Summary of Convective Storm Initiation and Evolution during IHOP: Observational and Modeling Perspective

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(Manuscript received 9 August 2004, in final form 19 January 2005)

ABSTRACT

The data-rich International H2O Project (IHOP_2002) experiment is used to study convective storm initiation and subsequent evolution for all days of the experiment. Initiation episodes were almost evenly divided between those triggered along surface-based convergence lines and elevated initiation episodes that showed no associated surface convergence. The elevated episodes occurred mostly at night, and the surface-based episodes occurred during the afternoon and evening. Surface-based initiations were mostly associated with synoptic fronts and gust fronts and less so with drylines and bores. Elevated initiations were frequently associated with observable convergent or confluent features in the Rapid Update Cycle (RUC) wind analysis fields between 900 and 600 hPa. The RUC10 3-h forecast of the precipitation initiation episodes were correct 44% of the time, allowing a tolerance of 250 km in space and for the forecast being early by one period. However, the accuracy was closely tied to the scale of the initiation mechanism, being highest for synoptic frontal features and lowest for gust fronts.

Gust fronts were a primary feature influencing the evolution of the initiated storms. Almost one-half of the storm complexes associated with initiation episodes did not produce surface gust fronts. Storm systems that did not produce gust fronts most often lived 2–6 h while those that did frequently lived at least 8 h. The largest and longest-lived storm complexes had well-developed intense gust fronts that influenced the propagation of the storm system. The RUC10 was generally not successful in forecasting the evolution and motion of the larger, more intense storm complexes; presumably this was because it did not produce strong gust fronts.

Implications for forecasting convective storm initiation and evolution are discussed.

1. Introduction

One of the four objectives of the International H2O Project (IHOP_2002) was to better understand and predict the processes that determine where and when convective storms first form (Weckwerth et al. 2004). An operating hypothesis during IHOP was that convective storm initiation, particularly during the afternoon and evening, occurred along boundary layer convergence lines (boundaries) in response to the focused convergence provided by the boundaries. The forecasting challenge was to determine where and when storms would form along these boundaries. With the exception of colliding boundaries or intersecting boundaries there was limited foresight into the specifics of where and when they would initiate. The scientific challenge was to understand the specific initiation process. Many of the papers in this special issue are observational studies focused on the specifics of convective storm initiation as identified by high-resolution three-dimensional wind fields, moisture transport, and stability in the vicinity of convergence lines.

The purpose of this paper is to provide a broad perspective of storm initiation and evolution during the entire 44 days of IHOP. Documented are the time, location, and primary convection initiation and evolution mechanisms (sections 3 and 4). This includes examination of the common occurrence of nocturnal initiation of elevated storms. A second purpose is to examine the ability of an operational numerical model with very-short period prediction capabilities (3 and 6 h) to forecast the initiation and evolution of convective precipitation (section 5).
The high frequency of nocturnal convective rainfall over the study area is well known (Palmen and Newton 1969; Wallace 1975; Dai et al. 1999). Part of this maximum can be explained by the propagation of squall lines eastward from the initiation of afternoon thunderstorms over the Rocky Mountains (Carbone et al. 2002). Other causes have been advanced, such as convergence created by the region’s nocturnal low-level jet (Pitchford and London 1962) and large-scale nocturnal convergence east of the Rockies (Wallace 1975). Laing and Fritsch (1997) in their global study of mesoscale convective complexes (MCCs) examined the time initial storms formed that evolved into MCCs. They observed an afternoon peak and secondary nighttime maximum for the initial storms that evolved into an MCC. Section 4 will show a similar distribution of storm initiation versus time.

A considerable amount of literature shows that afternoon and evening thunderstorm initiation by the dryline is a common occurrence through Texas, Oklahoma, and Kansas (Rhea 1966; Schaefer 1986; Hane et al. 1993; Ziegler and Rasmussen 1998). The “triple point” where two boundaries intersect separating three air masses was considered during IHOP as a likely location for initiation and thus a location for focusing project observation facilities. Carbone et al. (1990) and Koch and Clark (1999) have shown that undular bores initiate nighttime storms. These three initiation mechanisms (dryline, triple point, and bores) will be examined in sections 4b and 4c.

The relative importance of storm initiation within the IHOP area compared to the propagation of storms into the area can be appreciated from the following. There were 26 occasions when storm complexes moved into the IHOP study area. Over half of these rapidly dissipated. As will be described, there were 112 initiation episodes (defined in section 3b) within the study area and these were responsible for producing the large majority of heavy-rain-producing systems.

In section 5 we discuss the Rapid Update Cycle 10-km version (RUC10) and examine its ability to forecast the initiation and evolution of IHOP convective storms. Several other short-period forecasting models were also run specifically for IHOP (see Table 2 of Weckwerth et al. 2004). The intent here was to choose just one model that was run in real time that was easily accessible to us. The decision to use the RUC10 was largely driven by the practicalities of ease availability, a minimum of data gaps, and a format we could easily accept and overlay on our other fields. The purpose here is not to intercompare models as is done by Szoke et al. (2004) but to obtain a general understanding of an operational model’s strengths and weaknesses in forecasting convection initiation and evolution. The combined use of operational numerical forecast models with heuristic forecast methods for operational nowcasting (0–6 h) of convective weather is an active area of development and operational implementation at the National Center for Atmospheric Research (NCAR) and in several foreign countries (Mueller et al. 2003; Fritsch and Carbone 2004). The RUC is presently being used in an NCAR 0–2-h operational convective storm nowcasting system where it is being blended with heuristic nowcasting techniques (Mueller et al. 2003).

In section 6 we examine the evolution of initiation episodes and look specifically at storm organization, lifetimes, and forcing mechanisms. We also examine how well the RUC10 captured the evolution of the 11 most significant (size, intensity, and organization) events.

It is hoped that this examination of convection initiation on all days of IHOP will provide (a) insight into enhanced procedures for blending numerical and observational nowcasting techniques and (b) a climatological perspective and context for the specific IHOP case studies presented by others.

