of the squall line in Oklahoma (Fig. 2d). The line of convergence that was just behind the stratiform precipitation region has fallen farther behind the precipitation though it maintains an almost continuous line through a large portion of the northwest to north central region. The cold pool was concentrated in the south central stratiform precipitation with a few solitary triangles elsewhere in cold pools.

c. 20 May 2011 Case

One of the more notable cases during the Mid-Latitude Continental Convective Clouds Experiment (MC3E) occurred on 20 May 2011 (Fig. 3). Scattered convective cells formed in central Oklahoma and by 0400 UTC the cells stretched from the Oklahoma-Texas border southwest to the Texas panhandle. These cells organized into a squall line and started to build north through southwestern Oklahoma with the fronts and cold pools tracked with the algorithm.

At 0900 UTC (Fig. 3a) the front analysis shows a strong front stretching from southwestern Oklahoma northward. There was a well-defined squall line as well as convergence ahead of the front and areas of strong divergence behind the front. The structure of the line appears less organized at the northern end of the front as strong convection juts out ahead of the rest of the front. This was due to an isolated thunderstorm from earlier that was merging into the squall line. Due to the merging of that thunderstorm, the frontal boundary was not as well defined in that area and there was only some semblance of a convergence-divergence couplet. Since the line had just developed northward into the area the previous 2 hrs, only two triangles have cold pools present at 0900 UTC.

Over the next couple of hours the squall line builds throughout northern Oklahoma. By 1100 UTC the line had developed a bow shape (Fig. 3b). Notably, the easternmost part of the bow had lower FSs and contained a break in the high convergence area as well as having slightly lower radar returns. However, a strong divergence area behind the line did remain intact in that region. The northern part of the squall line has convergence ahead of the front but the FSs at some stations were not high enough to trigger a front to be drawn in that area. Since the northern edge of the front was the most recent to form, it was not strong enough to meet minimum front score thresholds. A distinct line of triangles containing cold pools stretches through two thirds of the meridional length of the state just behind the front. Unlike the 1997 case, the cold pool does not extend as far back behind the front.

From 1100 to 1300 UTC the northern part of the bow began to fall apart. Convection ahead of the front led to a more scattered area of thunderstorms in northeastern Oklahoma (Fig. 3c) as well as thunderstorms popping up several counties east of the squall line. The structure of the line was oriented southwest to northeast by 1300 UTC. The front analysis retained the southern half of the front as meeting the strong front threshold while a few triangles on the northern end have the lower FS threshold met. Similarly the cold pool area has decreased with only the southern Oklahoma portion of the front managing to exceed the divergence threshold.

The front continues through the state, exiting through northeastern Oklahoma around 1500 UTC (Fig. 3d) while the southern end of the front exits the state a couple hrs later before a second line of storms moves into southeastern Oklahoma. There were no areas of strong divergence behind the northeastern Oklahoma portion of the front. The cold pool region covered only a few triangles in southeastern Oklahoma.

d. 24-25 May 2011 Case

The final case study is another system that occurred during the MC3E experiment a few days after the previous case. On 24 May the 1800 UTC sounding (not shown, UCAR archive) from Norman, Oklahoma (KOUN) had strong southerly winds at low-levels veering with height. A strong stable layer at roughly 825 mb was in place; however, low-level moisture and unstable mid-levels resulted in CAPE values over 2500 Jkg^{-1}. The Storm Prediction Center (SPC) had issued a high risk convective outlook for central and northeastern Oklahoma.

By 2000 UTC the first thunderstorm cells had formed, rapidly developing into severe thunderstorms with a threat of tornadoes. The frontal passage and cold pool (Fig. 4) analysis had some difficulty capturing the front and any associated cold pool with these thunderstorms due to the low resolution of the Mesonet station grid

(Fig. 4a). There was a large region of convergence both ahead of and behind the supercells at this time. The front, although strong, did not extend throughout all of the supercells, and only one triangle observed a cold pool at this time.

Over the next couple hrs, more cells had flared up and a clear north-south line had formed (Fig. 4b) though there were gaps between the cells that made up the line. There was only a slight signature of the usual convergence-divergence pattern ahead of and behind the front, likely, though not necessarily, a result of the strong rotation in tornadoes, or systems capable of potentially producing tornadoes. At this point multiple tornadoes had formed, including one that struck the El Reno Mesonet station at 2120 UTC recording a maximum wind gust of 151 mph. Only a few stations in north central and northwestern Oklahoma observed cold pools at the time. Strong rotation tends to lead to surface inflow from all directions, reducing the likelihood of divergence and cold pools behind a front.

By 0000 UTC, however, the squall line was straighter and had fewer, smaller gaps between individual storm cells (Fig. 4c). A convergence-divergence distribution ahead of and behind the front was more well-defined in the north central Oklahoma line and the smaller, weaker (in terms of front strength) line in south central Oklahoma. A large region of convergence is present in western Oklahoma where a secondary front was present that lacked precipitation. Cold pool coverage had grown behind the main line in central Oklahoma. Additionally, one triangle was marked as in a cold pool in the northwest corner of Oklahoma. Generally, the lack of stratiform precipitation makes it likely that this case is closer to what other studies would identify in terms of cold pool area compared to the other cases in this chapter.

