EVALUATION OF A FORECAST STRATEGY FOR NOCTURNAL THUNDERSTORMS THAT PRODUCE HEAVY RAIN

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Abstract

Previously published studies have identified the low-level jet and a frontogenetic boundary as two lower-tropospheric features whose interaction frequently precedes the occurrence of strong nocturnal thunderstorms in the Midwest. Properly anticipating the development of these features can serve as one strategy for predicting heavy rain. However, the seminal study used late afternoon and early evening observations to identify these precursors, limiting the lead time of a forecast to a few hours. The present study evaluated the effectiveness of using Eta model output valid for the established observation time, but available earlier, to prognose the presence of established precursors and to increase the lead time of forecasts for nocturnal heavy rains. The forecast strategy identified 36 cases during the summer of 1998 that fit the conceptual model, and had a success rate of 81% in anticipating nocturnal heavy rains, here defined as radar-estimated rainfall of 2 inches or more over at least 1000 km^2. The results should smoothly transfer to operational forecasters in the National Weather Service since the study's diagnostic method uses fields that are readily available to forecast offices.

1. Introduction

Despite the general public's perception that thunderstorms typically occur during the afternoon, climatological studies, such as that of Wallace (1975), have established that summer thunderstorms and heavy summer precipitation in the Midwest are actually most common near midnight. Many nocturnal thunderstorms produce heavy rain that can lead to flash flooding. Deaths due to flash flooding have been increasing in the United States and flooding has become the number one weather-related killer. The 30-year average (1968-1997) for flash flood/flood fatalities was 140, as compared to 81 fatalities for lightning, 69 for tornadoes, and 24 for hurricanes (National Weather Service 1997). In the case of nocturnal thunderstorms, it is especially important that outlooks or forecasts be issued with appropriate lead times since the ability to disseminate an updated forecast is greatly diminished after late-night, local television news shows end.

The work presented here evaluated a method of increasing the lead time of forecasts for nocturnal thunderstorms that produce heavy rain. The forecast strategy is that of Augustine and Caracena (1994), hereafter A&C, who identified the low-level jet (LLJ) and a frontogenetic boundary as two lower-tropospheric features whose interaction frequently precedes the occurrence of strong nocturnal thunderstorms in the Midwest. The original study used late afternoon and early evening observations to identify these precursors, limiting the lead time of a forecast to a few hours. This work sought to independently verify that numerical weather prediction model output, rather than observations, could be used to identify the established precursors, a method briefly mentioned in the original work and one that has the potential to increase the useful lead time of a forecast.

2. Background

The importance of forecasting heavy rainfall that can lead to flash flooding was, tragically, highlighted by several extreme events in the 1970s, among them the Rapid City flood of 9 June 1972, and the Big Thompson Canyon flood of 31 July 1976. Maddox et al. (1979) identified three basic meteorological patterns associated with flash flooding in the central and eastern United States. A fourth category was developed for events in the western states. Many of the events had common features, including the tendency to occur at night.

Glass et al. (1995) examined heavy rainfall events in the middle Mississippi Valley as an expansion of Maddox et al. (1979). They again noted the nocturnal nature of most such events and the importance of the LLJ to favorable lower-tropospheric forcing, indicating that it may be the most important mechanism for forcing organized heavy rain events.

Junker et al. (1999) examined 85 heavy rain events in a 9-state region and developed a corresponding synoptic climatology. Favorable lower-tropospheric flow, with its attendant moisture and temperature advection, and the presence of a surface boundary were found to be very important to the scale and intensity of the rainfall.

A&C used 104 large and small nocturnal Mesoscale Convective Systems (MCS) from the summers of 1990-1992 to construct composite analyses of precursor lower-tropospheric conditions. The results of their work show that large, long-lived, nocturnal MCSs are likely to mature downwind of an observed late afternoon surface geostrophic wind maximum if that region is frontogenetic at 850 mb.