2. Data

Weckwerth et al. (2004) describes the rich dataset that is available for IHOP studies. Particularly important for the studies reported here are the mesonet, radiosonde, radar, and satellite data. Within the IHOP study area there were about 275 surface stations generally reporting wind, temperature, and dewpoint at time intervals between 1 and 60 min. Figure 1 shows the study area, instrumentation, and mosaic radar data. Visible and IR data were available from the Geostationary Operational Environmental Satellite-8 and -11 (GOES-8 and -11). GOES-11 was available from 3 to 21 June at 5-min intervals and GOES-8 at 15-min intervals for the entire project. These datasets were used to identify storm initiation locations and times, as well as to identify and characterize boundaries. Figure 1b shows a mosaic of 10 Weather Surveillance Radar-1988 Doppler units (WSR-88Ds) and the NCAR S-band dual-polarization Doppler radar (S-Pol; Keeler et al. 2000). Radar mosaics were prepared at 10-min intervals for the entire 44-day period of IHOP. Their primary use was to identify storm initiation locations, identify and track boundaries, and monitor storm evolution.

As reported by Weckwerth et al. (2004) the number of radiosondes available was substantially increased for IHOP. This included 3-hourly soundings from five Atmospheric Radiation Measurement Program (ARM) facilities (Fig. 1: HBK, LMN, MRS, PRC, VICI) for a
FIG. 1. Study area for this paper. (a) Visible satellite data from GOES-11. White three-letter station codes are radiosonde sites and wind barbs from 275 surface stations. (b) Radar reflectivity mosaic of the 0.5° elevation scans from the WSR-88D and S-Pol radars. Most of the observed echoes are clear-air insect scattering. Note reflectivity scale ranges between −15 and 25 dBZ. Radar sites are indicated by the white letters.
3-week period from 25 May to 15 June. Upon special request, supplemental soundings were taken at National Weather Service (NWS) radiosonde sites (Fig. 1: AMA, DDC, FWD, OUN, TOP) and at Texas Tech University (REE). In addition soundings were available from a fixed NCAR site (ISS in Fig. 1) and two mobile facilities.

In sections 5 and 6 comparisons are made between the RUC10 6-h (3 h) forecasts of convective precipitation accumulation and radar reflectivity. The accumulation forecasts are for a 3-h period 3–6 h (0–3 h) after forecast time, whereas the radar reflectivity images are instantaneous fields available every 10 min. While these are far from equivalent, comparisons are still informative.

3. Analysis

a. Convergence lines

The role of convergence lines (boundaries) on storm initiation and evolution is well documented (Byers and Braham 1949; Purdom 1976; Wilson and Schreiber 1986; Koch and Ray 1997) and is an important part of this study. The locations of boundaries were entered into the database every 20 min for the entire period of the project. The location and type of boundary was based on analysis of the National Centers for Environmental Prediction/Hydrometeorological Prediction Center (NCEP/HPC) 3-hourly surface maps, Storm Prediction Center (SPC) analysis prepared specifically for IHOP participants, and inspection by the authors of radar reflectivity thin lines, Doppler velocity convergence features, surface station reports, and cloud lines in the visible satellite data.

The presence of a boundary was based on radar and surface station observations (Wilson et al. 1994). A boundary was classified as a gust front if it could be traced back to have emerged from a convective storm. Considering the density of surface stations and radars we estimate that surface convergence features with lengths of >10–20 km will be observed. Very shallow, short-lived, small-scale gust fronts are the most likely to go undetected. These are less likely to be a factor in storm initiation.

b. Storm initiation

Storm initiation was declared when a convective radar echo at the 0.5° elevation angle first reached 40 dBZ and occupied an area of at least 4 km². An enhancement was added to a radar software package¹ that detects, tracks, characterizes, and extrapolates storms to also mark storm initiation location and time on the radar display (see ‘+’s in Fig. 2).

¹ This software package is called Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN; Dixon and Wiener 1993).

Fig. 2. Example of a convective initiation episode (within white polygon). (a) The initial time and (b) the end of the initiation episode. Reflectivity is shown in gray shades (scale in dBZ on right). The ‘+’s indicate the location where individual cells first reach 40 dBZ and cover an area of at least 4 km².
Storm initiations that clustered in time and space were identified and called storm initiation episodes. An episode consisted of two or more cell initiations whose close appearance in time and space suggested a common forcing mechanism. The number of cells in an initiation episode varied between 2 and 55 over time periods varying between 10 and 200 min. An initiation episode consists of storms that appear in a region without any apparent forcing from existing storms. For example, an initiation episode would include storms initiated by a gust front that was no longer associated with active convection. Storms being initiated by the gust fronts of active convection were not considered an initiation episode, but rather secondary convection initiation. Also not included is the initiation of an isolated cell, the initiation of cells within existing stratiform precipitation, or within or near an existing storm complex. Thus initiation of storms associated with storm systems moving into the IHOP study area were not included in the study; however, storms initiated by a gust front moving into the area no longer associated with active convection were included.

Figure 2 is an example of an initiation episode (19 initiations in 140 min) along a synoptic stationary front. A total of 112 initiation episodes were identified during the 44-day study period. For each initiation episode the following were recorded: location, number of individual cells that initiated between the beginning and end of the episode, the orientation and size of the episode, and the suspected initiation mechanism. These are recorded in Table A1 in the appendix.

c. Storm initiation mechanism

Forcing mechanisms for initiation episodes were divided into two groups: surface based and elevated. The classification of surface based required the observation of a nearby boundary. Wilson and Schreiber (1986) showed that convective storm initiation over the eastern plains of Colorado takes place typically within about 20 km of a boundary. If no surface convergence feature was identified near a storm initiation it was classified as an elevated initiation episode. Ideally the distinction of elevated versus surface-based initiation should be based on the location of the updraft roots; however such observations were not possible, and thus we used observation of surface convergence as a proxy for updraft roots at the surface.

