DIAGNOSIS OF THE JULY 6 2002 OGALLALA, NEBRASKA FLASH FLOOD

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Abstract

During the early morning hours of 6 July 2002, a mesoscale convective system (MCS) traversed southwestern Nebraska and produced more than 40 cm of precipitation, resulting in a flash flood that closed Interstate 80 and caused one fatality near Ogallala, Nebraska. Regional climatology yields that this flash flood ranked first in precipitation amount for a 24 hour period over the past one hundred years. Synoptic and mesoscale features similar to other flash flooding events and conducive to extremely heavy precipitation were in place over the Central Plains, including a weak upper level ridge, high precipitable water values (180% of normal), significant moisture advection and weak mid level flow permitting slow storm motion. Somewhat unique to this flash flood case was the lack of a "traditional" initiation mechanism, such as a synoptic front or distinct boundary often observed in other cases. Convective initiation was aided by an upslope flow component along terrain in northwestern Kansas as well as an outflow boundary from pre existing thunderstorms that developed earlier that day. The existence of a low-to mid level moisture and instability axis and low-level jet were noted as well, which aided to focus and maintain convection over Ogallala. An analysis of the synoptic and mesoscale environments responsible for producing the flash flooding convection is presented.

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1. Introduction

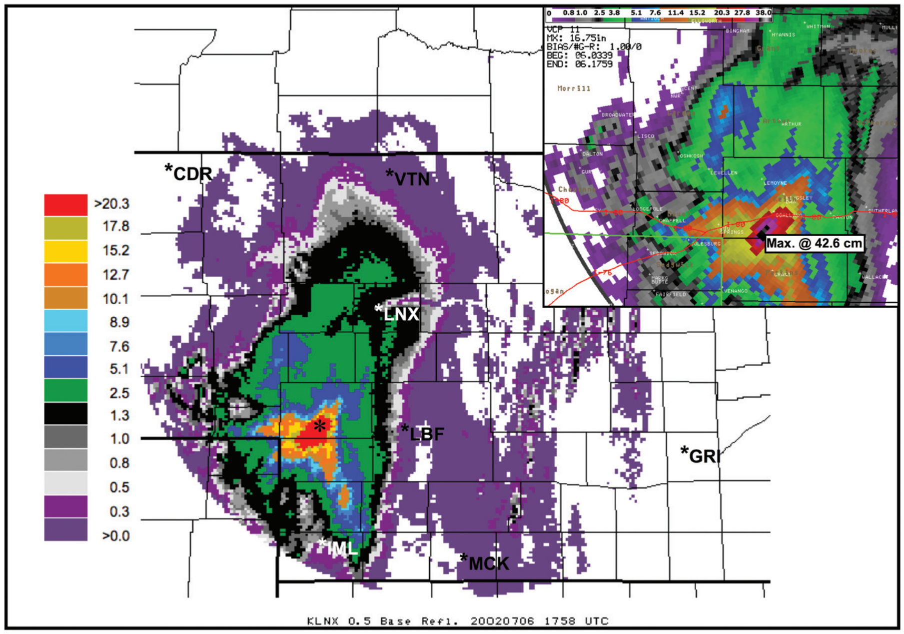

Fig. 1. Storm total precipitation (cm) estimates (12-hr.) from the Thedford, Nebraska (LNX) WSR-88D radar ending at 1758 UTC 6 July 2002. An asteris ipitation estimate of 42.6 cm. Color scale on each is defined in centimeters.

During the early morning hours of 6 July 2002, convective storms that developed over eastern Colorado and northwestern Kansas moved into southwestern Nebraska, resulting in a significant flash flooding event. The heaviest precipitation was highly localized (Fig. 1, Table 1). Storm total amounts, as recorded by rain gauges, varied from 21.59 cm at the Ogallala, Nebraska Regional Airport (OGA) to less than 2 cm at Imperial, Nebraska (IML). At Kingsley Dam, Nebraska (KING), downstream along the Platte River just to the northeast of OGA, more than 13 cm of precipitation was recorded by the NOAA/National Weather Service (NWS) Cooperative Observing (COOP) station, illustrating the localized nature of the heaviest precipitation. The NOAA/NWS Weather Forecast Office (WFO) Thedford, Nebraska (LNX) Weather Surveillance Radar-1988 Doppler (WSR-88D) estimated a maximum rainfall of 42.6 cm of precipitation southwest of OGA (Fig. 1). Precipitation rates exceeding 20 cm hr^{-1} were estimated south of OGA by the LNX WSR-88D radar during the storm. The excessive precipitation that fell over the Ogallala and Kingsley Dam region was confined to a twelve-hour period, with the most intense precipitation occurring over the 5-hour time period from 0700 to 1400 UTC 6 July 2002 (precipitation totals from gauges were based on observational periods and not occurrence of precipitation). According to the Moore et al. (2002) criteria for discriminating between significant and extreme convective precipitation events, this event would be classified as "extreme," since 15–25 cm fell within 24 hours.

Deep moist convection initiated along the Colorado - Kansas border east of a mid-level trough and coincident with an upper-level low that moved northward from Texas on 4-5 July 2002. A quasi-stationary mesoscale convective system (MCS) resulted over southwestern Nebraska and continued to backbuild to the southwest along a low-level thermal ridge. Precipitable water values exceeding climatological normals, weak flow aloft, a strong low-level jet, localized vertical motion enhanced by the terrain of western Kansas, and an environment exhibiting little mid-level wind shear all contributed to focus excessive precipitation over southwestern Nebraska. Typical of other flash flooding situations (see example from Zapotocny and Byrd 2002), there were no reports of large hail or strong winds (NCDC 2002) within the region. By the time the event ended the town of Ogallala was flooded and a bridge on Interstate 80 was washed out, causing a fatality and major disruption to 4th of July 2002 holiday travel. This paper will focus on a discussion of the synoptic and mesoscale environments that initiated and maintained deep moist convection over southwestern Nebraska for several hours.

2. Data and Methodology

Upper air, wind profiler, surface observations, radar and satellite products were obtained from the WFO North Platte, Nebraska (LBF) data archive for analysis. The upper air data contained standard rawinsonde observations (RAOB) of temperature, dew point temperature, wind speed and wind direction for mandatory and significant levels at all reporting locations for 0000 and 1200 UTC 5 and 6 July 2002. Derived thermodynamic quantities were calculated using the General Meteorological Package (GEMPAK, desJardens et al. 2002), and all observed upper air charts were objectively analyzed using the included Barnes analysis scheme (Koch et al. 1983). Major features were subjectively adjusted based upon further meteorological analysis. Hourly surface observations of temperature, dew point temperature, sea level pressure and wind speed and direction were also plotted using GEMPAK and were objectively analyzed, with appropriate synoptic and mesoscale features overlaid. Hourly automated surface observing systems (ASOS/AWOS) and COOP gauge precipitation data were obtained from the

NOAA/National Climatic Data Center (NCDC) and the High Plains Regional Climate Center (HPRCC). ETA211 (80 km), RUC211 (80 km) and Meso-ETA (12 km) analysis fields were also obtained from LBF and used to calculate gridded thermodynamic fields over the Central Plains for spatial interpretation. Level II WSR-88D radar base reflectivity and storm total precipitation data from LNX were analyzed using GEMPAK, Unidata's Integrated Data Viewer (IDV, Murray et al. 2003), and the Interactive Radar Analysis System (IRAS) from NOAA's National Severe Storms Lab (NSSL) online at: www.ncdc.noaa.gov/oa/radar/iras.html). No bias correction was made for differences in the radar-derived and gauge measured precipitation. The profiler at McCook, Nebraska (RWD) was not operational during the duration of this event. All visible, infrared and water vapor satellite imagery were used to determine movement of the cloud elements associated with the MCS. Consecutive 15-minute GOES-10 visible satellite images were used to estimate the position of cloud elements associated with the upper-low that traversed from Texas to Colorado.

Station	24 Hour Precipitation (cm)*	48 Hour Precipitation (cm)**
Ogallala (OGA)	16.51	21.59
Kingsley Dam (KING)	13.30	13.76
Madrid (MADR)	6.17	7.11
Lamar (LAMR)	5.43	5.43
Imperial (IML)	1.83	1.95
Waunita (WAUN)	3.35	3.60
Benkelman (ENKL)	0.97	0.97

* ending 6 July 2002
** ending 7 July 2002

Table 1. Precipitation totals as recorded by COOP and ASOS/AWOS stations in southwest Nebraska from 6–7 July 2002. Stations containing a four–letter identification signify a COOP station. Stations with a three–letter identification are ASOS/AWOS observing platforms.

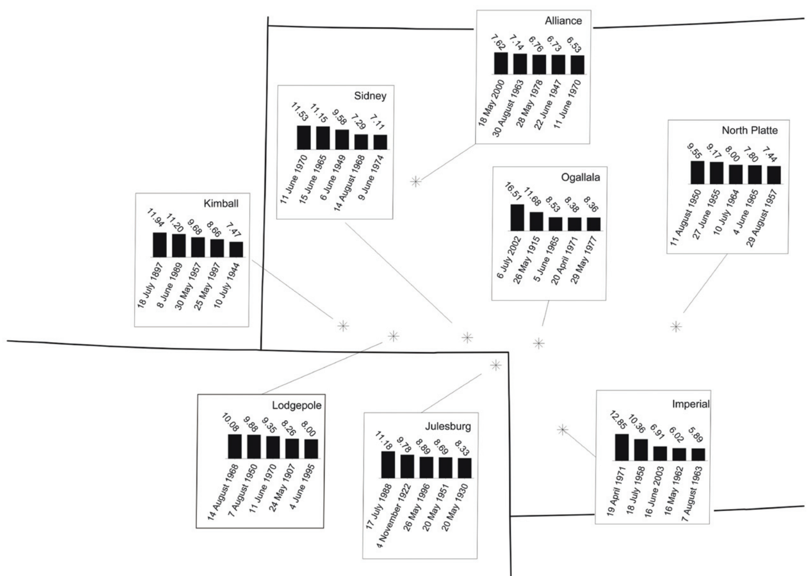

Fig. 2. Climatological top five 24–hour precipitation total (cm) events for selected southwestern Nebraska locations, ranked from left (top event) to right.