As the main front progressed further eastward the strength of the front began to weaken slightly with regards to FSs (Fig. 4d). However, convection was still intense with radar echoes reaching up to 60 dBZ. The fronts in western Oklahoma had a disorganized structure and covered more area at the time. The cold pools at 0200 UTC remained just behind the main front with one triangle in western Oklahoma in a cold pool as well. Radar coverage in northwestern Oklahoma was sparse by comparison, though the secondary line does not appear to develop precipitation as it moves throughout the state the next few hours. At 0300 UTC (not shown) there was a faint green line visible on the radar signifying this secondary front.

e. Cold Pool Time Series

Observing the change in cold pool area over time allows for greater visualization of the size and time scales of the areas experiencing a cold pool (Fig. 5).

From roughly 0300 to 1100 UTC in the 13 June 1997 case at least one Mesonet triangle resided in a cold pool (Fig. 5a). The peak size of cold pool area was around 0930 UTC at a size of nearly 1.4×10^{10} m^2. Around a third of the cold pool areas retained a cold pool for at least 30 mins, and some triangles, particularly later in the period, retained cold pool status for over an hr.

For the 15-16 June 2002 case the cold pool time series shows a slightly larger maximum cold pool area than the first case study with a maximum size of roughly 1.8×10^{10} m^2 (Fig. 5b). The duration of the cold pools tended to be longer than the first case study. Later in the time period over half the cold pool area comprised of locations which had been in a cold pool for half an hr or more. The cold pool area that was present for at least an hr peaked at roughly 5×10^9 m^2 around 0400 UTC.

For the 20 May 2011 case the cold pool time series showed a longer lasting period from initial to final cold pool and a lower maximum cold pool area that only reached roughly 8×10^9 m^2 (Fig. 5c). There are frequent jumps in the amount of area covered by cold pools. Many of the cold pools lasted half an hr; however, very few triangles maintained a cold pool for at least an hr. Considering the narrow width of the divergence region behind the storm line and the speed of the front, this result was expected.

The cold pool time series for the final case study showed a maximum cold pool area of just over 1.1×10^{10}

m^2 (Fig. 5d). The entire period with cold pools present lasted approximately 10 hrs. The cold pools were rather short in duration with few lasting half an hr and only one triangle retaining a cold pool over an hr. Cold pools later in the event had longer durations than cold pools in the first half of the event, a result likely due to the increased organization of the convergence-divergence gradient across the front over time.

f. Front Characteristics

For each of the four case studies the average divergence, pressure, and temperature timeseries were identified and centered on the time step when the front was halfway through the Mesonet triangle. The average time series is plotted along with the standard deviation for each variable and case (Fig. 6). For pressure and temperature, the values are normalized to 0 at the midpoint of frontal passage. As a result, the standard deviation near the midpoint was artificially low so the standard deviations for pressure and temperature 15 minutes before and after the frontal passage midpoint are removed.

For all four cases, the divergence profile begins in similar fashion with a dip towards strong convergence values before a reversal to strong divergence as the front crosses the triangle. However, for three of the cases the average divergence trends back towards 0 after the frontal passage while for the 15-16 June 2002 case the average divergence remains at an elevated level even two hours after the middle of frontal passage.

Temperature profiles start similarly with temperatures around 3-4 K higher on average before frontal passage than in the middle of a frontal passage. The drop in temperature begins around 30-45 minutes before the middle of a frontal passage and continues until around 15 minutes afterwards generally. After frontal passage three of the cases show a slighter rebound in temperature than the initial drop by 1-2 K for the 15-16 June 2002 and 24-25 May 2011 cases. On the other hand, the temperature continues to decrease on average for the 20 May, 2011 case.

Pressure profiles start with a wide range of lower pressure values before frontal passage but show an increasing trend during frontal passage. For the 13 June 1997 and 15-16 June 2002 cases there is a drop off in pressure after frontal passage, while for the 24-25 May 2011 case the average pressure drop after frontal passage is minimal. For the 20 May 2011 case the pressure continues to slightly increase.

g. Front Wind Maps

This is a placeholder for the wind map figures (Fig. 7) and (Fig. 8).

4. Conclusions

The four cases studies analyzed represent a very small fraction of the 15 yrs of Mesonet data. However, they highlight varying storm structures and profiles of key variables.

The 13 June 1997, 15-16 June 2002, and 20 May 2011 cases involve MCSs tracking through the Mesonet with a strong forward line of thunderstorms with a large region of trailing stratiform precipitation. In contrast, the 24-25 May 2011 case involved supercells which formed into a line crossing Oklahoma, with more rotation which likely resulted in the delayed formation of a convergence-divergence couplet in the storm line.

The cold pools in this study were similar to other studies in terms of length along a front. However, the width a cold pool extended behind the lead storm axis was typically only 50-100km in these cases while in other studies the distances can be 100-400 km for MCSs (Stensrud et al. 1999). Most triangles in the Mesonet case studies remained for 30-60 mins while in other studies mean lifetimes can exceed 2 hrs (Tompkins 2001; Young and Perugini 1995).