Surface-based forcing was classified into seven categories:

1) frontal—cold, warm, or stationary synoptic fronts
2) gust fronts—wind shift lines that originated from convective storm outflows; in accordance with the definition of an initiation episode, the storms that initiated the gust front would no longer exist
3) trough lines—wind shift lines associated with a trough of low surface pressure
4) drylines—wind shift lines with a general north–south orientation that had an evident moisture decrease from east to west
5) colliding—the collision of any two boundaries; typically at least one of these would be a gust front
6) bore—multiple closely spaced surface wind shift lines that appear on radar as a wave train of reflectivity thin lines moving in the same direction
7) unknown—surface convergent wind features whose origin is unknown

Bores present a classification issue. We include them as surface-based initiation events although it is quite possible the updraft roots for any convective storms may have been elevated. The observed bores appeared on the radar lowest scan and at the surface stations as convergence lines, thus fitting our earlier definition of surface based.

d. Storm evolution

The evolution of each initiation episode was followed and was classified at its mature stage of convection as a multicell complex, linear feature, or squall line. A squall line was differentiated from a linear feature by the presence of a gust front. Other features recorded and shown in Table A1 are size at maturity, development of a gust front, and if the initiation episode merged with other initiation episodes. It should be noted that on occasions the size at maturity may be less than the length of the initiation episode.

e. Environmental parameter

Computer programs were developed for obtaining (a) high-resolution near-surface divergence fields from the surface stations, and (b) high-resolution 2D gridded fields of convective available potential energy (CAPE) and convective inhibition (CIN) derived from the IHOP sounding dataset and a lifted surface parcel based on the mesonet data; these will be referred to in section 6 as surface CAPE and surface CIN. The divergence was computed from a surface wind velocity field on a 10-km grid. The wind analysis was performed on

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2 At each surface station location the surface temperature and dewpoint from that station was used as the lifted parcel for computing CAPE and CIN. The sounding used was the nearest in time and space.
all 275 surface stations using a Barnes analysis (Barnes 1964) with an influence radius of 125 km. These high-resolution fields are used in section 6 to follow the evolution of 12–13 June and 15–16 June storm complexes.

4. Initiation episode results

a. Surface based and elevated

The location and time of the 112 initiation episodes are shown respectively in Figs. 3a and 3b. A strong tendency can be seen for the daytime\(^3\) initiation to be oriented northeast–southwest, whereas the nighttime initiation has little preferred orientation.

The beginning times of the 112 initiation episodes are shown in Fig. 3b. The distribution is bimodal with a distinct peak in the afternoon between 1300 and 1600 central standard time (CST; 1900–2200 UTC) and a broader nocturnal maximum between 2200 and 0400 CST. It can also be seen in Fig. 3b that the number of initiations is almost evenly divided between surface and elevated. As might be expected, the afternoon initiation episodes were primarily surface based and the nocturnal ones were elevated. Thus we see that elevated nocturnal storm initiation is a contributing factor to the nocturnal maximum in rainfall that has been observed over the southern plains.

Figure 4 shows the boundary type associated with the surface-forced initiation episodes. Cold fronts, warm fronts, and stationary fronts were all grouped as frontal. Typically fronts were oriented NE–SW and were stationary or moved slowly during initiation periods. Figure 4 shows that a majority of the surfaced-based initiation episodes were associated with fronts and gust fronts that occurred during the afternoon and evening.

In an effort to determine the scale of the forcing

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\(^3\) The division between day and night does not strictly adhere to sunrise and sunset but rather 1–3 h later, which was more conveniently associated with a minimum in initiations just prior to 0600 and 2200 UTC.
mechanism for the large number of nocturnal elevated initiation episodes the upper-level RUC analysis wind field was examined for convergence features. Two-thirds of the elevated events were associated with convergence or confluence wind features between 900 and 600 hPa as observed in the RUC analysis; Fig. 5 is an example. This is important in that it shows the forcing mechanism was often of a sufficiently large scale that it could be observed in the analysis of conventional data. Wavelike features (Carbone et al. 2002), undular bores (Carbone et al. 1990), or upper-level fronts (Locatelli et al. 2002) may also be causes for nocturnal initiation; of these only bores are briefly examined here.

b. Drylines and triple points

The importance of the dryline in initiating thunderstorms has often been cited (Schaefer 1986). Rhea (1966) showed that on days with drylines the first radar echoes were likely to appear “very close” to the dryline. He reports that new radar echoes form within 400 km of the dryline on 70% of the days with drylines. In this study we would not have attributed forcing of an initiation episode to the dryline unless it was within about 20 km of the dryline.

Only five initiation episodes were associated with drylines (Fig. 4). There were a total of 15 days with drylines during IHOP. In addition to the five initiation episodes in Fig. 4 one other episode that was classified as a cold front initiation episode also initiated storms along a dryline, just not as many as along the cold front. The perceptions from previous studies in the literature suggest that 2002 may have had an anomalously low number of dryline initiation events.

There were a total of 8 days where triple points occurred; all involved a front. The second boundary was a dryline, trough line, or unknown boundary. Storm initiation occurred at the triple point on 6 of these 8 days. These storms had the tendency to be among the more intense storms.

c. Bores

The frequency of undular bores observed during IHOP was a surprise (Weckwerth et al. 2004). Given the strong vertical motions occurring with these mostly nocturnal events bores are a possible cause for some of the nocturnal storm initiation that was observed. There have been a number of case studies showing storm initiation by bores (Karyampudi et al. 1995; Carbone et al. 1990; Locatelli et al. 2002). The radar mosaic was particularly useful for observing and tracking bores.

Twenty bore trains were observed in the radar data on 15 different days. They were observed between 0230 and 1100 UTC (2030–0500 CST). Six of the bores did initiate storms; however in only three of these cases were the storms sufficiently large or intense to qualify as an initiation episode. Typically the initiation took place along a small portion of the bore and for a short time period. The bore on 4 June was an exception where a significant number of storms were initiated that eventually developed into a squall line (Flamant et al. 2003). In summary while bores were a frequently occurring phenomenon during the night they played only a very small role in initiating nocturnal thunderstorms during IHOP. However, the evidence from case studies in the literature reveals that on occasions they may be responsible for major storm initiation events.

5. RUC10 precipitation forecasts

a. Model description

The RUC10 was examined for its ability to provide very short period (3–6 h) forecasts of storm initiation and evolution. The National Oceanic and Atmospheric Administration (NOAA) Forecast System Laboratory specifically ran this 10-km version of the operational 20-km RUC for IHOP. Readily available were 3- and 6-h forecasts that were issued every 3 h.