3. Local Climatology

In order to assess the relative magnitude of the Ogallala event, one hundred years of 24-hour precipitation amounts were examined and ranked by amount for stations located in and around southwestern Nebraska (Fig. 2). The top five events for each location suggest that the precipitation received during the 6 July 2002 event at Ogallala ranked ahead of all others, surpassing other events at surrounding stations by 3-8 cm. Interestingly, the precipitation received from the 6 July 2002 event does not appear ranked in the top five for any other station, owing to its localized nature. Moreover, the 48-hour precipitation total of 21.6 cm from the event at Ogallala (Table 1) doubled the previous high amount and was also greater than all other local stations for the period.

Before the Ogallala flash flood, much of southwestern Nebraska remained well below normal in precipitation (Table 2). In fact, most stations had received less than one half of the normal amount by 30 June 2002. Ogallala would achieve near-normal annual precipitation as a result of this flooding event.

4. Synoptic and Mesoscale Analyses

The Great Plains receives much of its annual rainfall in the warm season, due in part to the high frequency of thunderstorm complexes that traverse the region (Fritsch et al. 1998). In addition, the existence of the Great Plains low-level jet is extremely important, as it serves as a transport mechanism for Gulf of Mexico moisture-laden air into the Plains. The strength and position of the jet has been shown to be a major factor affecting the location and intensity of warm season deep moist convection (McCorcle 1988; Arritt et al. 1997). Other cases of heavy rainfall and

Station (*type*)	2002 Precipitation (cm)	Normal Precipitation (cm)	Percentage of normal (%)
Ogallala (*AWOS*)	9.75	25.63	38.06
Kingsley Dam (*COOP*)	13.20	26.01	50.78
Big Springs (*COOP*)	9.98	24.49	40.77
Madrid (*COOP*)	8.81	27.03	32.61

Table 2. Precipitation statistics as recorded by COOP and ASOS/AWOS stations in southwest Nebraska from 1 January to 30 June 2002.

flash flooding events in the U.S. during the warm season have been well documented and studied in depth (e.g., Maddox et al. 1979; Schwartz et al. 1990; Peterson et al. 1999; Pontrelli et al. 1999; Zapotocny and Byrd 2002; Moore et al. 2004). Maddox et al. (1979) describe a set of criteria, based on 151 case studies of flash flood-producing systems, to assist the forecaster in recognizing a set of synoptic, mesoscale and storm scale patterns associated with these events. Four general categories were used to identify the majority of the events studied, and in most, the heaviest rain potential occurred with weak flow aloft and mean precipitable water values at 181% of the climatological norm (Maddox et al. 1979). Other studies of heavy rain producing events based upon ambient atmospheric and land surface conditions have been published (e. g., Maddox et al. 1978; Junker et al. 1999; Moore et al. 2003). For instance, Maddox et al. (1978) compared synoptic and mesoscale similarities between the Big Thompson, Colorado (1972) and Rapid City, South Dakota (1976) flash floods. Existence of a slow moving surface boundary, high moisture levels up to 300 hPa, a long wave trough with a ridge east of the focus region, and weak mid-to upper-level winds that allowed for slow system movement were all common synoptic features. More recently, Junker et al. (1999) produced a synoptic and dynamic climatology of heavy rain events relating spatial scale and intensity to the magnitude of warm advection, mean mid-level relative humidity, and moisture flux convergence. In addition, Doswell et al. (1996) describe a set of "ingredients" common to significant flash flood events. They concluded that the duration of a high precipitation rate is a function of storm translational speed, size of the system, and variations in intensity that occur within the convective complex. These characteristics are of particular importance in this case as well, as slow storm propagation of a small convective complex resulted in localized heavy precipitation over Ogallala.

In comparison to the synoptic and mesoscale criteria given by Maddox et al. (1979), the Ogallala case was somewhat unique in that it exhibited a combination of factors noted in their research. For example, the Ogallala event had a synoptic setup similar to their criteria for "frontal" events, characterized by a positively tilted upper-level ridge axis to the east and a shortwave trough to the west of the heaviest precipitation (Figs. 3a, b). However, there was no identifiable synoptic boundary in the vicinity of the initiation region or near the location of the deepest convective storms in this case. Moreover, the existence of an outflow boundary from prior thunderstorms in the Ogallala event helped to initiate and organize thunderstorms, similar to the "mesohigh" setup of Maddox et al. (1979). In addition, other key features on the mesoscale assisted in the initiation and maintenance of deep moist convection over Ogallala, such as upslope flow along the terrain of northwestern Kansas.

a. Upper-air analysis

Upper-air data combined with available profiler data and model initial hour analysis fields from 0000 UTC 6 July 2002 to 1200 UTC 7 July 2002, were used to assess conditions from just prior to, during, and just after the flash flood event. The Ogallala case consisted of a combination of scenarios identified by Maddox et al. (1979). Analysis of upper-level height fields at 300 hPa depicted western Nebraska as located on the backside of a positively tilted mid- to upper-level ridge centered over Illinois at 0000 UTC 6 July 2002 (Fig. 3a). This ridge had propagated eastward from the Northern Plains between 0000 UTC 4 July and 0000 UTC 6 July 2002. A negatively-tilted shortwave trough existed southwest of Ogallala, centered over northern New Mexico, allowing for mid-level upward motion east of the trough in eastern Colorado and western Kansas (Fig. 3b). Southwesterly flow and two broad regions of upper-level divergence extended from northeastern Colorado northeastward to North Dakota at 300 hPa (not shown). Longwave troughs were located off the East Coast and over south central Canada (Fig. 3a). This general synoptic pattern remained intact for the next 24-36 hours throughout the United States.

At 500 hPa at 0000 UTC on 6 July 2002, closed lows were centered over northeastern New Mexico and eastern Colorado in the vicinity of the shortwave trough. Each drifted slowly northeastward over the next 12 hours (Fig. 3b). The upper-level low found in Colorado originated over southeastern Texas on 0000 UTC 4 July 2002 and propagated northwesterly by 0000 UTC 5 July 2002. The anticyclone associated with the upper-level ridge to the east, combined

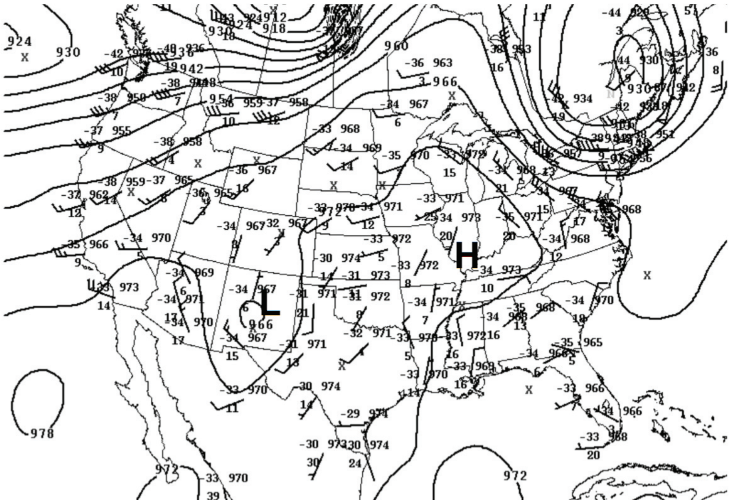

Fig. 3(a). 300 hPa valid 0000 UTC 6 July, 2002. Observed values of geopotential height (dm), temperature (°C), dew point depression are plotted in conventional station model form. Winds are in units of m s^{-1}. Thick solid lines are ETA-initial hour objective analysis of geopotential height at conventional intervals.

with the lows over Colorado and New Mexico, resulted in enhanced southerly flow near 10 m s^{-1} into Nebraska. Small 12-hour changes in the 500 hPa heights noted at WFO Dodge City, Kansas (DDC) and LBF, less than 10 dm from 1200 UTC 5 July to 0000 UTC 6 July, were indicative of little movement of the lows or shortwave trough.

The shortwave trough is also evident on 0000 UTC 6 July at 700 hPa (Fig. 3c) over Colorado and New Mexico, embedded within the western edge of the ridge and associated with the closed lows at 500 hPa. Enhanced southerly flow over the Plains is noted by moisture advection with a dew point depression of 3°C at LBF, indicating nearly saturated air at 700 hPa. The 850 hPa level depicted a broad area of lower heights over the inter-mountain west, extending northward from New Mexico to Nevada (Fig. 3d). As a result, a gradient in the mass field existed over the Central Plains at both the 500 hPa and 850 hPa levels (Figs. 3b, d) with southerly winds advecting moist air from the Gulf of Mexico northward into the Ogallala region. The moisture was especially evident at 850 hPa, where dew points of 14-17 °C were noted east of the low and trough from southeastern Texas northward into southern Nebraska (Fig 3d). Mean surface to 700 hPa winds greater than 11 m s^{-1} (20 kts) at DDC and 8 m s^{-1} (15 kts) at LBF generally persisted from 0000 UTC 5 July to 0000 UTC 6 July 2002 (not shown). This southerly flow regime provided copious amounts of moisture through a deep tropospheric layer over southwestern Nebraska. Cumulus clouds developed after 2200 UTC on 6 July 2002 (not shown) southwest of Goodland, KS (GLD) along the northeastern periphery of

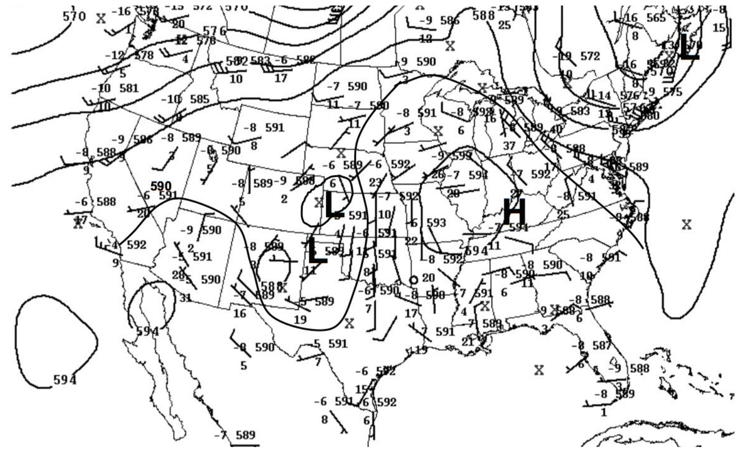

Fig. 3(b). Same as in Figure 3a except at 500 hPa. Wind profiler data at 5000 m are included and a 590 hPa height contour is subjectively analyzed. Absolute vorticity maximums and minimums are depicted with 'X' and 'N' markers, respectively.