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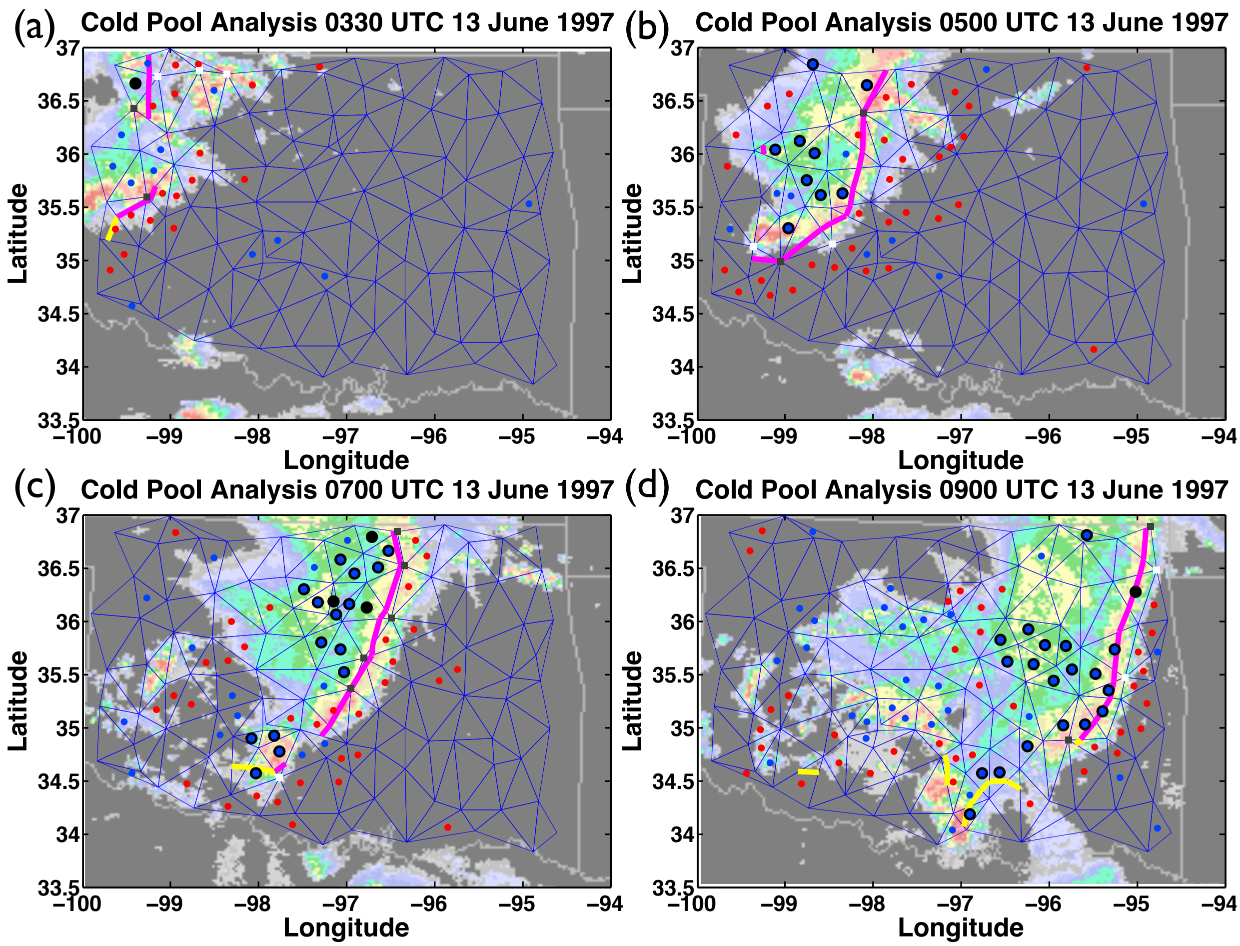

FIG. 1. Front and cold pool analysis for 13 June 1997 (a) 0300 UTC, (b) 0500 UTC, (c) 0700 UTC, and (d) 0900 UTC. Red dots are $D_i < -10^{-4}\mathrm{s}^{-1}$ while blue dots are $D_i > 10^{-4}\mathrm{s}^{-1}$. Yellow lines are frontal passages with FSs of $3 <= \mathrm{FS} < 5$ while magenta lines are frontal passages with FSs of 5+. White squares are stations where at the current timestep the FS is $3 <= \mathrm{FS} < 5$; gray squares designate stations currently with FSs at 5+. Black dots indicate triangles currently designated as cold pools. Radar images are from the UCAR image archive, NEXLAB - College of DuPage.