The RUC is an analysis–forecast numerical model

\[\text{Figure 5. Example of wind confluence at midlevels (625 hPa in this case) with an elevated initiation episode (within white polygon).}\]
that is routinely run hourly at the NCEP. It is described in detail in Benjamin et al. (2004a,b); we offer here only a brief description. The RUC is an advanced version of the hydrostatic primitive equation model developed by Bleck and Benjamin (1993). It is unique among operational numerical weather prediction models in two primary aspects: its hourly assimilation cycle and its use of a hybrid isentropic-terrain-following vertical coordinate for both assimilation and forecast model components. The parameterization scheme for triggering convective precipitation is based on an ensemble approach described by Grell and Devenyi (2002). The procedure includes examining each grid column for CAPE. Provided any CAPE is found in the lowest 300 hPa, and the distance (in terms of pressure) between the convective condensation level and the level of free convection is less than a preset distance, a four-scheme closure process is invoked to determine the amount of triggered precipitation.

What can we expect from the RUC10 with respect to producing cold pools, convection type, and evolution of convection? The RUC10 has the ability to produce downdrafts and cold pools through the above parameterization schemes but is unable to maintain them with time because these outflows are too shallow and also usually insufficiently cool relative to their environment to build up to a depth and strength necessary to propagate realistically. This hinders the ability of the model to evolve and propagate the parameterized convection and to form realistic convectively driven mesoscale structures such as frequently observed “leading line convection—trailing stratiform” (J. Brown 2004, personal communication). The model is able to represent large-scale features such as synoptic fronts, and propagate convection along these fronts. This points out certain pitfalls in trying to accurately forecast evolution of convection and mesoscale convective systems using models with horizontal grid spacing of ~10 km. At this resolution, it should in principle be possible to produce the mesoscale component of the mesoscale convective system circulation. However the dynamical feedbacks between the parameterized convection and the explicitly predicted mesoscale component of the circulation are not up to the task (J. Brown 2004, personal communication). Further Weisman et al. (1997) have shown that explicit treatment of convection (no parameterization) at these grid resolutions, even in a nonhydrostatic model, also fails to produce realistic squall-line structures, and explain this in terms of the inability to realistically capture nonhydrostatic effects in convection at horizontal grid spacings greater than about 4 km.

During IHOP the RUC10 ran and assimilated every hour a number of special datasets including mesonets (like the Oklahoma Mesonet), profilers (including Radio Acoustic Sounding System), integrated precipitable water from GPS sites, satellite cloud drift winds, VAD winds from Doppler radar, and winds and temperatures from commercial aircraft. In addition, the presence of satellite-identified areas of convection was used to reduce CIN restrictions during the first one-half hour of the forecast.

Precipitation hydrometeor information was ingested using two schemes. In the first the “estimated cloud amount” product, which is produced by the Cooperative Institute for Meteorological Satellite Studies (CIMSS), and lightning occurrence data were used to estimate where convection was occurring. At these locations model-parameterized convection was encouraged by removing restrictions on convection due to the presence of CIN. This scheme is used in the operational RUC (Benjamin et al. 2004b). In the second scheme low-resolution base-scan reflectivity data from the WSR-88Ds were combined with 1-h forecasts of precipitation hydrometeors and beam blockage information to add or remove model precipitation hydrometeors at the initial time. This scheme is not presently part of the operational RUC.

b. RUC10 precipitation initiation forecasts

The ability of the model to predict accurately the onset of precipitation for the 112 initiation episodes was explored and the results are presented here. Beyond the scope of this study is examination of forecasts of storm initiation by the RUC that did not develop. No RUC data were available for 10 of the episodes; thus only 102 initiation episodes have been examined.

Model performance assessment was done by overlaying the initiation episode contour onto the RUC precipitation forecast fields. For example, for initiation episode 3 on 16 May (initiation time = 2150–2350 UTC; all times are in UTC hereafter unless otherwise noted; see Table A1), evaluation of the 3-h forecasts involved examining the sequence of 3-h RUC forecasts for 1800–2100, 2100–0000, and 0000–0300 for new precipitation within or in the vicinity of the initiation contour zone. For this case if precipitation was forecast for 2100–0000 within the initiation zone it was classified as correct. If the precipitation was not forecast until the 0000–0300 time period then it was classified as a missed forecast. This was because the model likely introduced precipitation into the forecast only after it was observed in the data ingest. If precipitation was forecast for the 1800–2100 period then it was classified early by one forecast period. Another example would be if the observed initiation episode was from 1700 to 1900, that is, straddling two RUC forecast periods. If the RUC forecasts pro-
duced precipitation for either 1500–1800, 1800–2100, or both, the forecast was classified as correct. Spatial coverage, orientation, and offset (distance and direction) from the center of the observed initiation zone to the center of the model-forecast precipitation was noted and listed in Table A1. The spatial offset of the center of the forecast area was recorded in two categories within 50 or 50–250 km. Temporal offsets were noted as early by one 3-h forecast period or late one period.

Even after taking into consideration that the model forecast is a 3-h accumulation and the radar is a series of instantaneous precipitation images throughout the initiation episode there was a tendency for the RUC10 to forecast too large an area of precipitation (cf. the size columns in Table A1).

Comparisons of the model-forecast performance relative to the different initiation mechanisms are presented in Table 1. The elevated cases are separated into “elevated frontal”—those occurring behind (cold side) a front—and “elevated isolated”—those occurring far (hundreds of kilometers) from a front. The trough line, dryline, colliding, bore, and unknown boundaries discussed in section 3 are grouped into “Other boundaries.” The gust fronts are listed separately since their gust fronts are listed separately since their forecast statistics differed significantly from, and they tended to be smaller scale than, the other surface boundaries.

Table 1 shows that the percentage of correct forecasts tends to decrease as the spatial and temporal tolerances are decreased for a correct forecast (moving left to right through the table) and as the scale of the initiation mechanism decreases (moving top to bottom through the table). Specifically, the RUC10 correctly forecast 44% of the 102 convective storm initiation episodes given a liberal spatial tolerance of 250 km and credit for being early by one 3-h forecast period. The correct forecasts decrease to 13% if the tolerance is tightened to 50 km but no time offset, and C_{250T} and C_{50T} allowed the forecast to be early by one 3-h forecast period and still be correct. The total number of cases is 102 instead of 112 because of missing RUC forecasts.

<table>
<thead>
<tr>
<th>Initiation mechanism</th>
<th>No. of events</th>
<th>C_{250} (%)</th>
<th>C_{50} (%)</th>
<th>C_{250T} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevated (frontal)</td>
<td>10</td>
<td>80</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Fronts</td>
<td>18</td>
<td>61</td>
<td>33</td>
<td>22</td>
</tr>
<tr>
<td>Elevated (isolated)</td>
<td>43</td>
<td>40</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>Other boundaries</td>
<td>19</td>
<td>37</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>Gust fronts</td>
<td>12</td>
<td>17</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>All</td>
<td>102</td>
<td>44</td>
<td>21</td>
<td>13</td>
</tr>
</tbody>
</table>

The domain, overwhelming and obscuring any forecasts that may result due to elevated related triggering.