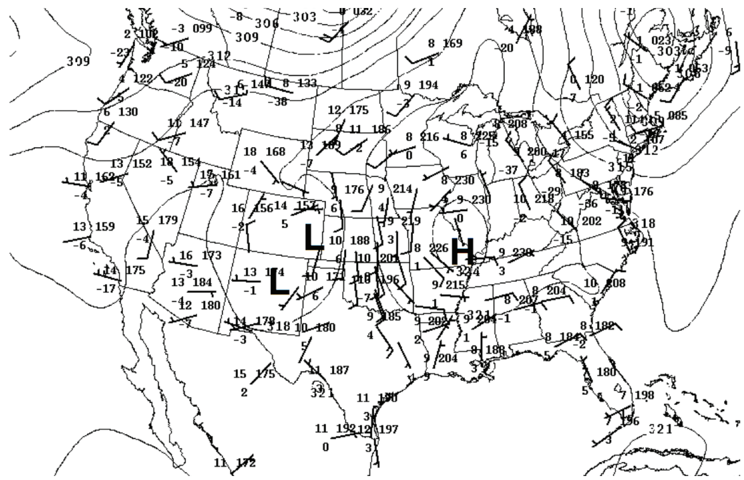

Fig. 3(c). Same as in Figure 3a except at 700 hPa. Wind profiler data at 3000 m are also included

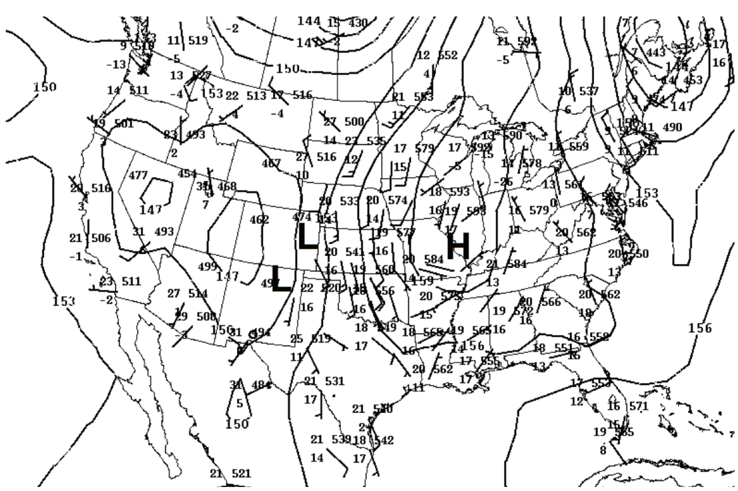

Fig. 3(d). Same as in Figure 3a except at 850 hPa and dewpoints are given at each station. Wind profiler data at 1500 m are also included.

the northern upper-level low found in Colorado and along a region favored for upward motion east of the trough. The convective thunderstorm cells that eventually resulted moved slowly to the north/northeast into southwestern Nebraska by 0400 UTC 6 July 2002 (not shown).

By 0600 UTC 6 July 2002, strong convective cells were apparent in eastern Colorado and western Kansas, ahead of the shortwave (not shown). The upper-level lows over Colorado and New Mexico moved only slightly to the northeast (Fig. 4a) over the six hours from 0000 to 0600 UTC 6 July 2002. The winds at the Granada, CO (GDAC2) profiler at 5000 m depicted a southeasterly flow at 5 m s^{-1}, suggesting that the center of the upper-low was located northwest of the profiler location. The RUC 500 hPa absolute vorticity (Fig. 4a) field shows a broad region of positive vorticity along the Colorado-Kansas border, indicative of the circulations and trough found in the region. Winds at profiler locations (Fig. 4a) in Oklahoma and Kansas were predominately from the south and southeast at speeds of 10 m s^{-1} or less, which would ultimately aid in the slow translational speeds of the convective cells.

At 700 hPa (Fig. 4b), the RUC 00-hour analysis of vertical motion valid at 0600 UTC 6 July 2002 shows an enhanced area (with minimum values of -9 μb s^{-1}) located within a moisture axis with relative humidity values greater than 90% extending into the Ogallala, Nebraska region. These ingredients provided a favored region for convective development northeastward of the upper-low in Colorado, and would aid in convective initiation for several hours. Profilers in the area (Fig. 4b) indicated winds at 3000 m were southerly and stronger than at 500 hPa. Speeds of 15 m s^{-1} were noted at Vici, Oklahoma (VICI2) and Haviland, Kansas (HVLK1) at 0600 UTC, indicating the presence of a low-level jet.

By 1200 UTC 6 July 2002, winds at 500 hPa and 5000 m backed to the southeast throughout the region (Fig. 5a) and maintained speeds near 10 m s^{-1}. Dew point depressions of less than 2°C were noted throughout western Oklahoma and western Kansas, as moisture advection continued into southwestern Nebraska. The position of the upper-lows changed little since 0000 and 0600 UTC 6 July 2002, as the northern-most low was located just west of GLD, having moved slightly to the north. At 850 hPa and 1500 m, winds were predominately southeasterly with speeds of 10-15 m s^{-1} (Fig. 5b). The position of the upper-low was not well defined at this pressure level with the conventional observing network.

b. Regional sounding analysis

One important aspect of this event was the copious amounts of atmospheric water vapor present. In particular,

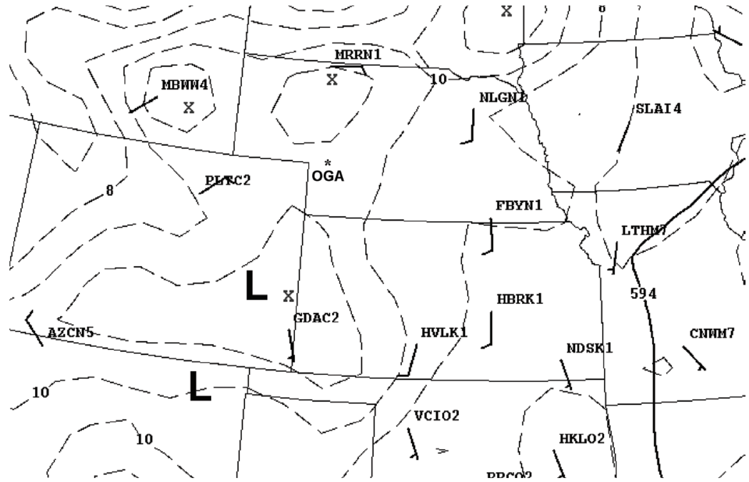

Fig. 4(a). RUC-initial hour objective analysis of geopotential height (solid, dm) and absolute vorticity (dashed, x10^{-5} s^{-1}) at 0600 UTC 6 July 2002 at 500 hPa. Observed profiler data at are at 5000 m and given in m s^{-1}. The location of Ogallala, NE (OGA) is noted with an asterisk.

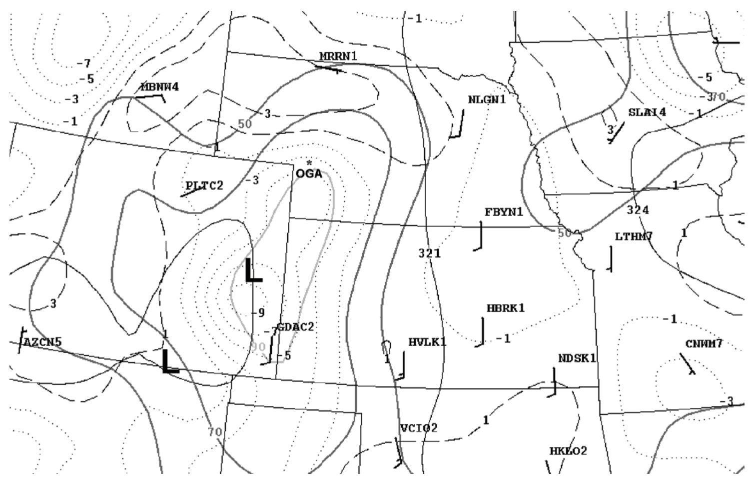

Fig. 4(b). Same as in Fig. 4a except for 700 hPa. Vertical motion is given by the thin dotted lines, (μb s^{-1}) and relative humidity in solid grey. Wind profiler data is at 3000 m.

precipitable water values exceeded 40 mm prior to the onset of deep moist convection. Compared to normal climatological values (1948–2000) for LBF in July (Fig. 6), the value exceeded the mean by nearly two standard deviations and was approximately 180% of the mean value of 25 mm. Thus, one of the major contributors to this flash flood was the occurrence of extremely high values of precipitable water.