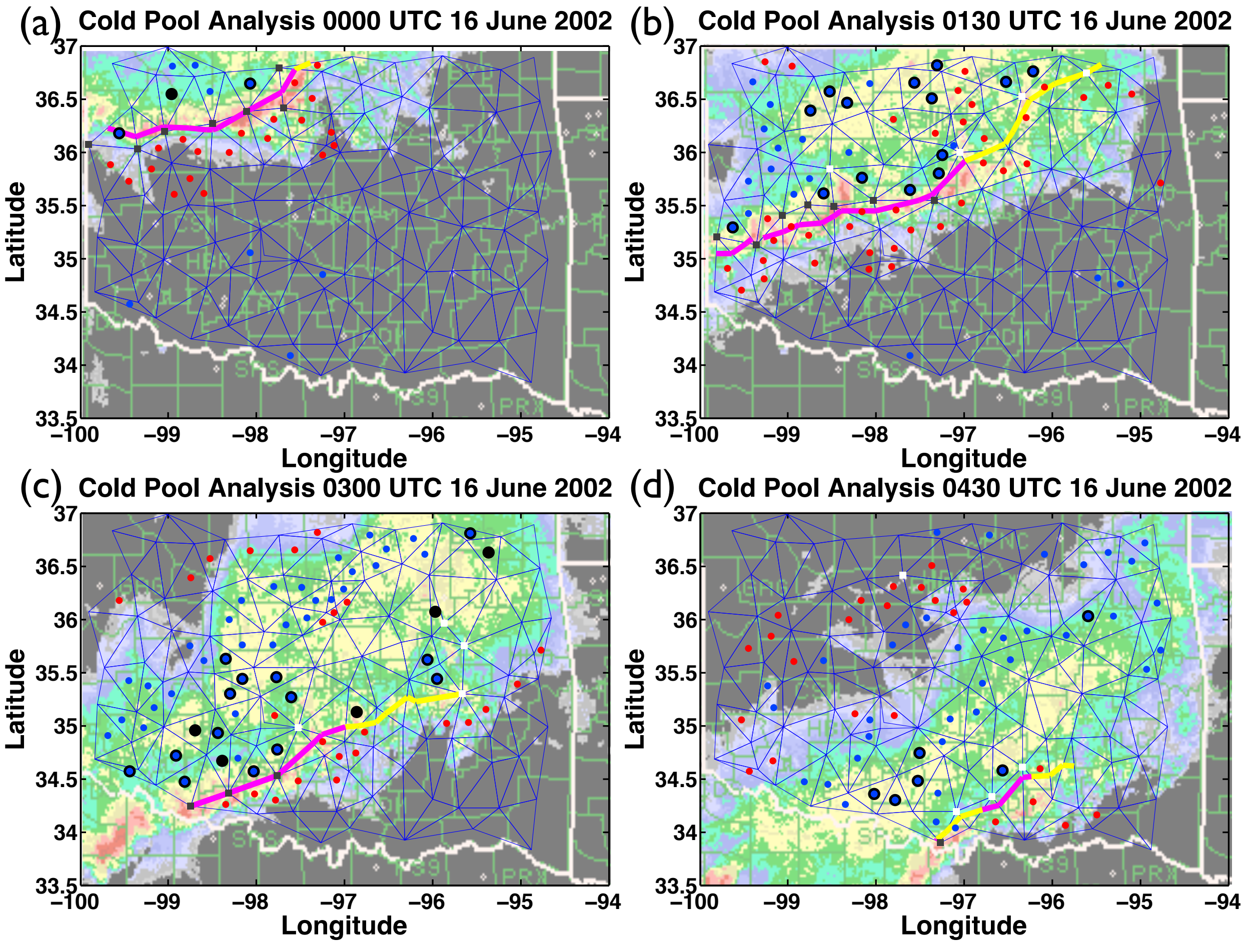

FIG. 2. Same as Figure 1 except for 16 June 2002 (a) 0000 UTC, (b) 0130 UTC, (c) 0300 UTC, and (d) 0430 UTC.