6. Storm evolution results: Observational and model

a. Storm evolution statistics

The evolution for each initiation episode was examined. Numerical simulations and observational studies have shown the organization and lifetime of storm systems is dependent on the relative motion between the storms and gust front, the vertical wind shear relative to the gust front, and stability parameters (Moncrieff and Miller 1976; Droegemeier and Wilhelmson 1985; Weissman and Klemp 1982; Rotunno et al. 1988; Wilson and Megenhardt 1997; Wilson et al. 2001). Detailed tracking of these and other parameters for each episode is beyond the scope of this paper. The focus in this section is on the organization of the episode at maturity, the lifetime of the event, and whether a gust front was produced. In sections 6b(1) and 6b(2) below, other factors like the magnitude of the convergence associated with boundaries, vertical shear, and stability parameters are examined for two squall-line cases.

The organization of each episode at maturity was classified as a squall-line, linear, or multicell complex (see Table A1). Figure 6 shows the classification and maximum dimension (determined from radar) of the initiation episodes at maturity. If two or more episodes merged the organization type at maturity was only counted once; thus the total in Fig. 6 does not add to 112. Forty-one of the initiation episodes merged with another initiation episode.

Squall lines tended to have the longest length (Fig. 6) and also the longest lifetime. While the lifetime of individual cells is generally only about 20–30 min (Battan...
1953; Foote and Mohr 1979) we see that the lifetime of
the complex of storms associated with an initiation epi-
sode is measured in hours. Figure 7 shows that the life-
time of the storm systems was related to whether the
convective system produced a gust front. Those systems
that produced gust fronts were likely to live at least 8 h
while those that did not were most likely to live be-
tween 2 and 6 h. Typically the gust front develops
within the first 1–2 h of a system’s lifetime. Character-
istics of gust fronts produced from individual storms
prior to storm merger are likely related to precipitation
microphysics, stability, vertical shear, and characteris-
tics of air entrained into the cloud. Study of these fac-
tors is planned for a future paper.

The median lifetime of the elevated initiation epi-
isodes was about 4 h (not shown), which was consider-
ably less than that of the surface-based initiation epi-
sodes. One reason appears to be that only 31% of the
elevated episodes produced gust fronts. The 10 el-
evated cases that did produce gust fronts all had life-
times greater than 4 h and half of them longer than 8 h.
The reason for longer-lived convective systems when
gust fronts are produced can be found in the squall-line
literature (e.g., Thorpe et al. 1982; Bluestein and Jain
1985; Hane 1986; Rotunno et al. 1988; Weisman et al.
1988; Ray 1990; Fovell and Ogura 1989; Weisman and
Rotunno 2004). Gust fronts act to maintain existing
storms and regularly initiate new storms that contribute
to the long-lived system.

b. Evolution of 11 most significant systems

Evolution of the 11 most significant storm complexes
(based on size, intensity, and organization) that evolved
from the initiation episodes was examined. These storm
complexes had almost continuous lines of storms >40
dBZ with lengths from 350 to >800 km. Storms from 30
initiation episodes merged to become part of these 11
systems. These systems developed from a variety of
different types of initiation mechanisms (cold fronts,
drylines, elevated, trough lines, and gust fronts). Often
more than one type merged to form the larger system.
Cold fronts were the most common triggering mecha-
nism, being solely responsible for four of the cases and
partially involved in three others.

In all but one of these storm complexes extensive
gust fronts developed and the system propagated with
the motion of the gust front. The one exception is 24–25
May where a 700-km-long multicell disorganized line of
storms initiated. However, the southern portion of this
line did produce a gust front and became more orga-
nized, intense, and longer-lived than the northern por-
tion.

As mentioned in the introduction there were 26
storm complexes that moved into the IHOP study area
in contrast to the 112 that initiated there. Examination
of the 26 cases showed that only 4 of these matched the
size, intensity, and duration of the 11 most significant
storm complexes discussed in this section. Three of
these 4 cases merged with 1 of the 11 cases. Thus at
least during IHOP local initiation was more important
than propagation of storms into the area with respect to
the overall occurrence of major rain-producing systems.

We now examine in more detail the evolution from
initiation to squall line for two cases during 12–13 and
15–16 June.

1) 12–13 June

A squall line about 350 km long formed during the
late afternoon in north-central Oklahoma and moved

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Fig. 6. Character of initiation episodes at maturity classified
into squall lines (SQ), linear systems (L), and multicell complexes
(M). These are grouped into three size categories by longest di-
mension (0–199, 200–399, and ≥400 km).

Fig. 7. Lifetime of convective storm complexes associated with
initiation episodes grouped by whether the complex produced a
gust front. The 10 cases that moved out of the study area before
they were 6 h old were not included.
southeast. Figure 8 shows a single time period (12 June at 2140 UTC) when storm initiation is just beginning along two intersecting boundaries. The boundaries are a dryline and an outflow boundary left behind from an earlier squall line. The surface convergence and surface CAPE and CIN (see section 3e) are also plotted. Figure 8 shows that (a) along the boundaries there is a maximum in convergence with a peak where they intersect, (b) surface CIN is generally very small (less than 15 J kg$^{-1}$), (c) surface CAPE is high (between 4000 and 5000 J kg$^{-1}$) with the highest values along the outflow boundary, and (d) in the visible satellite image there is incipient convection along much of the boundaries. Also there are relatively large surface to 6-km shear values (Table 2). The low CIN values, high CAPE, substantial convergence, and observed cumulus along the boundaries indicate a promising situation for continued storm initiation.

Figure 9 presents the evolution showing the boundaries and radar reflectivity at 3-h intervals. A mature
A squall line at 0300 (Fig. 9c) has evolved from the storms that initiated about 5 h earlier along the outflow boundary. However, it was only the storms that initiated along the outflow boundary and at the intersection with the dryline (see dotted oval in Fig. 9a) that were eventually responsible for forming the squall line in Fig. 9c. Subsequent CAPE and CIN plots during the period of evolution showed these fields were quite uniform; thus it is unlikely they played a significant role in determining which storms would evolve into the squall line.