Well before convective initiation (which occurred at approximately 0100 UTC 6 July in northwest Kansas), the LBF sounding at 1200 UTC 5 July 2002 (Fig. 7a) gave an indication of the pre-storm environment. A shallow morning inversion existed from the surface to 880 hPa with a nearly isothermal layer extending to 850 hPa. The

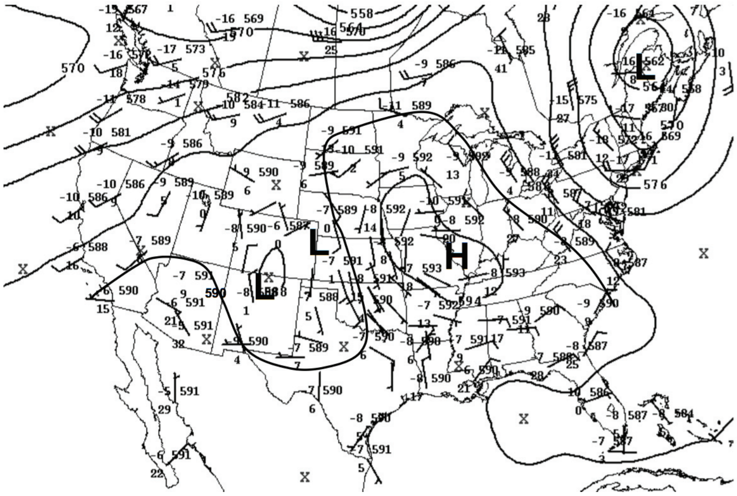

Fig. 5(a). Same as in Fig. 3b except for 1200 UTC 6 July 2002.

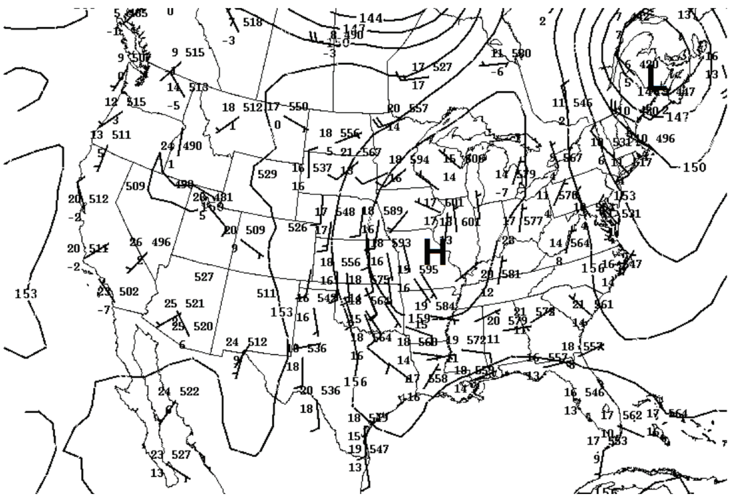

Fig. 5(b). Same as in Fig. 3d except for 1200 UTC 6 July 2002.

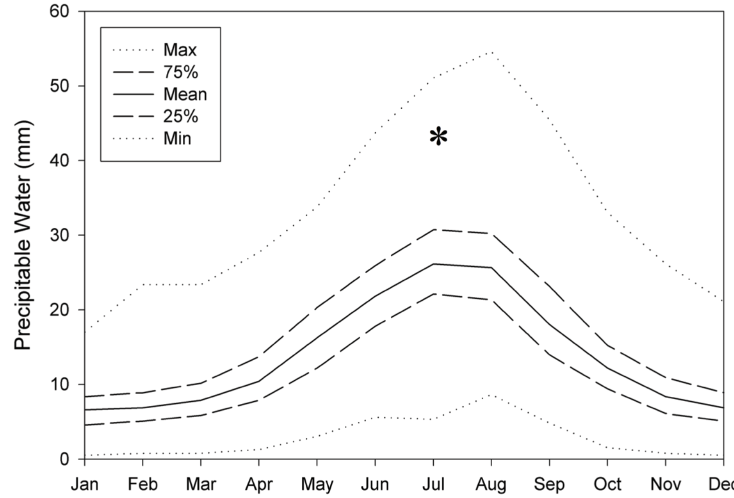

Fig. 6. Climatological precipitable water values (mm) for North Platte, Nebraska (LBF) to 300 hPa from 1948–2000 (data courtesy of M. Bunkers, NWSFO Sioux Falls, SD). The 75th and 25th percentiles of the data are each noted with dashed lines. Asterisk indicates the observed value from LBF at 0000 UTC 6 July 2002.

entire troposphere was unsaturated with weak conditional instability noted in the 850 hPa to 725 hPa layer. The mean layer convective available potential energy (CAPE) value, a common measure of instability and potential for convective precipitation (assuming the parcel has the mean thermodynamic properties of the lowest 100 hPa of the sounding in this analysis) was 0 J kg^{-1}. A Total Totals Index (TTI) value of 44, and a 25 K-Index (KI) value were both less than values typically found for convective storms producing heavy rain (Maddox et al. 1979). High dew point depressions yielded a lifted condensation level (LCL) of 788 hPa, while the 0°C isotherm was located at 580 hPa or 3.9 km above ground level (AGL). A precipitable water value of 27 mm (120% of normal) was the most unusual characteristic at this time, indicative of the high tropospheric moisture. Winds were light in the mid-troposphere (Fig. 7a) with speeds less than 10 m s^{-1} in the 600 to 250 hPa layer. From the surface to 650 hPa, predominately southerly flow was noted with speeds ranging between 10 and 20 m s^{-1}, providing additional evidence of a low-level jet in the region. The DDC sounding at this same time (not shown) depicted a much lower LCL of 874 hPa which was located within the air mass that would continue to advect northwestward toward Ogallala.

Twelve hours later at 0000 UTC 6 July 2002, the DDC sounding (south of the Ogallala region) sampled the air to the east of the upper-lows in the region where convection would initiate (Fig. 7b). A nearly dry adiabatic layer existed from the surface to 750 hPa with mid-tropospheric moisture evident from 800 hPa to 525 hPa. A CAPE value of 1123 J kg^{-1} was noted at this time, and a LCL value of 801 hPa indicated that cloud bases would be close to the surface in this area. The distribution of the CAPE was of particular interest. CAPE was found throughout a large deep tropospheric layer, from about 800 hPa to 200 hPa. With such a small difference between the environmental and the parcel temperature over this depth, the CAPE distribution suggested updraft strengths would be rather weak, limiting the production of hail (Edwards and Thompson 1998) while maximizing warm rain processes within the cloud layer (Edwards and Thompson, 1998). A TTI value of 47 indicated a weak possibility for thunderstorms; however, the KI value of 37 was quite high, and similar in magnitude to values found for other heavy rain events (e.g., Zapotocny and Byrd 2002). Precipitable water values of 43 mm (1.6 in) were up slightly from 1200 UTC 5 July 2002 at DDC (41 mm, not shown), while the height of the freezing level was 590 hPa, or about 4 km AGL. The warm cloud depth, computed between the LCL and the freezing level, was approximately 2.75 km. Winds at the surface and mid-levels were 5-10 m s^{-1} and veered slightly throughout the depth of the atmosphere. A speed maximum of 15 m s^{-1} was noted at 850 hPa, reflective of a low-level jet. The mean 0-6 km AGL wind vector yielded a speed of 10 m s^{-1} at 178°, indicating a northerly cell motion.

The 0000 UTC 6 July 2002 sounding at LBF (Fig. 7c), taken approximately 95 km to the east of Ogallala and four hours prior to the onset of the event indicated that the atmosphere was nearly saturated from 800 hPa to 550 hPa with a dry adiabatic lapse rate from the surface to 800 hPa. Higher CAPE values (792 J kg^{-1}), relative to 1200 UTC 5 July 2002, resulted from increased moisture in the 750-175 hPa layer and heating of the boundary layer. The TTI and KI values also increased above the values observed from 1200 UTC 5 July 2002. The KI increased by 13, falling within the range commonly noted for heavy precipitation (Zapotocny and Byrd 2002). Precipitable water increased by 13 mm from the previous sounding to 40 mm (180% of normal). The height of the freezing level rose to 4.1 km AGL , along with a warm cloud depth of 2.3 km, suggesting a deep and warm tropospheric layer, where warm rain processes would dominate. A southerly wind speed maximum was noted (Fig. 7c) in the wind profile in the 875 hPa to 800 hPa layer. Wind speeds weakened with height to around 5 m s^{-1} within the 600 hPa to 400 hPa suggesting slow translational speeds for convection during the period. Moreover, the mean 0-6 km flow was southerly at 9 m s^{-1} and the 9-11 km winds northwesterly at 8 m s^{-1}, owing to the slow steering flow on this day.

After precipitation moved into the Ogallala region by 1200 UTC 6 July 2002, the LBF environment (Fig. 7d) remained favorable for the development of convection with heavy rainfall. The atmosphere was saturated from the surface to 825 hPa and from 650 hPa to 450 hPa, while conditionally unstable throughout a majority of the troposphere. Total Totals and K-Index values were nearly identical to the previous time period, indicating the likelihood of thunderstorms. Moreover, precipitable water values increased to 47 mm and the LCL dropped to 847 hPa, which is close to the surface at this location. CAPE is distributed through a deep layer with a value of 1414 J kg^{-1} (Fig. 7d), almost doubling the amount of CAPE from 0000 UTC 6 July 2002 (Fig. 7c). Low-level winds remained similar to the previous sounding, with southerly flow at 15-20 m s^{-1} within the lowest 100 hPa—a reflection of the low-level jet.