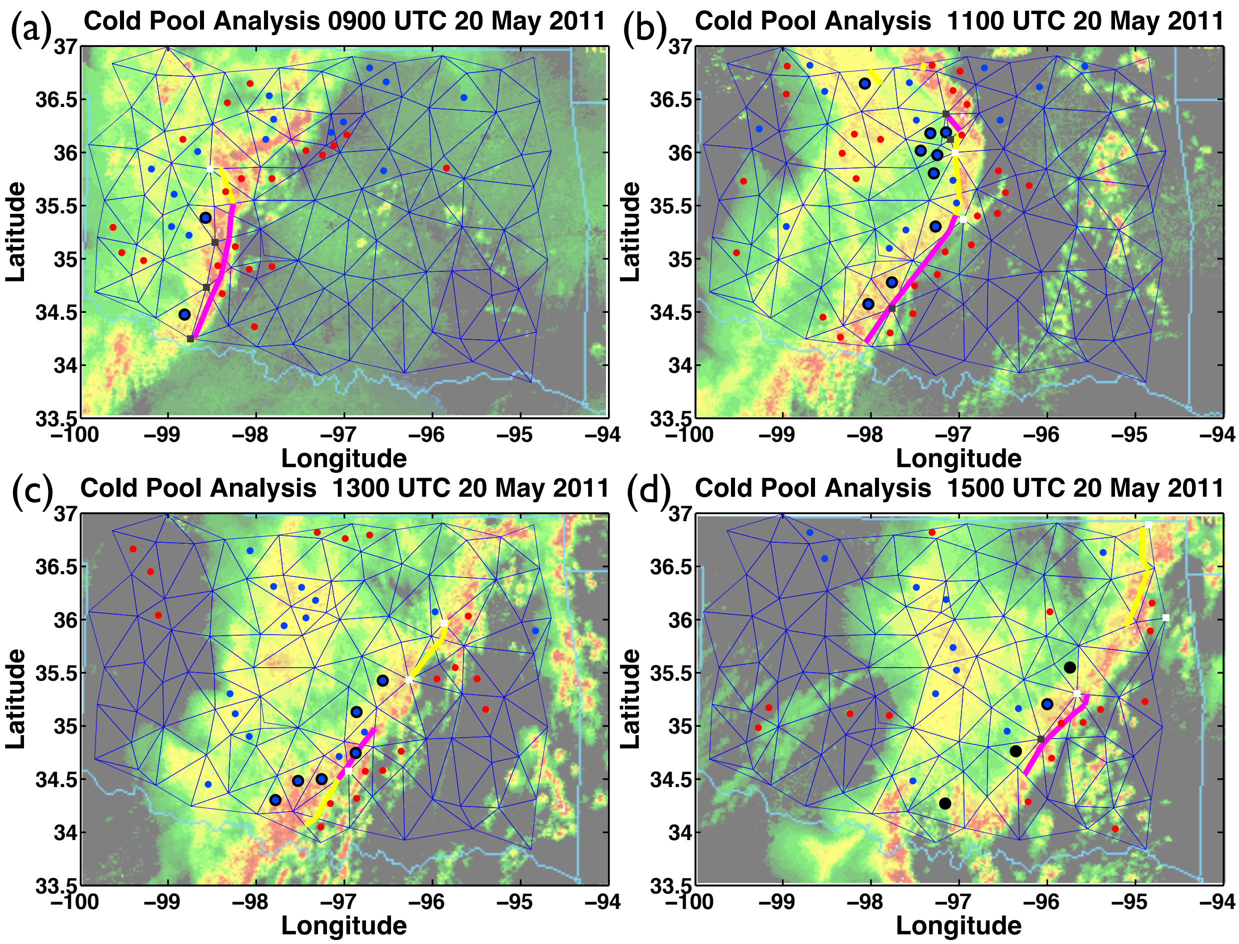

FIG. 3. Same as Figure 1 except for 20 May 2011 (a) 0900 UTC, (b) 1100 UTC, (c) 1300 UTC, and (d) 1500 UTC.

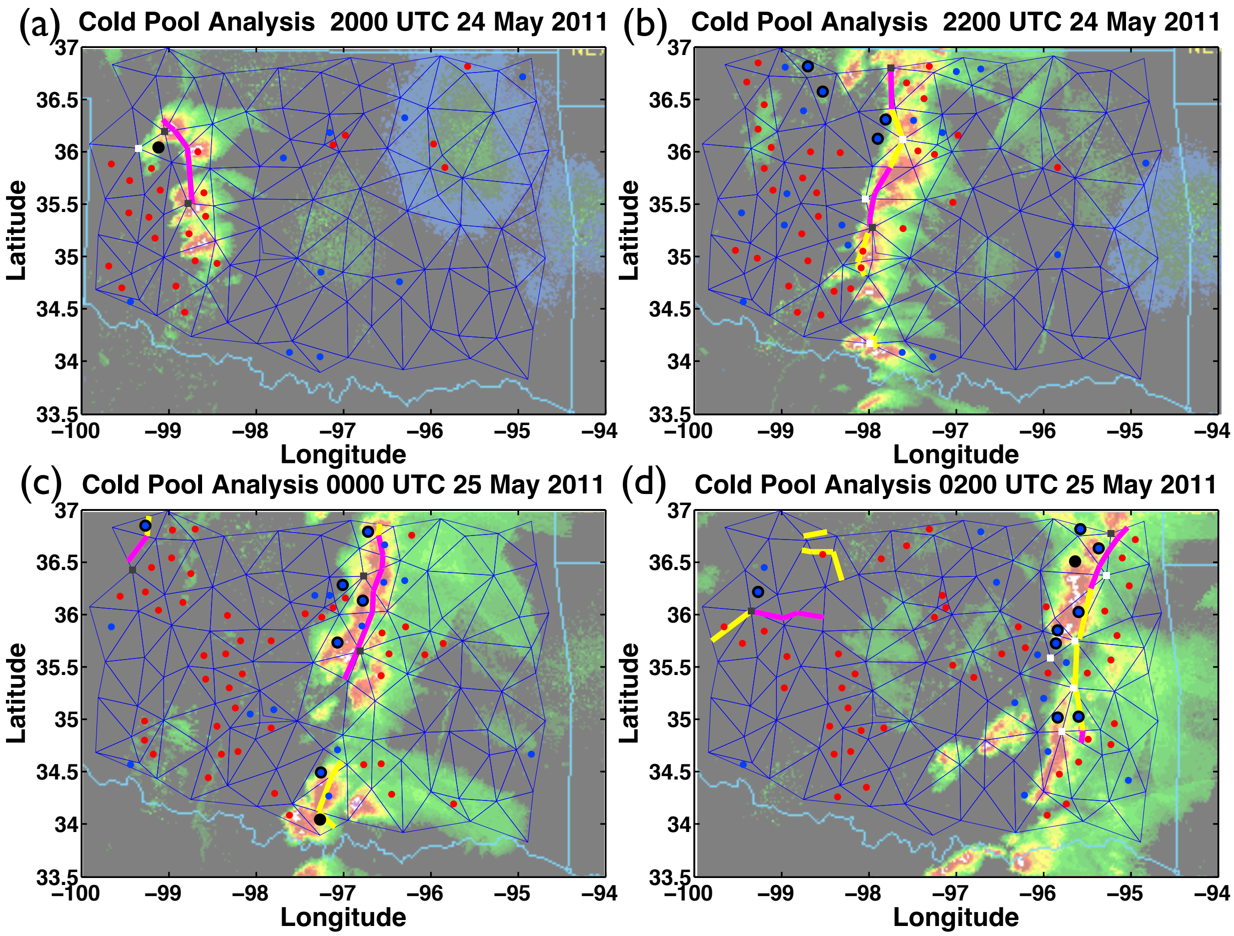

FIG. 4. Same as Figure 1 except for 24 May 2011 (a) 2000 UTC, (b) 2200 UTC, 25 May 2011 (c) 0000 UTC, and (d) 0200 UTC.