In Fig. 9b four gust fronts are labeled (1–4). These were produced by the storms along the dryline and outflow boundary. Gust fronts 3 and 4 were produced by the storms within the oval in Fig. 9a. These gust fronts initiate many more storms than gust fronts 1 or 2. With time gust fronts 3 and 4 merge and a continuous squall line results in Fig. 9c. The storms with gust front 2 soon die, as does the gust front. The storms with gust front 1 live longer but never organize into a significant squall line. Several environmental parameters that have been shown to be useful in determining storm initiation, intensity, and longevity were examined for each gust front. These parameters are surface to 6-km vertical wind shear (Weisman and Klemp 1982), surface to 2.5-km vertical wind shear normal to the gust front (Thorpe et al. 1982; Rotunno et al. 1988), surface wind differential across and normal to the gust front (a proxy for convergence), and boundary-relative cell speed (Moncrieff and Miller 1976; Wilson and Megenhardt 1997). Shear computations were based on surface wind station data and RUC wind analysis.

Table 2 lists values for each of these parameters for each gust front during the time period from 0000 to 0100 UTC 13 June. Favorable values for initiation and longevity are (a) high values of surface to 6-km shear, (b) high values of surface to 2.5-km shear, (c) high values of differential wind velocity across the gust front, and (d) storms staying with the gust front. Gust front 3 had the most favorable values. The gust front differential wind velocity appeared to be the most important factor that differentiated 3 and 4 from 1 and 2 followed next by the surface to 6-km shear. The east–west orientation of gust fronts 3 and 4 played a role in producing the strongest wind components normal to and in advance of the gust fronts. The magnitude of the outflow with the storms behind gust fronts 3 and 4 tended to be stronger. The reason for the stronger downdrafts is not clear because it is unknown what role precipitation microphysics may have played in producing the downdrafts. However, the most intense storms tended to be associated with these two boundaries, which are supported by the greater surface to 6-km shear.

2) 15–16 June

A squall line about 600 km long develops in the late afternoon in southern Kansas and northern Oklahoma (see Fig. 10c). It develops from the merger of three smaller systems. Figure 10b shows these three systems (numbered 1–3) at 2200 UTC, which is 3.5 h prior to Fig. 10c. Storm system 1 developed about 1200 UTC in north-central Kansas as part of an area of slow-moving storms that extended NW into western Nebraska. These storms started as elevated convection. Satellite data show convective system 2 initiated at about 1300 UTC along the Colorado Front range near the center of a weak small surface low that moved east to the position shown in Fig. 10a at 1700 UTC. This area of weak convection rapidly intensifies after 1900 UTC when it intercepts a north–south trough line (see Fig. 10a). A strong gust front develops with system 2 and moves SSE. This gust front becomes the dominant triggering mechanism for additional storms and growth. System 3 developed at about 1700 UTC over high terrain near the New Mexico–Colorado border. Animation of radar data showed storms initiating close to the boundaries as they moved south and southeast. The mature squall line in Fig. 10c is the result of the merger of the three boundaries and their associated storms.

Examination of the surface CIN and surface CAPE showed that systems 2 and 3 prior to 2100 UTC and during their early evolution phase moved through an area of moderate CAPE (1000–3000 J kg$^{-1}$) and near-

<table>
<thead>
<tr>
<th>Gust front</th>
<th>Surface–6-km shear (°/m s$^{-1}$)</th>
<th>Surface–2.5-km shear (°/m s$^{-1}$)</th>
<th>Surface–2.5-km normal shear (m s$^{-1}$)</th>
<th>Gust front normal shear (m s$^{-1}$)</th>
<th>Storms stay with gust front?</th>
<th>Gust front diff. velocity (°/m s$^{-1}$)</th>
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<tbody>
<tr>
<td>1</td>
<td>310/20</td>
<td>320/10</td>
<td>9</td>
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<td>312/10</td>
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<td>260/17</td>
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<td>20</td>
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<tr>
<td>3</td>
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<td>290/10</td>
<td>11</td>
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<tr>
<td>4</td>
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<td>294/8</td>
<td>4</td>
<td>350/7</td>
<td>Yes</td>
<td>27</td>
</tr>
</tbody>
</table>
zero CIN, whereas system 1 was located in a region of low surface CAPE (<750 J kg⁻¹) and high surface CIN (>100 g kg⁻¹). This is demonstrated in Figs. 11b and 11c. After 2100 UTC when system 2 developed a strong gust front, it moved into an environment more similar to system 1. Figures 11e and 11f show that the merged systems 1 and 2 moved through areas of high CIN and relatively low CAPE. As seen in Fig. 11d strong convergence was associated with the merged gust fronts. The strong convergence seemed to overcome the less than favorable low CAPE and high CIN. The squall line moved southeast at 21 m s⁻¹, which was more southerly than would be expected from steering-level winds alone (260°–300° at 7–15 m s⁻¹). This behavior was also observed with the 12–13 June case and is a common occurrence for squall lines (e.g., Newton and Newton 1959; Stensrud and Fritsch 1993; Corfidi et al. 1996).

Environmental wind parameters were examined during the period 1900 to 2400 UTC. The surface to 6-km shear vector across the area of interest was west-northwest at 20–25 m s⁻¹, similar in magnitude to 12–13 June. The surface to 2.5-km shear normal to the gust fronts ranged between 12 and 20 m s⁻¹ for the

![Diagram](image-url)
three systems, which was generally higher than 12–13 June.

In summary storm initiation was favored in areas of near-zero CIN and sustained strong convergence for both the 12–13 June and 15–16 June cases. The exception was the elevated storm initiation, system 1 on 15–16 June. Both cases had large surface to 6-km shear values and large surface to 2.5-km shear values normal to the gust fronts, which are all favorable for storm initiation and intense long-lived storms. Specifics of storm evolution appeared to be heavily influenced by the characteristics and motion of individual gust fronts and less so by stability parameters.