The occurrence of heavy precipitation in conjunction with an equivalent potential temperature (θ_e) ridge and a well-defined lifting mechanism have been documented in other studies (e.g., Zapotocny and Byrd 2002; Moore et al. 2004). Junker et al. (1999) reported that heavy rain events attributed to MCSs were often found just downwind to the

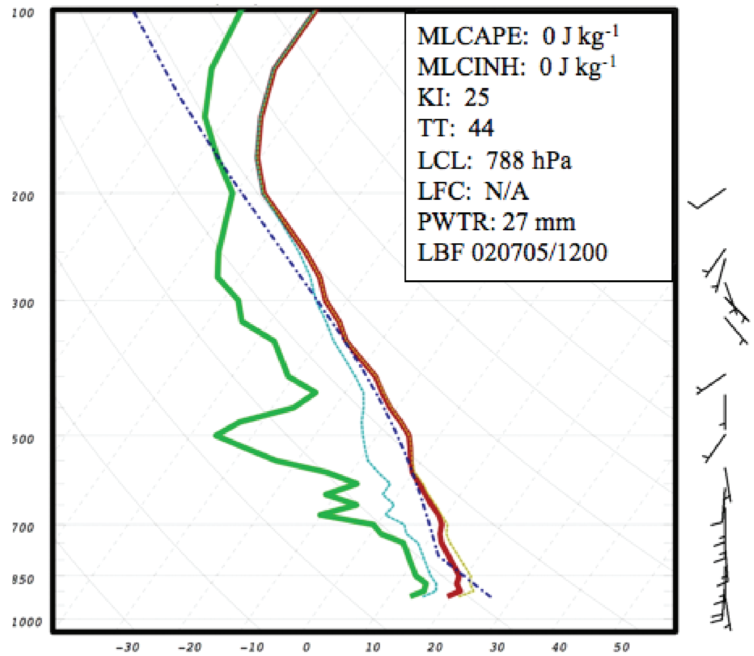

Fig. 7(a). North Platte, NE (LBF) sounding valid 1200 UTC 5 July 2002. Full barbs are 10 m s^{-1}; half barbs are 5 m s^{-1}. Stippled area represents CAPE as computed from an air parcel with mean thermodynamic properties of the lowest 100 hPa layer. Environmental temperature is shown as a red line and dewpoint in green. The lifted parcel profile is depicted with a dark blue dash-dot curve, wet bulb temperature by the thin blue dashed line, and virtural temperature with the thin yellow line.

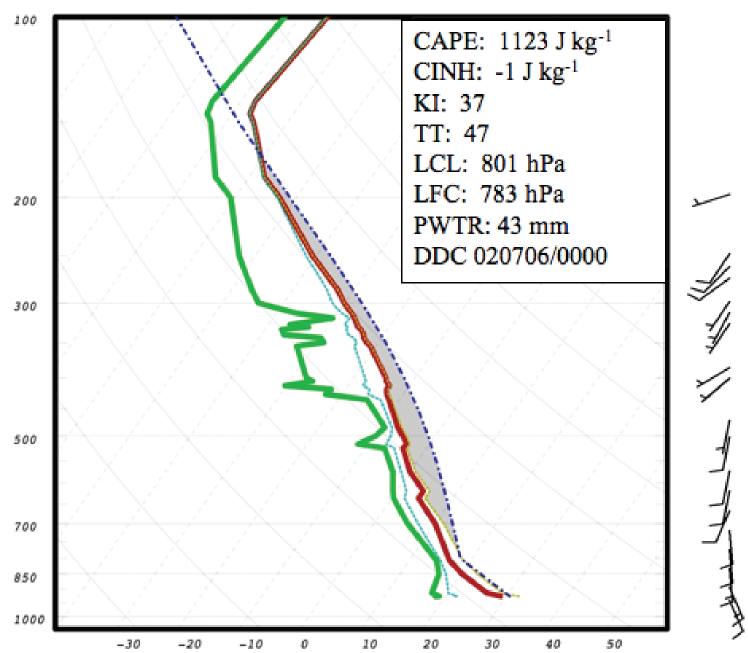

Fig. 7(b). Same as in Fig. 7a. except for Dodge City, KS (DDC) at 0000 UTC 6 July 2002.

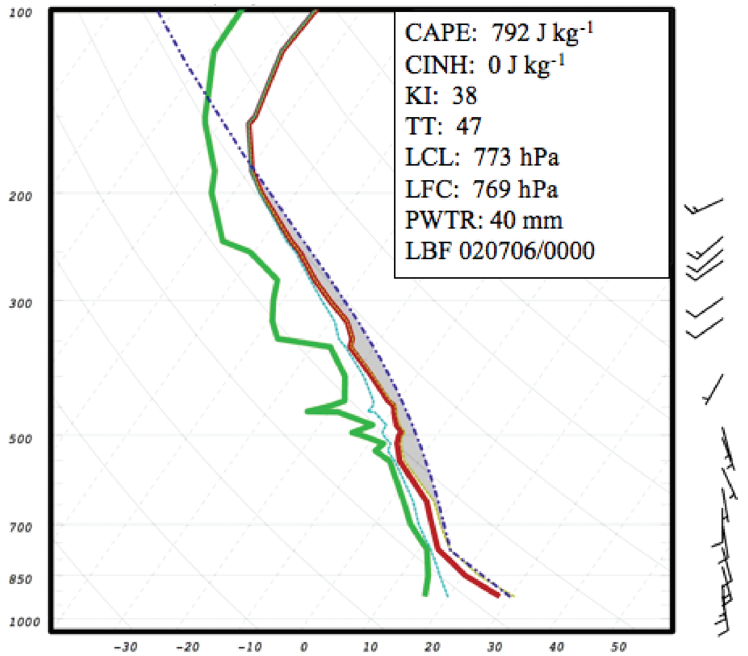

Fig. 7(c). Same as in Fig. 7a. except for 0000 UTC 6 July 2002.

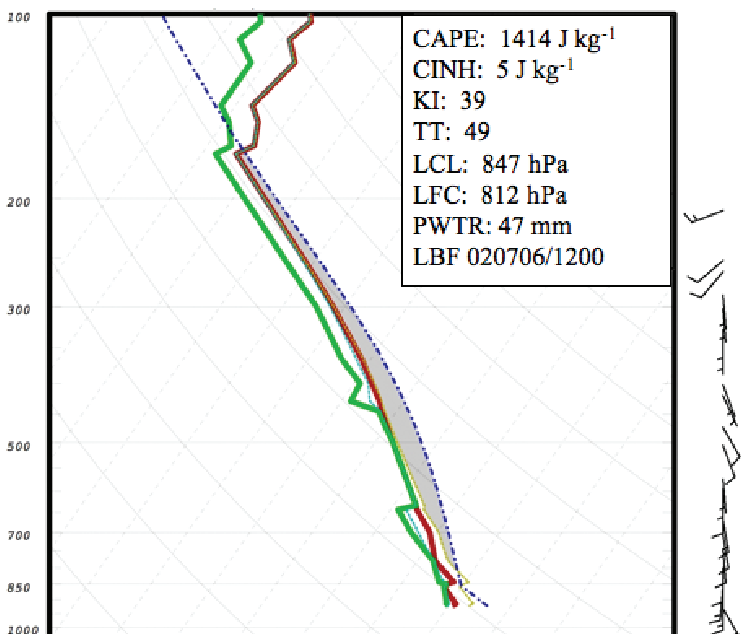

Fig. 7(d). Same as in Fig. 7a. except for 1200 UTC 6 July 2002.

north or northeast of the 850 hPa θ_e maximum values (see their Fig. 12). To further document the existence of moisture and instability in the Ogallala region prior to convective initiation, the existence of a ridge axis of θ_e in the mean 850-700 hPa layer was observed in the RUC analysis fields at 0000 UTC (Fig. 8a) and 0600 UTC (Fig. 8b) 6 July 2002 . The mean 850-700 hPa θ_e field depicted a prominent ridge axis extending from southeastern Colorado into northern Nebraska, with values of 345 K over the Ogallala area by 0600 6 July 2002 (Fig. 8b). The collocation of the θ_e ridge with a maximum in upward vertical motion, associated with the shortwave trough and the Colorado upper-level low, aided in destabilizing the atmosphere and enhancing lift in northwestern Kansas. The θ_e ridge also provided the first indication that developing convective cells would tend to generate toward the higher θ_e air located to the south and southwest of Ogallala. Moreover, the 700 hPa vertical motion field (Fig. 8b) reflected the shortwave trough and lows in northern New Mexico and south central Colorado, and the low to mid-level vertical ascent to the north.

c. Storm motion

System storm motion is defined as the vector sum of the advective and propagating motions of the convective cells (Corfidi 1996, 2003). In many flash flooding events where storm cells continually redevelop over a focused area, storm motion is slow as storm propagation is in the direction opposite to the advective component of the individual cells. To assess the potential for the Ogallala convective complex to either backbuild or remain quasi-stationary over the area, the storm propagation vector was computed for 0600 UTC 6 July 2002 (Fig. 9). For this computation, the storm motion vector was estimated from infrared satellite imagery at 0645 UTC to be 205° at 2.5 m s^{-1} (4.9 kts). The cell motion of the individual convective elements was determined from the LNX WSR-88D imagery at this time to be approximately 170° at 8.8 m s^{-1} (17 kts). The resulting propagation vector was 357° at 106 m s^{-1} (12 kts). With the storm propagation vector aligned nearly equal in magnitude and opposite in direction to that of the cell motion, the tendency for development of new convection was upstream (southwest) of Ogallala. Moreover, a closer inspection of available radar data over the duration of the heaviest rainfall indicated that the highest reflectivities were aligned to the south and southwest of the centroid of the convective complex throughout a majority of its lifetime.

d. Surface analysis and convective initiation

At the surface on 0000 UTC 6 July 2002 (Fig. 10a), a low pressure system was evident in south central Canada with an associated stationary front trailing southwestward into a weaker secondary surface low. This secondary low was centered over South Dakota with a quasi-stationary front trailing to the south and west across the Nebraska -Wyoming border. A weak surface high was located over southwestern Colorado, and a lee trough was evident in the pressure and wind fields extending southward from the main stationary front in northeastern Colorado to