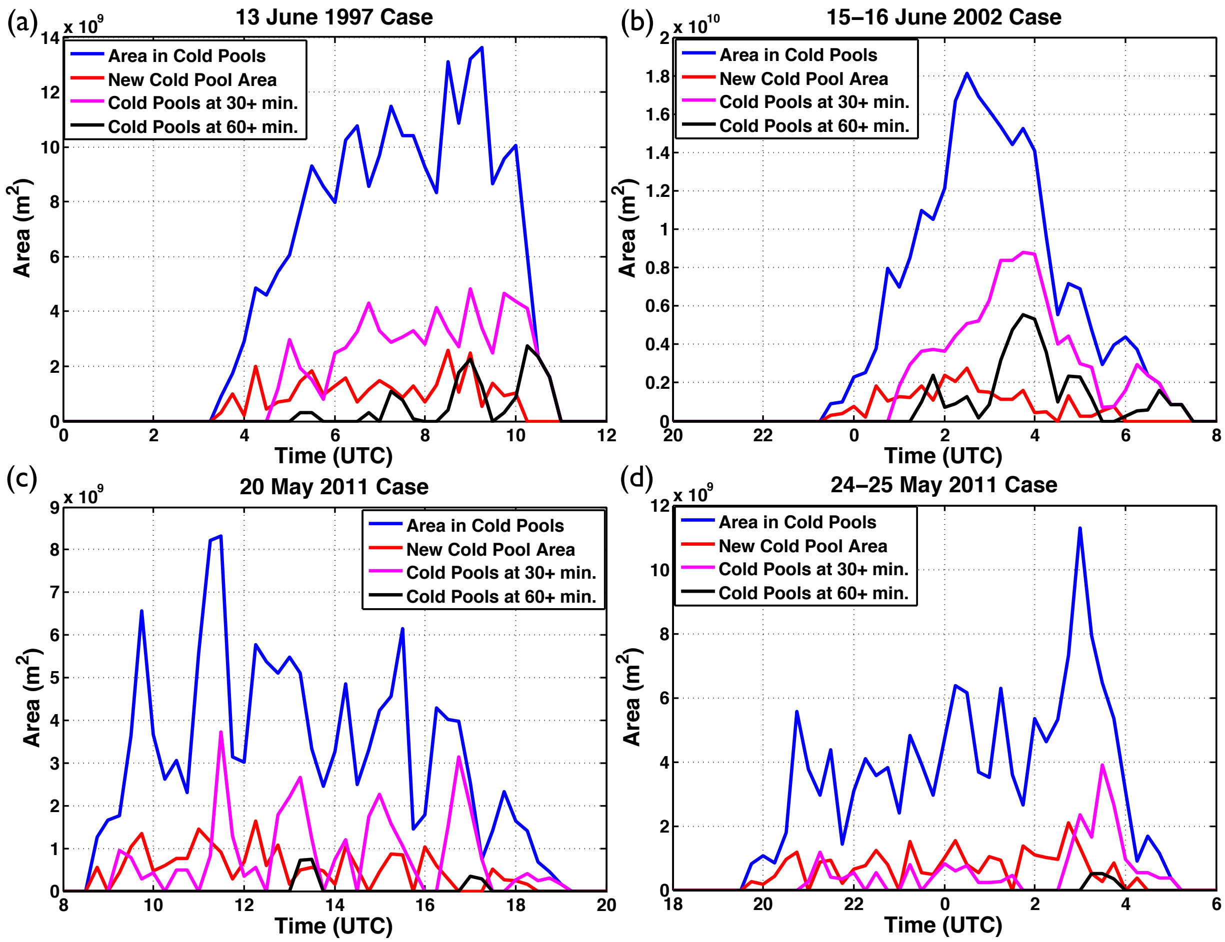

FIG. 5. Cold pool areas for the case studies: a)13 June 1997 0-12 UTC, b) 15-16 June 2002 20-8 UTC, c) 20 May 2011 8-20 UTC, d) 24-25 May 2011 18-6 UTC. Cold pool areas are shown as 15 minute averages for total area in cold pools (blue), area that becomes part of a cold pool in a given timestep (red), area residing in a cold pool at least 30 mins (magenta), and area residing in a cold pool at least 60 mins (black).