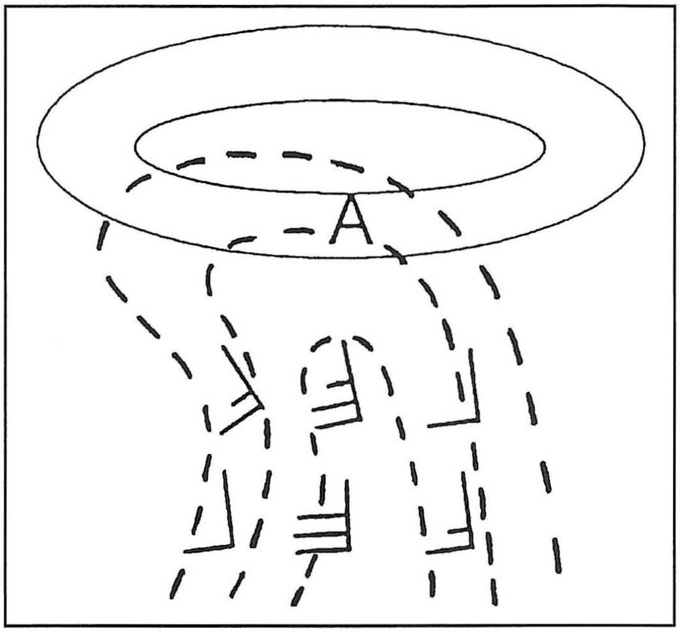

Fig. 1. Composite presursors to probable nocturnal MCS location (A) at maturity: the 850-mb frontogenetic region (solid), surface geostrophic isotachs (dashed) and wind barbs in standard notation, after Augustine and Caracena (1994).

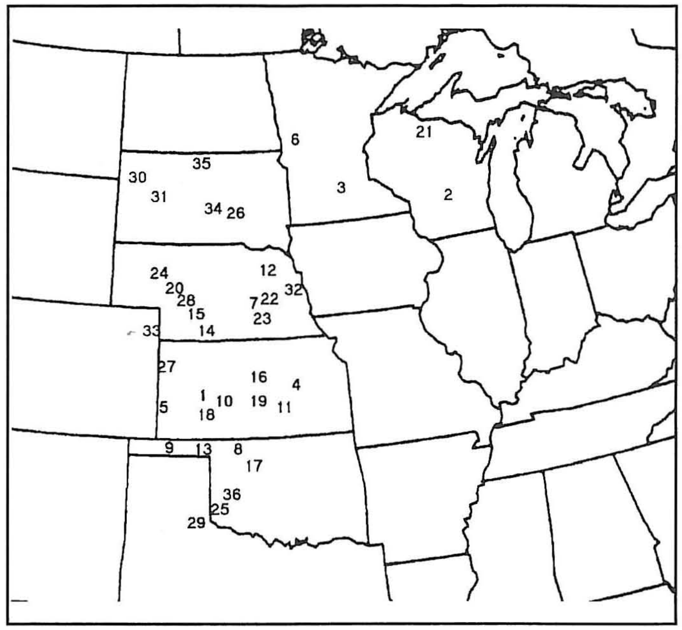

Fig. 2. Forecast locations of point A (see Fig. 1) for each positive prognosis. Numbers correspond to case identifiers in Tables 1 and 3.

Figure 1, adapted from A&C, depicts the composite lower-tropospheric conditions that isolate the probable location of a large nocturnal MCS at maturity, which is identified by point A in the figure. A&C used the vector form of the frontogenesis function (Keyser et al. 1988) to identify frontogenetic regions at 850 mb. Frontogenetic regions are accompanied by a thermally direct circulation (e.g., Bluestein 1993). The 850-mb level was chosen since it is in the upper portion of the daytime boundary layer where the geostrophic assumption can be used. Geostrophic winds were computed for the 500-m level (above mean sea level, or MSL) using pressure fields based on extrapolated 700-mb temperatures. These were then considered to be "surface" winds. A&C note that the enhanced pressure gradient forcing for southerly flow that develops through boundary layer processes during daylight hours in the central United States remains in the neutral layer above the nocturnal inversion. This forcing plays an important role in the development of the nocturnal LLJ. Where the forcing is greatest, and thus where the LLJ will form, is marked by the late afternoon low-level geostrophic wind maximum, which is responding to the same pressure gradient. Convergence, and upward motion, is enhanced where the LLJ intersects the upward motion of the frontogenetic region's thermally direct circulation. Heavy rains may result from late afternoon thunderstorms that develop in or move through the region of intersection.