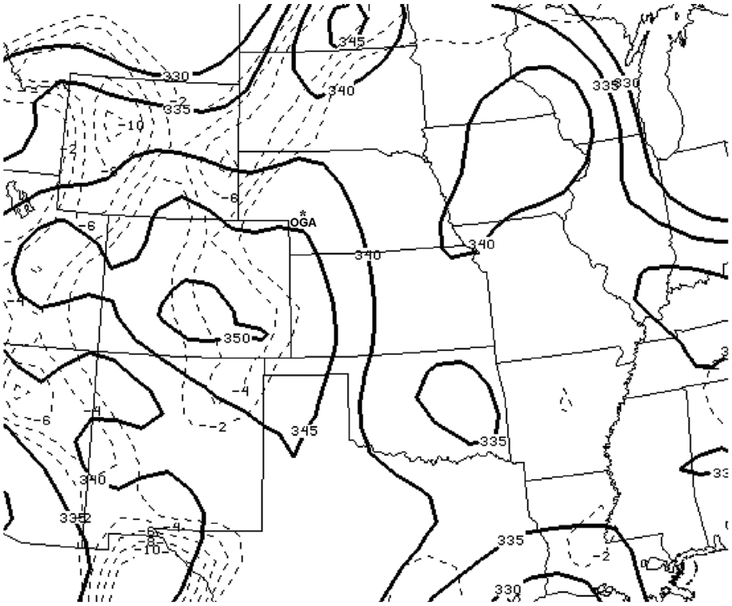

Fig. 8(a). 0000 UTC 6 July 2002 RUC analysis of the 850–700 hPa mean layer equivalent potential temperature (solid, K) and 700 hPa vertical motion (dashed, in 2 m s^{-1} intervals). The location of Ogallala, NE (OGA) is denoted with an asterisk.

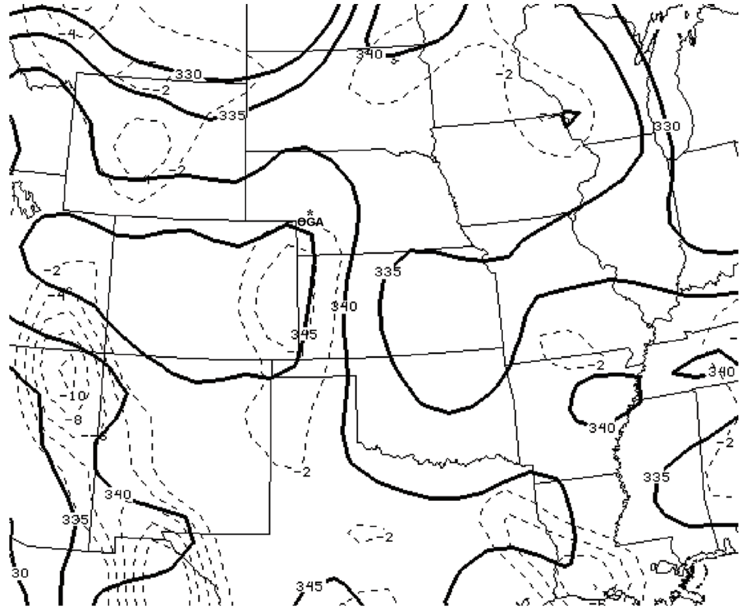

Fig. 8(b). Same as in Fig 8a except for 0600 UTC 6 July 2002.

eastern New Mexico. By 0600 UTC 6 July 2002 (Fig. 10b), the main surface low in Canada shifted to the east, while the secondary low located in South Dakota remained nearly stationary. The quasi-stationary front pushed slightly to the south and was analyzed north of Ogallala through the northern Nebraska Panhandle. The lee surface trough remained nearly stationary in eastern Colorado.

Inspection of visible satellite imagery (Fig. 11) provided interesting insight into the initiation of the convection that would produce the Ogallala flash flood. A cumulus cloud cover and cooler surface air was noted from DDC northwestward toward GLD. There the temperatures were in the low 20s °C, some 4-5 degrees cooler than locations to the south and east. This area of cooler air resulted from a continuous cloud cover that affected the area during the daytime on 5 July 2002, inhibiting isolation, suppressing afternoon temperatures and limiting the destabilization of the airmass. Surface dew points in this cool region were in the mid-teens (°C). It was within this area of cloudiness and cooler surface air, east of the shortwave trough, that a field of cumulus clouds developed by 0000 UTC 6 July 2002 along an old outflow boundary that had been produced by thunderstorms in central Oklahoma several hours earlier. The outflow boundary at 2345 UTC 5 July 2002 (Fig. 11) remained just to the south of DDC. It then pushed north-northwestward at about 10 m s^{-1} associated with the low-level southeasterly flow. With the passage of this outflow boundary, the temperature at DDC dropped 4 °C and the resulting hydrostatic pressure increased 0.9 hPa between 0000 and 0100 UTC 6 July 2002 (not shown). By 0109 UTC 6 July 2002, the outflow boundary progressed northwest of DDC (Fig. 12), and began to play an important role in focusing a line of convection that would move northwestward toward Nebraska. A mesoanalysis of the region as convection initiated in northwestern Kansas at 0000 UTC 6 July 2002 revealed additional features, such as low pressure systems associated with the upper-level lows and a cool air pocket over western Kansas (Fig. 13).

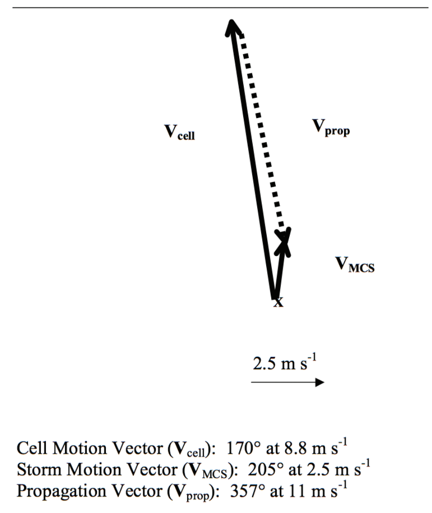

Fig. 9. Estimated storm propagation (Vprop), storm motion (V_{MCS}), and cell motion (Vcell) as outlined in Corfidi et al. (1996).

Moreover, the upslope flow of warm and moisture-laden surface air over the terrain in western Kansas contributed to the development of convection by 0000 UTC 6 July 2002 . Note that the surface flow in western Kansas slowly backed from 1800 UTC 5 July 2002 (Fig. 14a) to 0300 UTC 6 July 2002 (Fig. 14b), resulting in a more southeasterly component, normal to the orientation

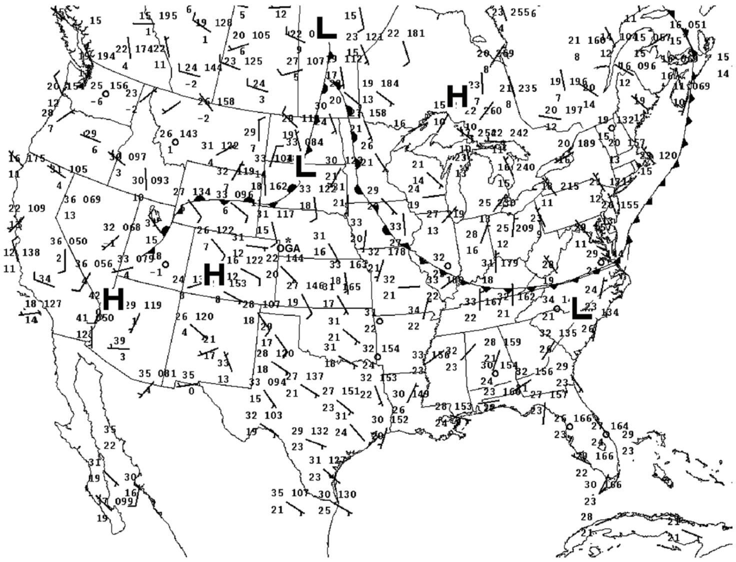

Fig. 10(a). Surface frontal positions from the National Center for Environmental Prediction (NCEP) valid at 0000 UTC 6 July 2002. Synoptic scale features are denoted in conventional symbols. Station models are plotted in conventional format. The location of Ogallala, NE (OGA) is denoted with an asterisk.

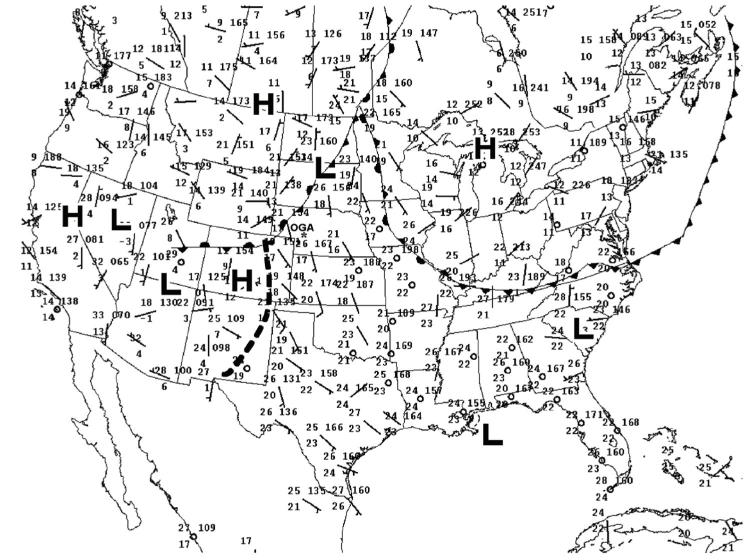

Fig. 10(b). Same as in Fig. 10a except for 0600 UTC 6 July 2002.

of the topography. Hence, the existing outflow boundary promoted additional lift and helped to focus and organize the initiation of convection just to the south of GLD by 0100-0200 UTC. If the depth of the outflow boundary was on the order of several hundred meters, as is typical in a thunderstorm outflow boundary (Mahoney 1988), a surface based parcel within the warmer air north of the outflow should have attained enough lift along the topography to reach its respective LCL. Between 0000 and 0300 UTC 6 July 2002, the LCL would had occurred somewhere near 1500-2000 m, assuming a pressure value between 800 and 850 hPa. This was depicted in the 1200 UTC 5 July and 0000 UTC 6 July 2002 thermodynamic profiles for DDC, indicative of the airmass that continued northward toward Ogallala. Developing cells continued to track to the north (Fig. 14c) and entered southwest Nebraska by 0430 UTC 6 July 2002.