3) EVALUATION OF RUC10 PRECIPITATION FORECASTS

The RUC10 forecasts were available for 10 of the most significant cases and they are examined here in relation to how precipitation evolution was handled. There were four cases where the forecasts could be considered mostly a failure in that either nothing was forecast, the forecast for initiation was 6–24 h too early, or the system was immediately dissipated. For the other six cases the RUC generally captured the initiation but once the gust fronts developed and the observed system propagated with the gust front the RUC failed in all but...
Fig. 11. Evolution of reflectivity, convergence, CIN, and CAPE during the time period of squall-line development on 15 June: (left) 1920 and (right) 2300 UTC. (a) and (d) Convergence (white contour starts at $5 \times 10^{-4}$ s$^{-1}$ with an interval of $5 \times 10^{-4}$ s$^{-1}$; there is no significant convergence in (a). (b) and (e) CIN (first contour is 15 J kg$^{-1}$ with an interval of 100 J kg$^{-1}$); (c) and (f) CAPE (contour interval 1000 J kg$^{-1}$).
one case to forecast the movement of precipitation. The one case where the RUC did correctly forecast the motion of the squall line was for a case where the precipitation was moving east with the cold front. We speculate that the RUC was forecasting the motion of the precipitation correctly because it was correctly forecasting the motion of the cold front, which was the same as the gust front.

RUC forecasts are presented in Figs. 12 and 13 for the cases of 12–13 June and 15–16 June, respectively, illustrating the RUC handling of the initiation and propagation phases.

In Figs. 12a and 12b it can be seen that the RUC-initiated storms for 12–13 June are 3–6 h early. The 6-h forecast for 0000 UTC (Fig. 12c) is remarkably well placed although more extensive and no accumulations reached 10 mm. In Fig. 12c the gust fronts are just emerging, and by 0300 (Fig. 12d) and 0600 UTC (Fig. 12e) the matured system is propagating southeast. In Figs. 12d and 12e it is evident that the RUC is not forecasting the propagation of the system southward. It may be that successive RUC runs are systematically initiating the convection to the northwest where it had been. This does not seem likely since the RUC assimilation scheme ingests information on the precipitation's location at initialization time (see section 4).

Figure 13 for 15–16 June shows similar behavior. The initiation forecast is roughly in the correct location although the orientation is incorrect (Fig. 13a). Figures 13b and 13c shows the RUC has not propagated the system southward sufficiently fast. In both cases the RUC precipitation accumulation forecasts appear low and lack any evidence of the typical leading-edge strong convection and trailing weaker stratiform, although this detailed structure would be more difficult to observe in a 3-h accumulation versus an instantaneous rate display. Similar RUC forecasts were observed for all but one of the other nine cases.

As discussed in section 5a we believe the reason the RUC10 did not propagate the storm systems correctly was due to limitations in model parameterizations; the model cannot accurately develop strong cold pools associated with storm development. As a consequence, the model is unable to realistically produce gust front evolution and forecast storm propagation.

7. Conclusions and implications

There were 112 convective storm initiation episodes during IHOP. An episode consisted of two or more cell initiations (>40 dBZ) whose close appearance in time and space suggested a common forcing mechanism. The initiation episodes were almost evenly divided between surface based and elevated. The surface-based initiations occurred mostly during the afternoon and early evening, and the elevated initiations during the night and early morning. The surface-based episodes were forced mostly by synoptic fronts and gust fronts. Only 9% of the surface-based episodes were initiated by drylines. The low number of dryline-forced initiation episodes was unexpected and leaves open the question of how representative 2002 was of previous years.

Our experience suggests that elevated convective initiation episodes are common in the IHOP area, relatively common in the upper Midwest, and infrequent during the summer in Colorado and Florida. The cause of many of the elevated initiations during IHOP appeared to be associated with synoptic or mesoscale wind convergence or confluence at midlevels (between 900 and 600 hPa) that were of a scale that could frequently be observed in the RUC analysis. We speculate that the high frequency of elevated initiation episodes in the Midwest is a result of relatively frequent midlevel synoptic and mesoscale convergence features coupled with an abundance of midlevel instability. Synoptic-scale features in Florida are less frequent and moisture in Colorado is much less. The high frequency of elevated storm initiation in the study area brings up the question, How much of the nocturnal maximum in rainfall in the Midwest is the result of locally initiated storms versus those that advect from the west?

While many of the elevated initiations were associated with synoptic or mesoscale convergence features observed in the RUC analysis there is no known method for anticipating the specific time of initiation. Improved basic understanding of elevated storm initiation will require fundamental research. However, means for directly observing detailed midlevel wind and stability parameters are not yet possible.

While the lifetime of individual cells is typically measured in minutes, the lifetime of the complex of storms evolving from an initiation episode was hours. The lifetime of the storm complex was related to whether the convective system produced a gust front. Those systems that produced gust fronts were likely to merge with other similar systems, which then formed a large-scale complex that lived at least 8 h while those that did not were more likely to live between 2 and 6 h. The evolution movement and lifetime of the initiated storms appeared to be primarily influenced by the emerging gust fronts and their characteristics rather than stability parameters. As often observed, the organized squall lines propagated with the motion of the gust front and not the steering-level flow.

The RUC10 3-h convective precipitation forecasts
Fig. 12. (a)–(e) The 12–13 June RUC 3–6-h precipitation forecasts (solid white contour) overlaid on radar reflectivity fields at the end of the 6-h period (grayshade scale in dBZ on right) at 3-h intervals. The forecasts are 3-h accumulations ending at the given time. The reflectivity is the instantaneous field at the given time. The first precipitation contour represents an accumulation of 1 mm during the 3-h period; the second contour [only reached in (b)] is 10 mm. Rainfall rates of 1 and 10 mm h$^{-1}$ roughly correspond to dBZ values of 25 and 35, respectively. Observed boundaries are shown by thick white lines.
were able to correctly forecast precipitation for 44% of the initiation episodes given a generous tolerance of 250 km in space and allowance to be early by one 3-h forecast period; if tolerance is limited to 50 km and correct 3-h forecast period, only 13% were correct. The ability to correctly forecast initiation was dependent on the scale of the initiating mechanism, with the highest accuracy being for frontal situations. For large squall lines the RUC10 frequently forecast the wrong motion. This is undoubtedly because the motion of the squall line was influenced by the gust front and the model failed to produce a sufficient gust front.

Given the observed importance of gust fronts and their associated convergence on the evolution and motion of the initiation episodes, it is essential for very short period forecasting techniques to anticipate which storms will produce gust fronts and the strength of the cold pools; this is a major research challenge for observational and numerical model scientists. Precipitation microphysics probably plays a key role in determining the timing and characteristics of the downdraft and associated gust front. This suggests that precipitation particle type and drop size distributions derived from polarimetric radar should prove a profitable avenue for research.