The so-called Sangster signal was also noted in their study. Sangster (1979) showed that a sharp westward turning of the streamlines north of an afternoon surface geostrophic wind maximum is closely associated with subsequent nocturnal heavy rains. A&C found the Sangster signal in the composite wind patterns associated with large MCSs, but it was less pronounced for small MCSs.

3. Methodology

A&C used late afternoon surface and early evening upper-air observations to develop their forecast strategy. In the present work, 12-h forecast fields from the 1200 UTC run of the 32-km Eta model were analyzed using PCGRIDDS. In A&C, the frontogenesis vector at 850 mb and its divergence were used to locate frontogenesis and probable vertical motion. Here, quasigeostrophic frontogenesis was evaluated at 850 mb. Ascent is inferred on the warm side of frontogenetic regions (Sawyer 1956). In place of the "surface" geostrophic winds used by A&C, this study focused on the maxima in the 10-m, total-wind vectors with a southerly component. The reason for this substitution was the easy availability of these fields in the Eta files. The winds at 10 m (i.e., anemometer level) cannot be expected to be identical to the geostrophic winds at 500 m MSL. The assumption used here is that the pressure gradient operating at the 10-m level would be very similar to that at 500 m MSL, and wind speed maxima at 500 m would likely be reflected in the 10-m winds. Static stability variations and momentum mixing parameterizations in the model could alter both the direction and speed of the 10-m winds from geostrophic, resulting in a shift in the wind maximum from its position at 500 m MSL. However, it is assumed that such shifting is small.

The intersection of a wind maximum with the warm side of a frontogenetic region was noted as a positive prognosis and the region was monitored for subsequent nocturnal heavy rains. The presence or absence of the Sangster signal in the 10-m winds was also noted.

The four possible outcomes for each day in the study period were: a) positive prognosis and heavy rain observed, b) positive prognosis and no heavy rain observed, c) negative prognosis and heavy rain observed, and d) negative prognosis and no heavy rain observed. Of these, the two that were evaluated were cases where heavy precipitation was predicted and subsequently was either observed or not observed. This work acknowledges that heavy rains can be produced by processes other than that described by A&C. The focus of this study was on the application of one particular conceptual model. Therefore, cases where no heavy rain was predicted but did subsequently occur were not given special attention. Also, no attempt was made to determine whether the rains resulted from a large or a small MCS, though the conceptual model was developed from observations of large MCS events.

The forecast strategy was evaluated on 59 (80% of possible) days during the period from 20 May to 1 August 1998. Problems with missing or incomplete data kept the sample from spanning the entire period. The geographic focus of the study was identical to that of A&C (i.e., the region east of the Rocky Mountains, west of the Appalachians, north of the Gulf of Mexico, and south of Canada) and is depicted in Fig. 2. Numbers in the figure correspond to case identifiers in Tables 1 and 3 and are positioned at the forecast location of point A (see Fig. 1) for each positive prognosis.

Several working definitions were necessary for evaluation of the strategy's performance. While "nocturnal" is best defined as the period from dusk to dawn, the operational definition used was the period from 0000 to 1200 UTC. Rainfall that principally occurred during this period was considered nocturnal.