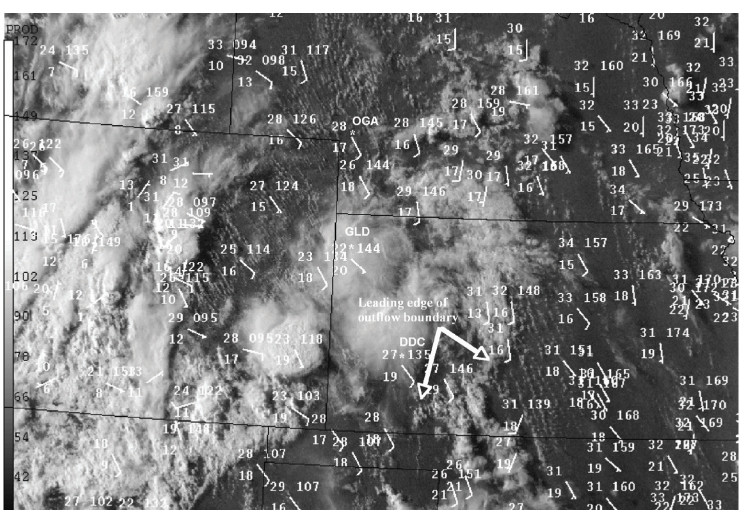

Fig. 11. GOES-10 1 km visible satellite and surface (white) plots labeled with temperature (°C), dew point (°C), mean sea level pressure (hPa) and winds speed, (m s^{-1}) valid at 0000 UTC 6 July 2002. The locations of Ogallala, NE (OGA), Goodland, KS (GLD) and Dodge City, KS (DDC) are denoted with asterisks.

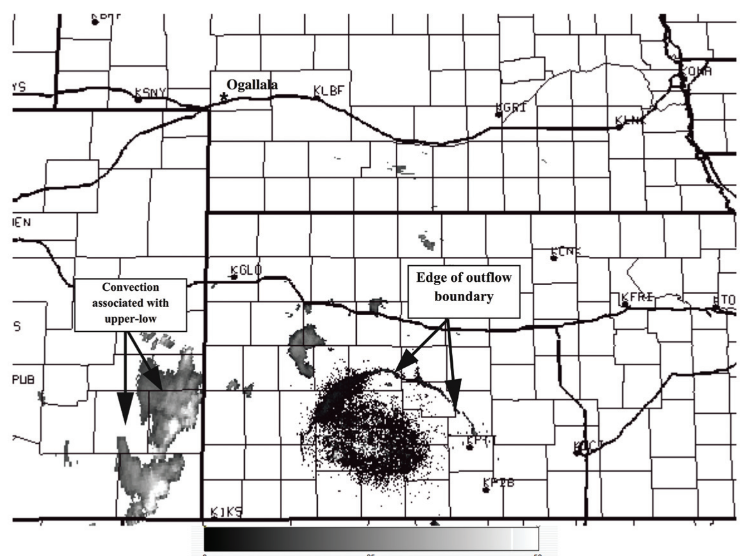

Fig.12. DDC 0.5° radar reflectivity valid at 0109 UTC 6 July 2002. Selected weather station locations are denoted in conventional format and Ogallala, NE is shown with an asterisk.

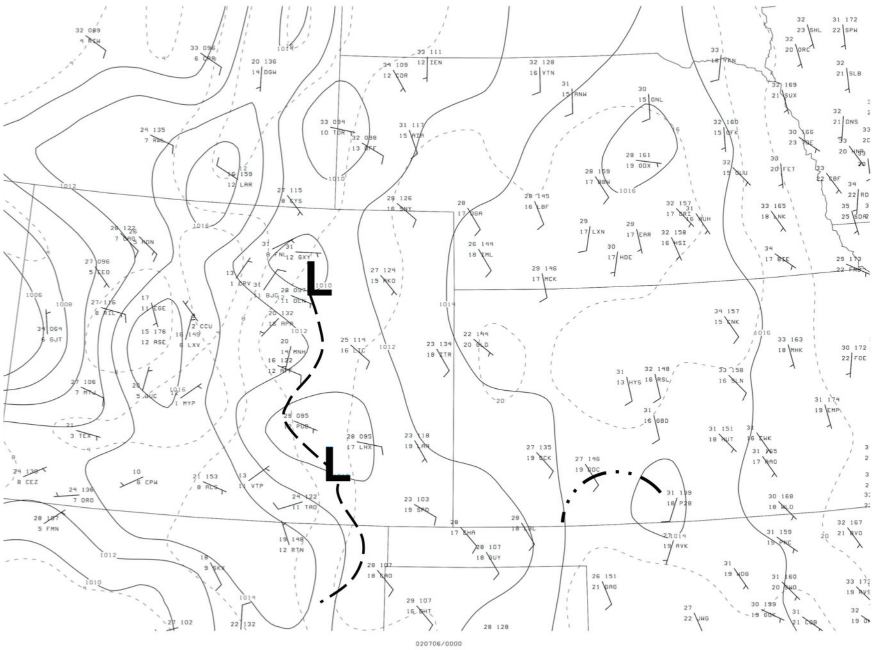

Fig. 13. Surface mesoanalysis valid 0000 UTC 06 July 2002. Isobars (solid) are contoured in 2 hPa intervals and isodrosotherms (dashed) every 2 °C. Full wind barbs are 10 m s^{-1}, half barbs 5 m s^{-1}. Surface trough is shown with a heavy dashed line and the approximate location of the outflow boundary is depicted in conventional form.

5. Discussion

Forced ascent of air parcels gradually rising over the topography in western Kansas, combined with the additional focusing and lift caused by an outflow boundary permitted convective cells to develop and mature during the early morning of 6 July 2002. By 0849 UTC 6 July 2002 (Fig. 15a), convective cells were located in southwestern Nebraska with continued development to the south and southwest along the major axis of moisture, instability and mesoscale forcing associated with a θ_e ridge and upper-level trough. Storm motion was quite slow (less than 5 m s^{-1} to the north-northeast) due to a very weak environmental flow associated with the western half of the upper-level ridge and northeast of the upper-low.

Base reflectivity values during the six-hours of the most intense echoes were between 50 and 55 dBZ, with the highest values approaching 60 dBZ, predominantly south of the Ogallala area during the heaviest precipitation (Figs. 15 a-d). By 1041 UTC 6 July 2002 (Fig. 15c), the most intense echo returns remained aligned parallel to the major axis of mesoscale forcing and instability to the southwest of Ogallala. Using the WSR-88D convective Z-R relationship (Z=300R$^{1.4}$) yielded a maximum rainfall rate of about 205 mm (~8 in.) per hour for the most intense radar echoes just south of Interstate 80 and the town of Ogallala. This axis of sustained high reflectivities persisted as convection continued to backbuild and develop for about 6 hours. The net movement of the system continued to be northeastward, while the individual cells continued to propagate southwestward in the direction of the greatest forcing. Vertical radar cross sections through the convection depicted shallow heights of the highest reflectivity cores, generally under 4 km (not shown). Therefore, with a high freezing level, warm rain collision/coalescence processes dominated the event. This is a common signature noted in other flash floods, including the more recent Kansas Turnpike event of 2003 (Kelsch 2005). Once the convective cluster formed, it maintained a slow northward track aligned with the axis of the greatest moisture and instability while continuing to backbuild to the south and southwest within the axis of greatest instability and forcing. The heaviest precipitation cores produced rain that quickly filled drainage basins emptying into the Platte River, eventually damaging an overpass along Interstate 80.

By 1600 UTC 6 July 2002, precipitation ended in the Ogallala region (not shown). The MCS continued to track to the north-northeast, slowly weakening as it crossed the Nebraska-South Dakota border and progressed into a less thermodynamically favorable environment.

6. Summary

An extreme convective precipitation event occurred during the early morning hours of 6 July 2002 in southwestern Nebraska. While the convective system responsible for the flash flooding exhibited many features similar to other events, including the "frontal" regime of Maddox et al. (1979), the mechanisms by which it was generated and sustained to produce over 21 cm of precipitation were somewhat unique. In particular, the juxtaposition of an upper-level low within a deep tropical air mass, modest low-level flow impinging on topography and a pre-existing outflow boundary combined to initiate, organize and maintain deep moist convection over southwestern Nebraska. From an operational standpoint, this event was difficult to forecast in terms of identifying where convection would initiate, due in part to the subtle and small scale nature of the outflow boundary and role of the topography. While atmospheric conditions were favorable for heavy precipitation, noting the existence and relevance of these features which dictated when and where convection would initiate, did not prove trivial.