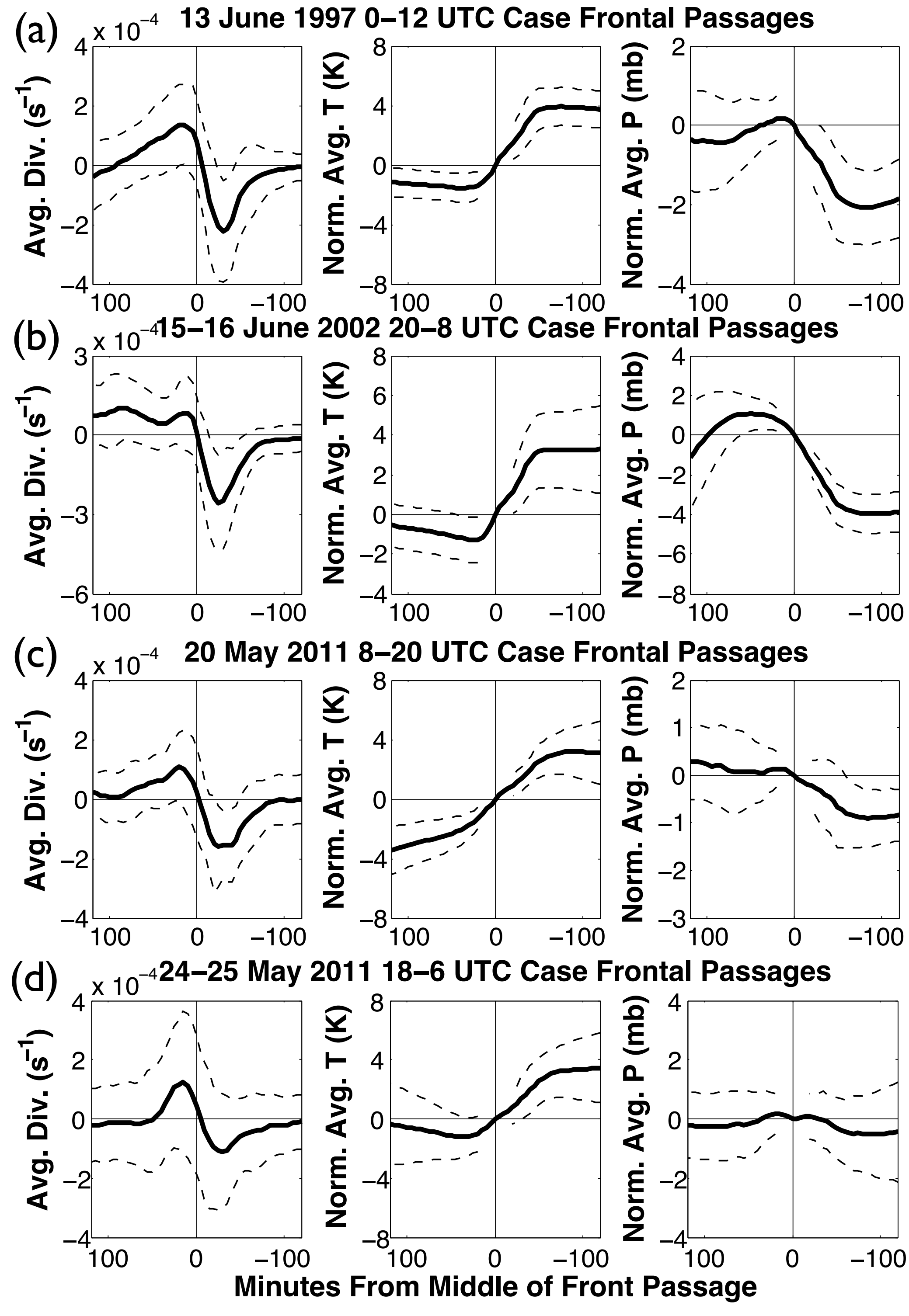

FIG. 6. Average (solid) and +- 1 standard deviation (dashed) divergence, temperature, and pressure values for frontal passages at Mesonet triangles. Pressure and temperature values are averaged for a Mesonet triangle and normalized. Case studies are: a)13 June 1997 0-12 UTC, b) 15-16 June 2002 20-8 UTC, c) 20 May 2011 8-18 UTC, d) 24-25 May 2011 15-15 UTC.