A singular definition of "heavy" rain is difficult to construct. Kodama and Barnes (1997) defined it as more than 10 cm (4 inches) in 24 hours at one or more rain gauge sites in their study over the southeast flank of Mauna Loa volcano in Hawaii. A study by Konrad (1997) used an amount of 5 cm (2 inches) or more at one or more stations within a 6-hour period where the rain-free breaks did not exceed 2 hours. Junker et al. (1999) defined several heavy rain categories based on the areal coverage of 3-inch rainfall amounts. Harnack et al. (1999) used 2-inch rainfall over 10,000 km^2 in a 1- or 2-day period with less than 6 continuous rain-free hours as their definition.

In this study, 24-hour rainfall of 2 inches or more over an area of at least 1000 km^2 was considered "heavy." This area is slightly more than two-thirds the size of an average county in Iowa (1470 km^2). Radar-estimated precipitation data (obtained from a commercial vendor) for the 24-hour period ending at 1200 UTC from the WSR-88Ds were used to identify regions with rainfall in excess of 2 inches. Basic image analysis techniques were used to estimate the areal coverage from the digital files. Subjective judgment was used to decide whether the rains occurred close enough to the expected location for the prognosis to be considered potentially successful. GOES-8 infrared imagery and WSR-88D reflectivity were then used to infer if the majority of the heavy rain occurred between 0000 and 1200 UTC, in which case the event was considered nocturnal. It should be noted that while some of the estimated rainfall amounts did include precipitation that occurred prior to 0000 UTC, for all heavy rain cases included in this study the evidence suggested that the bulk of the rain fell during the nocturnal period.

As the results of the study were examined, it became very apparent that rainfall of 2 inches or more over an area of 10,000 km^2 was a subset of the heavy rain events. Positive prognoses that resulted in 2-inch rainfall covering between 1000 and 10,000 km^2 are hereafter referred to as HEAVY cases, while those that covered 10,000 km^2 or more are referred to as VERY HEAVY cases. Positive prognoses that did not result in rainfall satisfying the HEAVY criteria are identified as No Heavy Rain cases.

4. Results

The forecast strategy indicated positive prognoses on 36 of the 59 days (61%) in the sample. Subsequent heavy nocturnal rains were observed with 29 of the 36 cases, representing a success rate of 81%, or a false alarm rate of 19%. Table 1 presents a summary of the 29 successful cases ranked by the areal coverage (km^2) of the 24-hour, radar-estimated precipitation totaling at least 2 inches. The table also lists the date at 0000 UTC for each case, the maximum contour value of the forecast quasi-geostrophic frontogenesis ("Max F" in the table, 10^{-10} K m^{-1} s^{-1}), the forecast maximum wind speed value ("Max Sp." in the table, m s^{-1}), a subjective assessment of the Sangster signal's presence (Y or N), and areal coverage for particular rainfall ranges, or bins.

Cases 1-16 in Table 1 comprise the VERY HEAVY category of events while the HEAVY category includes cases 17-29. Case 16 is included in the VERY HEAVY subset since, overall, it is more similar to cases 1-15 than to 17-29, even though it falls short of the areal coverage criterion for this category.

Table 2 is a summary of Table 1, listing the average areal coverage (km^2) for each rainfall bin and the number of cases that had rainfall of at least that amount. The results are categorized according to the HEAVY and VERY HEAVY criteria and the averages over all successful prognoses are also noted. The averages for each category were calculated using all cases in that category, including those that did not produce rainfall in a particular bin.

Nearly all (93%) of the successful prognoses produced rainfall of at least 3 inches and close to two-thirds (62%) had amounts of 5 inches or more. All of the VERY HEAVY cases produced at least 4 inches of rainfall and over two-thirds (69%) resulted in rainfall of at least 6 inches. All but one of the VERY HEAVY cases meet the Junker et al. (1999) definition of extreme rainfall (3 inches or more over 3,709 km^2). The average areal coverage of the VERY HEAVY cases exceeds that of the HEAVY cases for all rainfall bins in Table 2.