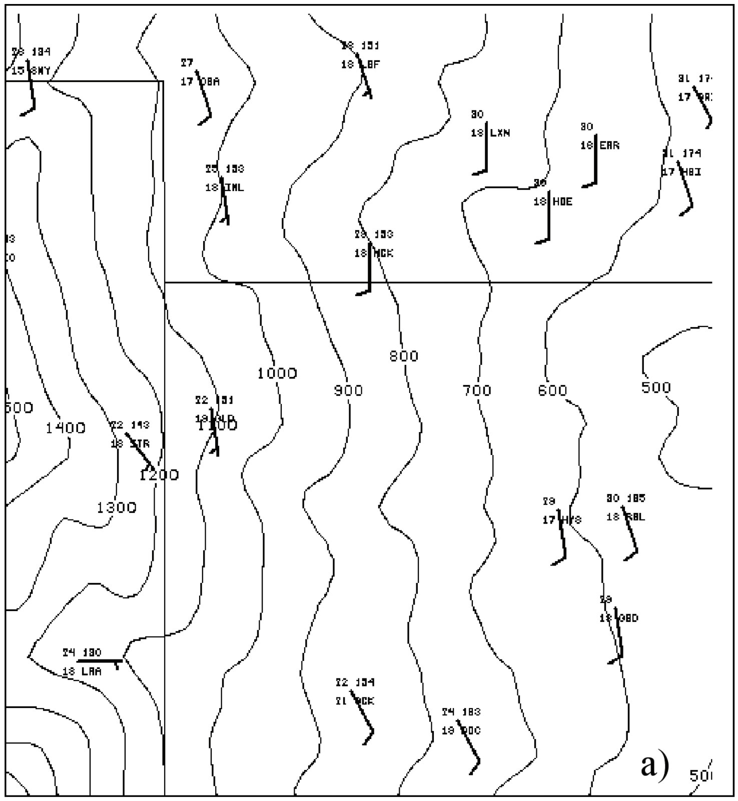

Fig. 14(a). Surface stations plots and terrain (m) for 1800 UTC 5 July 2002. Surface stations contain temperature (°C), dew point (°C) and mean sea level pressure in conventional plotting format. Winds are in m s^{-1}.

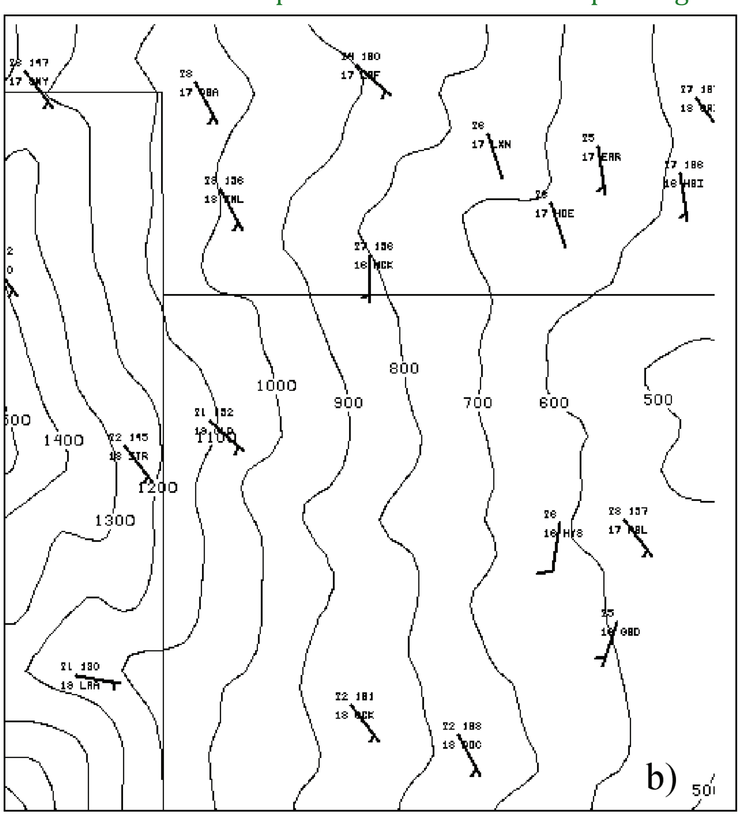

Fig. 14(b). Same as in Fig. 14a. except for 0300 UTC.

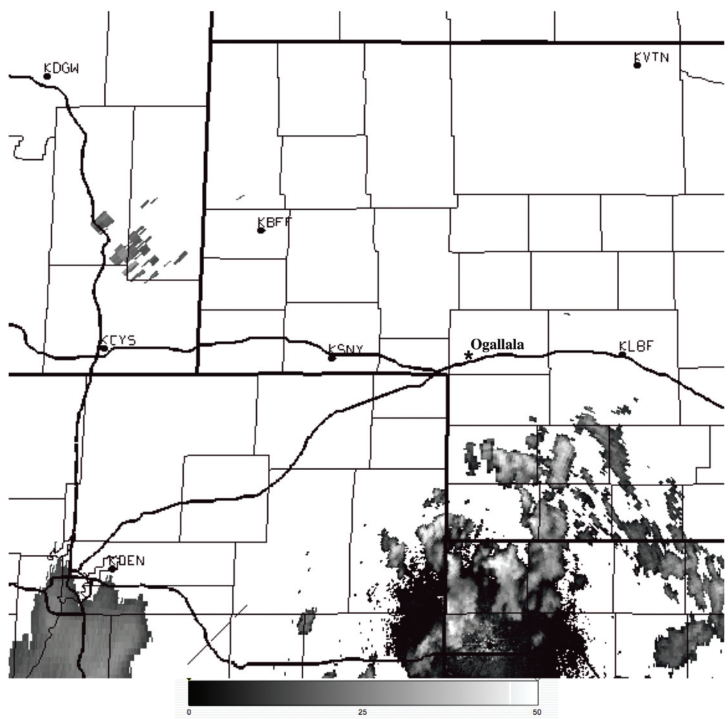

Fig. 14(c). Goodland, KS (GLD) 0.5° reflectivity valid 0436 UTC 6 July 2002. Selected weather station locations are denoted in conventional format and Ogallala, NE is shown with an asterisk.

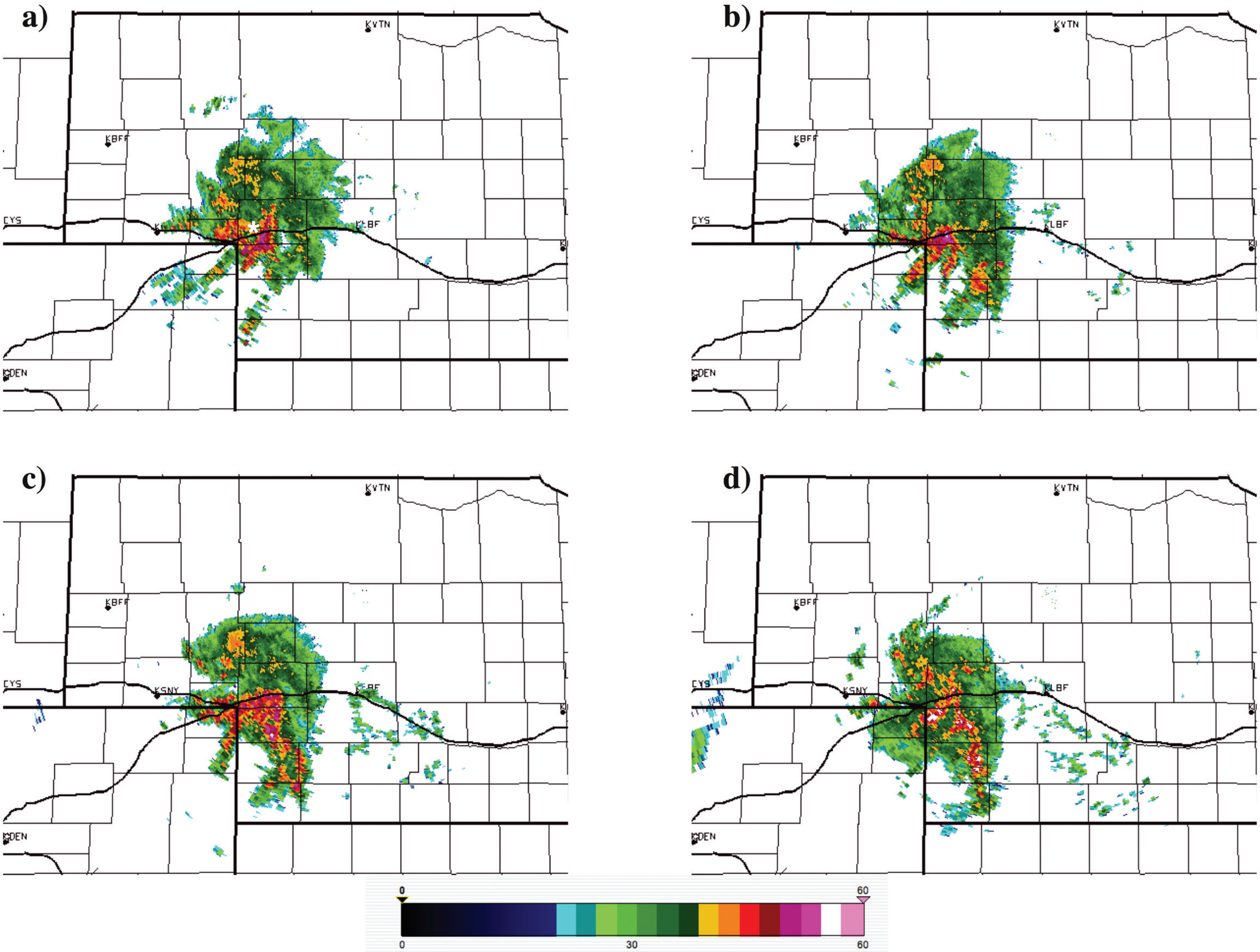

Fig. 15(a-d). LNX 0.5° reflectivity valid (a) 0849, (b) 0948, (c) 1041 and (d) 1151 UTC 6 July 2002. Selected weather station locations are denoted in conventional format and Ogallala, NE is shown with an asterisk.

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