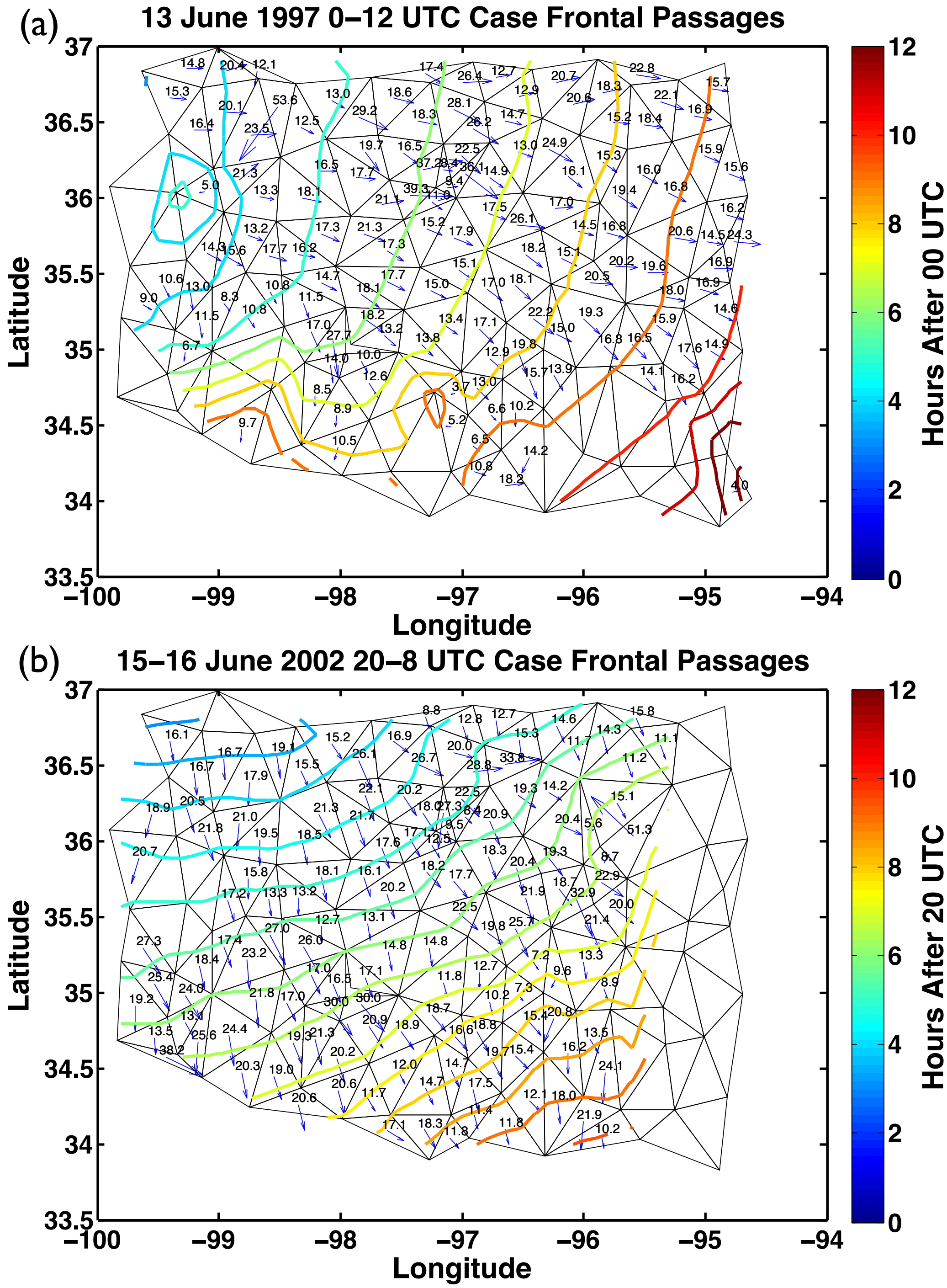

FIG. 7. Frontal passage location and timing (contours) with front speeds represented by quivers. Case studies are: a) 13 June 1997 0-12 UTC and b) 15-16 June 2002 20-8 UTC.

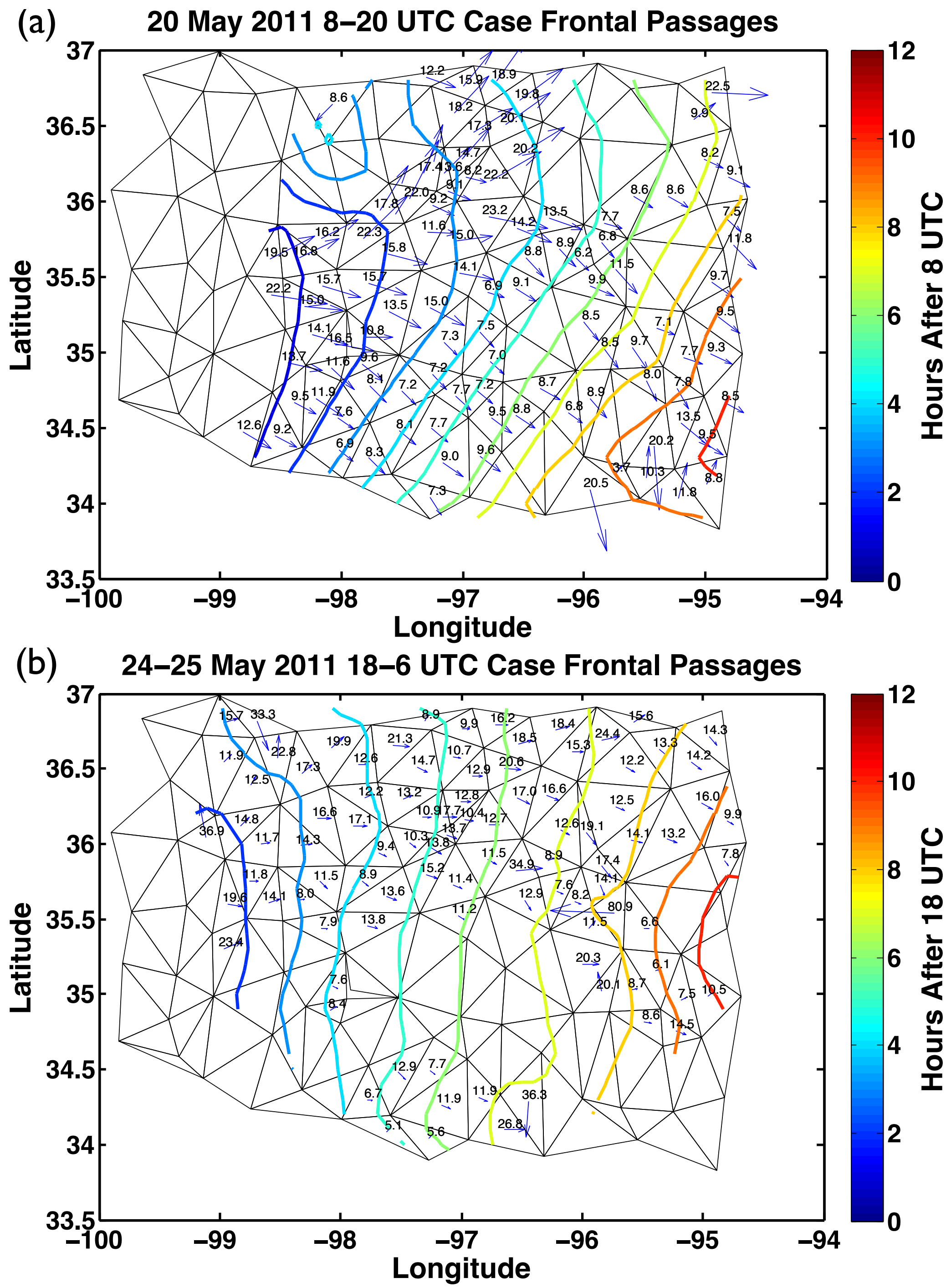

FIG. 8. Frontal passage location and timing (contours) with front speeds represented by quivers. Case studies are: a) 20 May 2011 8-18 UTC and b) 24-25 May 2011 15-15 UTC.