The successful prognosis valid at 0000 UTC 24 June 1998 (Case 7 in Table 1) is presented in Fig. 3. Note that the resolution displayed in the figure is more coarse than the 32-km resolution of the Eta model. The 3 x 10^{-10} K m^{-1} s^{-1} quasigeostrophic frontogenesis contour is dashed in the figure, and the solid lines are isotachs (m s^{-1}) at the 10-m level. Also plotted are selected 10-m wind barbs associated with the speed maximum and the frontogenetic region. The northern terminus of the speed maxi-

Table 1. Successful prognoses ranked by areal coverage (km²) of the 24-hour radar-estimated 2-3 inch rainfall.

Case	Date (00Z)	Max F	Max Sp.	Sang.	2-3 inch	3-4 inch	4-5 inch	5-6 inch	6-8 inch	> 8 inch
1	26 Jul	12	6	Y	46,606	19,009	8,334	2,816	618	0
2	31 May	8	7	Y	39,030	16,553	6,189	1,568	0	0
3	27 Jun	5	8	Y	23,301	8,512	3,091	900	31	0
4	30 Jun	8	7	N	22,261	14,119	7,862	3,202	331	0
5	24 Jul	10	5	Y	21,820	6,728	1,969	712	275	7
6	15 Jul	4	8	N	19,223	9,063	4,205	2,090	692	242
7	24 Jun	6	10	Y	17,917	6,119	862	9	0	0
8	30 Jul	6	6	Y	15,816	5,437	1,769	1,005	462	98
9	11 Jul	9	5	Y	13,689	2,185	315	7	0	0
10	23 Jul	5	4	Y	12,984	5,879	1,369	0	0	0
11	10 Jul	3	4	Y	12,858	4,400	1,733	525	44	0
12	29 May	2	6	Y	12,092	4,425	1,020	419	56	0
13	27 Jul	8	4	Y	11,248	4,701	1,062	0	0	0
14	22 Jul	8	6	Y	10,639	4,225	1,963	799	108	0
15	18 Jun	20	10	Y	10,074	4,738	2,984	1,225	252	0
16	29 Jun	5	7	Y	9,321	4,824	2,923	1,581	491	0
17	29 Jul	3	4	Y	9,153	339	0	0	0	0
18	25 Jul	10	6	Y	7,197	752	0	0	0	0
19	23 Jun	4	7	Y	6,461	1,810	535	233	97	0
20	20 May	6	5	Y	4,397	1,327	138	36	0	0
21	2 Jun	12	10	N	3,821	0	0	0	0	0
22	7 Jul	3	5	Y	3,431	464	0	0	0	0
23	28 Jun	8	9	N	3,266	1,409	609	102	0	0
24	17 Jun	12	7	Y	3,041	237	0	0	0	0
25	1 Aug	4	4	Y	2,107	726	290	72	0	0
26	19 Jul	7	6	N	1,917	10	0	0	0	0
27	10 Jun	8	8	Y	1,421	354	3	0	0	0
28	8 Jun	24	12	Y	1,195	0	0	0	0	0
29	28 Jul	4	4	Y	1,106	4	0	0	0	0

Table 2. Average areal coverage (km²) for radar-estimated rainfall bins and number of cases with rainfall within each bin.

	2 - 3 in.	3 - 4 in.	4 - 5 in.	5 - 6 in.	6 - 8 in.	> 8 in.
VERY HEAVY (16 cases)	18680	7557	2978	1054	210	22
No. of Cases	16 (100%)	16 (100%)	16 (100%)	14 (88%)	11 (69%)	3 (19%)
HEAVY (13 cases)	3732	572	121	34	7	0
No. of Cases	13 (100%)	11 (85%)	5 (38%)	4 (31%)	1 (8%)	0
All (29 cases)	11979	4426	1697	597	119	12
No. of Cases	29 (100%)	27 (93%)	21 (72%)	18 (62%)	12 (41%)	3 (10%)

mum intersects the warm side of a frontogenetic area in southeast Nebraska and southwest Iowa, and the wind barbs display the Sangster signal. These indicators fit A&C's conceptual model well and suggest the potential for nocturnal MCS activity in this area. The shaded region in Fig. 3 denotes the radar-estimated precipitation of at least 2 inches during the 24 hours ending 1200 UTC 24 June 1998. The inset in the figure provides greater detail of the rainfall amounts.