As indicated in the introduction, NCAR is developing techniques for the 0–6-h nowcasting of convective storms that merge numerical model output with observational-based heuristic methods. Central to improving these nowcasts is accurate determination of the where and when of convection initiation. The experience with the RUC10 reported here suggests that parameterized
convective precipitation is only useful for the synoptic-scale-triggered convection. The studies with the 12–13 and 15–16 June cases suggest that the explicit prediction of convective precipitation whether by numerical models or heuristic techniques will require the assimilation of high-resolution convergence, shear, and stability parameters. This will require mesonet station spacing as least as dense as in Oklahoma combined with WSR-88D reflectivity and Doppler velocity observations. Also likely required are high-resolution near-surface water vapor measurements and detailed observations of temperature capping inversions. Promise of high-resolution water vapor measurements was demonstrated in IHOP utilizing radar refractivity measurements from S-Pol (Weckwerth et al. 2005). We are planning future studies with the high-resolution IHOP datasets to better understand required data resolution and useful forecast parameters.

Acknowledgments. This research was funded through the NCAR/U.S. Weather Research Program, NCAR/Water Cycle Across Scales Program, and the FAA Aviation Weather Research Program. We are most grateful to John Brown and Steve Weygandt of FSL who were most patient in answering our questions about the RUC10. Two of the formal reviewers (John Brown and Morris Weisman) were exceptionally helpful in advising us on methods for improving the paper; this is particularly the case for section 5a. Mitch Moncrieff painstakingly provided reviews of an early version of the paper. Dick Oye of NCAR developed the software that produced the mosaic of the radars. Niles Oien of NCAR developed the software to identify the time and location of each cell initiation. Frank Hage of NCAR instituted a number of modifications to the display system specifically for IHOP. Kay Levesque and Dan Megenhardt of NCAR developed the format conversion codes that allowed display of the many different types of surface stations. Sue Dettling of NCAR coded the surface-based CAPE and CIN programs. Eric Nelson of NCAR conducted quality control of the surface station and sounding data for the surface convergence and stability fields. Carol Makowski of NCAR assisted in figure generation.

**APPENDIX**

**Storm Initiation Episode Statistics**

<table>
<thead>
<tr>
<th>Initiation episodes</th>
<th>Time (UTC)</th>
<th>Initiation trigger</th>
<th>Organization</th>
<th>Orientation (°)</th>
<th>Size (km)</th>
<th>Evolution Dir/offset (°/km)</th>
<th>Organization</th>
<th>RUC10 3-h forecast</th>
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</thead>
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<td>5–11–1</td>
<td>2030–2340</td>
<td>Cold front</td>
<td>Line broken</td>
<td>45</td>
<td>38</td>
<td>SQ500</td>
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<td>100</td>
<td>200</td>
<td>SQ130</td>
<td>N</td>
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<td>0</td>
<td>400</td>
<td>M130</td>
<td>N</td>
<td></td>
</tr>
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<td>1900–2200</td>
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<td>60</td>
<td>30</td>
<td>SQ130</td>
<td>300</td>
<td>70/50 E–W line C50</td>
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<td>Bore</td>
<td>Line solid</td>
<td>100</td>
<td>180</td>
<td>SQ280</td>
<td>200</td>
<td>0/50 Cluster C50</td>
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<td>Episode</td>
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<td>Organization</td>
<td>Size (km)</td>
<td>Evolution</td>
<td>Size (km)</td>
<td>Dir/offset</td>
<td>Orientation</td>
</tr>
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<td>5–16–2</td>
<td>2100–2200</td>
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<td>Line sparse</td>
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<td>SQ330 + GF</td>
<td>350 × 210</td>
<td>270/100</td>
<td>Organized</td>
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<td>Two clumps in a line</td>
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<td>SQ220</td>
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<td>E–W broken line</td>
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<td>480 × 225</td>
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<td>NE–SW cluster</td>
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<td>0530–0500</td>
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<td>Area solid</td>
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<td>SQ330 + GF</td>
<td>275 × 210</td>
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<td>C250</td>
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<td>200 × 270/60</td>
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<td>C250L</td>
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<td>30 × 250</td>
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<td>N–S line</td>
<td>C250</td>
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<td>Time (UTC)</td>
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<td>Size (km)</td>
<td>Evolution</td>
<td>RUC10 3-h forecast</td>
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<td>Initiation trigger</td>
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<td>Dir/offset (°/km)</td>
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<td>M450+</td>
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<td>Organization</td>
<td>Oriantation (°)</td>
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<td>125 × 75</td>
<td>330/100 Cluster</td>
</tr>
<tr>
<td>6–18–2</td>
<td>0900–0920</td>
<td>Elevated</td>
<td>Line solid</td>
<td>165</td>
<td>150 × 30</td>
<td>L60</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6–19–1</td>
<td>2050–2120</td>
<td>Cold front</td>
<td>Line solid</td>
<td>45</td>
<td>110 × 30</td>
<td>SQ200</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6–19–2&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2130–2210</td>
<td>Dryline</td>
<td>Line solid</td>
<td>60</td>
<td>100 × 20</td>
<td>SQ80</td>
<td>175 × 20</td>
<td>None</td>
</tr>
<tr>
<td>6–20–1</td>
<td>0910–1010</td>
<td>Elevated</td>
<td>Line solid</td>
<td>30</td>
<td>170 × 20</td>
<td>L170</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6–21–1</td>
<td>1920–2040</td>
<td>GF and unknown</td>
<td>Multicell</td>
<td>150</td>
<td>120 × 40</td>
<td>M130</td>
<td>250 × 50</td>
<td>None</td>
</tr>
<tr>
<td>6–21–2</td>
<td>2000–2040</td>
<td>Unknown boundary</td>
<td>Line broken</td>
<td>00</td>
<td>270 × 30</td>
<td>L260</td>
<td>180 × 30</td>
<td>None</td>
</tr>
</tbody>
</table>
Elevated Line solid/
broken

方向/偏移

GF, bore?

GF, bore?

GF, bore?

Elevated Line
broken

GF, bore?

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GF, bore?

Elevated
broken

GF, bore?

GF, bore?

Elevated
broken

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