Case 13 (see Table 1) is presented in Fig. 4. All plotted fields are as in Fig. 3. The conceptual model suggests the potential for heavy nocturnal rains across southern Kansas and northern Oklahoma. The heaviest precipitation occurred just to the west of the maximum prognosed quasi-geostrophic frontogenesis. The presence of a surface boundary is suggested by the wind barbs at the 10-m level. A defined zone of confluence was often evident in the frontogenetic regions of the successful cases, consistent with A&C's composite. However, as in their study, the orientations of the boundary varied widely from case to case.

Table 3 presents the results of the 7 unsuccessful prognoses. None of these cases produced significant, organized rainfall of 2 inches or more within the expected area. The prognosis for Case 32 valid at 0000 UTC 25 June 1998 is depicted in Fig. 5. The northern portion of the wind speed maximum over Kansas intersects the warm side of a frontogenetic region in eastern Nebraska and western Iowa, suggesting the potential for heavy noc-

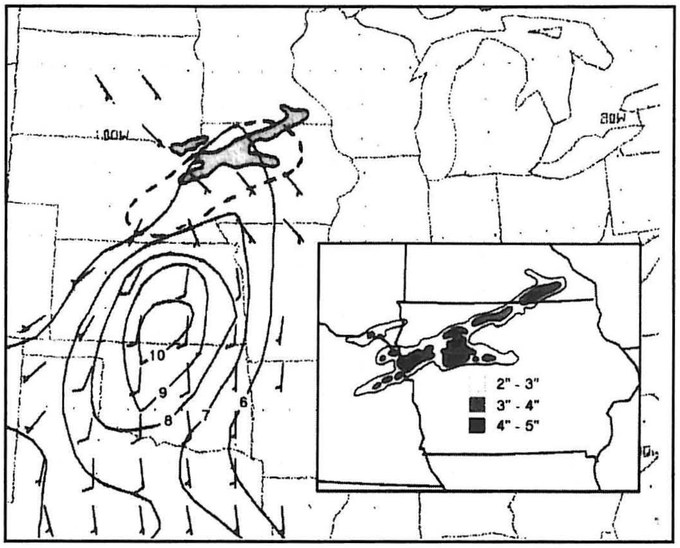

Fig. 3. Quasigeostrophic frontogenesis at 850-mb level (contour value of 3 x 10^{-10} K m^{-1} s^{-1} is dashed), isotachs at the 10-m level (m s^{-1}, solid) and wind barbs at the 10-m level from the 12-h Eta model forecast valid at 0000 UTC 24 June 1998 (Case 7). Shaded portion of figure depicts area where radar estimated precipitation during the 24 hours ending at 1200 UTC 24 June 1998 was at least 2 inches. Inset shows greater detail of estimated rainfall.

turnal rains in this area. Nocturnal thunderstorms did occur within the expected region, but produced amounts that were generally under 1 inch. The heaviest nocturnal rain fell across the eastern Dakotas and from southeastern Minnesota through central Wisconsin, as depicted by the shading in the figure. Amounts over 5 inches were estimated in Wisconsin and over 6 inches in North Dakota. While the parent thunderstorms were nocturnal, the rains fell well outside of the prognosed location and the case was included in the No Heavy Rain category.

Heavy nocturnal rains also occurred with Case 36 (not shown), but to the west of the expected location. For all of the remaining unsuccessful prognoses, nocturnal rains occurred within the expected locations but failed to meet the HEAVY criteria.

Eta model 00-h fields valid at the time of the prognoses were examined for 33 of the 36 cases. These fields were missing for one case in each of the categories HEAVY, VERY HEAVY, and No Heavy Rain. Table 4 presents a summary of the results. The averages and ratios from the 00-h data appear in parentheses. The results indicate that the Eta model, on average, under-forecast the maximum intensity of the quasigeostrophic frontogenesis for the No Heavy Rain and the VERY HEAVY cases, but over-forecast the intensity for the HEAVY cases. Perhaps more notably, the model consistently under-forecast the 10-m wind speeds, especially for the VERY HEAVY cases. Interestingly, both the average forecast frontogenesis and wind speed were greater for the HEAVY than for the VERY HEAVY cases, while the averages from the 00-h fields indicate just the opposite.

Table 4 suggests that the best discriminator between the HEAVY, the VERY HEAVY, and the No Heavy Rain categories may be the Sangster signal. The prognoses did quite well in anticipating this wind pattern when verified

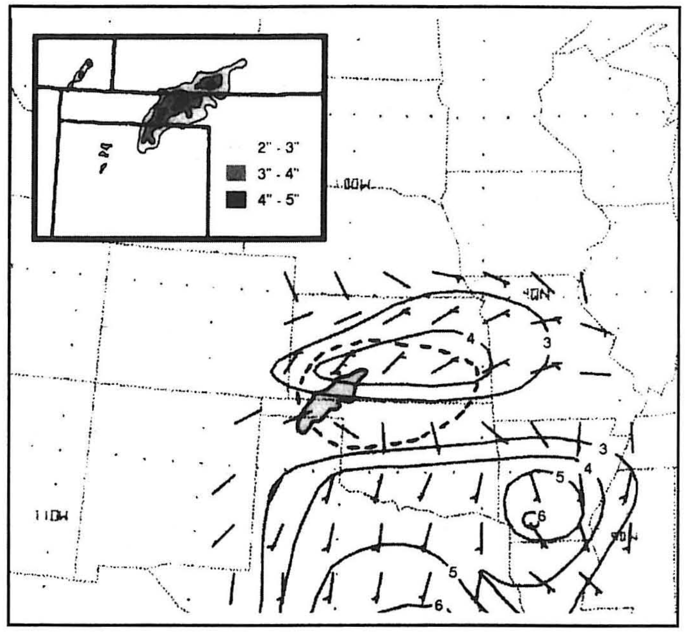

Fig. 4. Details shown as in Fig. 3, with forecast valid at 0000 UTC 27 July 1998 (Case 13). Estimated rainfall is for the 24-hour period ending 1200 UTC 27 July 1998.

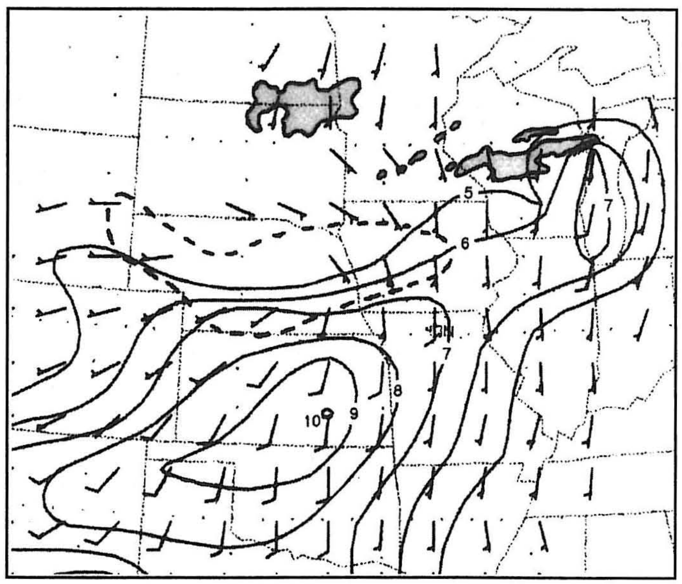

Fig. 5. Details shown as in Fig. 3, with forecast valid at 0000 UTC 25 June 1998 (Case 32). Estimated rainfall is for the 24-hour period ending 1200 UTC 25 June 1998.

Table 3. Unsuccessful prognoses (No Heavy Rain cases).

Case	Date (00Z)	Max F	Max Sp.	Sang.	2-3 inch
30	21 May	6	5	Y	0
31	30 May	5	6	N	0
32	25 Jun	6	10	Y	0
33	1 Jul	6	6	Y	0
34	17 Jul	3	5	Y	0
35	20 Jul	5	5	N	0
36	31 Jul	8	6	N	0

Table 4. Average maximum forecast quasigeostrophic frontogenesis and wind speed, and Sangster Signal Ratio for the study. The 00-h Eta model values valid at the forecast time appear in parentheses.

	Avg. Max. QG-Front. (10^{-10} Km^{-1} s^{-1})		Avg. Max. Wind Speed (m s^{-1})		Sangster Signal Ratio (Yes : No)	
VERY HEAVY (16 cases)	7.44	(8.82)	6.44	(9.47)	14:2	(13:2)
HEAVY (13 cases)	8.08	(7.33)	6.69	(8.92)	10:3	(8:4)
No Heavy Rain (7 cases)	5.57	(7.00)	6.14	(7.83)	4:3	(3:3)

against the 00-h wind fields. Differences in the table between the total number of forecast and 00-h cases in the Sangster signal ratios are due to the missing 00-h fields noted above. The No Heavy Rain cases were as likely to have the Sangster signal as not have it, while the VERY HEAVY cases overwhelmingly displayed a westward turning of the winds at the northern terminus of the speed maximum.

The forecast (and 00-h diagnosed, but not shown) frontogenesis and wind speed displayed a wide range of values in both the HEAVY and VERY HEAVY categories (see Table 1). This, in addition to the small differences between the averages presented in Table 4, makes it difficult to specify values of 850-mb quasigeostrophic frontogenesis and 10-m wind speed that a forecaster could use operationally to determine whether HEAVY or VERY HEAVY rains are indicated by this strategy. Nonetheless, the method's high success rate warrants its inclusion in a forecaster's decision making process.

5. Conclusions

The forecast strategy of A&C was highly successful in anticipating nocturnal heavy rains when evaluated with 12-h forecast fields from the 32-km Eta model. In this study, regions of intersection between wind maxima at 10 m and the warm side of quasigeostrophic frontogenetic regions at 850 mb were considered positive prognoses and were monitored for subsequent nocturnal heavy rains.

Of the 36 positive prognoses from the summer of 1998, 29 produced heavy nocturnal radar-estimated rainfall, a success rate of 81%. Sixteen of the 29 successful prognoses produced rainfall in excess of 2 inches over an area greater than about 10,000 km^2, with maximum estimated amounts in excess of 6 inches for more than two-thirds of these cases.

On average, the prognoses did not provide a clear distinction between cases that went on to produce the heaviest versus simply heavy rainfall. In fact, the average intensity of frontogenesis and wind speed in the Eta model forecasts was weaker for the cases that resulted in the heaviest rainfall. Diagnoses based on 00-h Eta fields indicated just the opposite to be true. Most notably, the Eta model consistently under-forecast the strength of the 10-m winds.

The presence of the Sangster signal in the low-level winds was most strongly associated with the prognoses that went on to produce the heaviest rainfall. The signal was absent as often as it was present for prognoses that did not result in heavy rain. This parameter should be closely monitored in regions where the low-level wind maximum intersects frontogenetic boundaries.

Despite the high success rate of the method, it should not be used in isolation from other diagnostics. Rather, it should be an integral part of a thorough examination of basic precursors to heavy rains, such as that suggested by Doswell et al. 1996.

The strategy of A&C has shown great potential to increase the useful lead time of forecasts of nocturnal thunderstorms that produce heavy rain. Use of this technique will help forecasters isolate spatially where flash flooding is more likely so that subsequent monitoring of developing thunderstorms can be more narrowly focused. This, in turn, could heighten public awareness of the potential for adverse conditions.

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