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ON THE CHARACTERISTICS OF QUASI-STATIONARY STORM-SCALE CONVECTIVE EVENTS OVER WESTERN SOUTH DAKOTA

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1. INTRODUCTION

Mesoscale convective systems (MCS's) may produce destructive flash floods when their structure is such that storms repeatedly move over the same area, or when the convective system exhibits little or no movement. Chappell (1986) found that quasi-stationary MCS's were most common within four atmospheric regimes: 1) synoptic forcing; 2) frontal forcing; 3) mesohigh forcing; and 4) joint frontal and mesohigh forcing. These scenarios assume that either a strong upper-level trough or some frontal boundary (either in the form of a synoptic scale front, or a pre-existing outflow from antecedent convection) helps focus or initiate the convective activity in a particular location. While these conceptual models address the conditions associated with quasi-stationary MCS's, the stationarity of individual (not necessarily isolated) thunderstorms frequently can not be explained within this synoptic or meso-α scale framework. These smaller, say, Meso-β (Fujita 1981), Meso-γ (Orlanski 1975), or storm-scale quasi-stationary convective events are not uncommon, and pose a challenging forecast problem because their stationarity will often be governed by elusive mesoscale (or storm scale) features difficult to identify in real time. In fact, the motion of storm-scale convective events may appear to act *independently* of the observed synoptic-scale atmospheric environment.

The purpose of this research is to investigate the significance of quasi-stationary storm-scale events, and assess the mesoscale conditions which promote their formation and maintenance. In this way, aspects of flash-flood events will be examined on a smaller scale than that in the work of Maddox *et al.* (1979) and Chappell (1986) (among others). Herein, four quasi-stationary storm-scale convective events which occurred over western South Dakota will be analyzed in order to address these issues.

2. ON THE NATURE OF QUASI-STATIONARY, STORM-SCALE CONVECTIVE EVENTS

The most significant flash floods events in western South Dakota during the 1996 and 1997 convective seasons were from quasi-stationary thunderstorms which impacted relatively small areas. Review of the WSR-88D Storm Total Precipitation products from these flood events revealed that the regions of heavy rainfall were indeed very limited, not covering areas greater than 500 km^2 (or 30 km in maximum horizontal extent). Frequently, the size was much smaller. Review of the synoptic conditions illustrated that these events often occurred outside the typical scenarios associated with flash floods in Chappell (1986). Though a formal review has not been performed, cursory observations of several flash-flood events nationwide revealed that many had very limited areas of heavy rainfall from similar quasi-stationary storm-scale events including the storms of 27 May 1984 in Tulsa, OK; 1 August 1985 in Cheyenne, WY; 27 June 1995 in Madison County, VA; and 28 August 1997 in Fort Collins, CO.

It is likely that many quasi-stationary storm-scale convective events are the result of the interaction between outflow-dominated (multicell) convection and the ambient shear environment. If the movement of a particular storm is assumed to be the sum of the advection of cell elements (estimated by the mean cloud-layer wind) and the propagation vector (typically down the low-level shear vector), then stationarity is simply one solution where these two vectors cancel each other out (Merritt and Fritsch 1984; Corfidi *et al.* 1996). Such storms may be isolated entities, or perhaps a stationary element within a larger group of mobile convection. Pre-existing fronts or boundaries are not required for the stationarity of these smaller-scale events (Chappell and Rogers (1988) and Akaeda *et al.* (1995) are two such examples), though they often occur near such a feature. When storms rotate (become supercells), or significant topography is present, the movement of the storms may be further complicated.

The scale of precipitation event described herein (referred to as *storm-scale*) has been deliberately restricted to those events which have a significant hydrological impact, through most of their lifetime, over an area generally less than 500 km^2, or with a maximum horizontal dimension of no greater than 30 km. This definition thus excludes most convective systems which exhibit significant motion (such as typical multicell and supercell storms which usually do not pose a flash-flood threat), and many larger, organized convective events commonly referred to as MCS's (Houze 1993).

3. FOUR EXAMPLES OF QUASI-STATIONARY STORM-SCALE CONVECTIVE EVENTS

Several quasi-stationary convective events have occurred over the past two years over western South Dakota which serve as lucid examples of the different processes which can lead to the quasi-stationarity of storm-scale convective events. The four events investigated here all caused significant flash flooding, and all were observed by the 88D radar near Rapid City, SD.

A. The 11 June 1997 multicell flash flood event

From 07Z - 13Z on 11 June 1997, a small group of thunderstorms persisted in a confined area over the plains of northwest South Dakota. More than 15 cm of rain fell in southern Perkins County which resulted in significant flooding and many road closures. An

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interesting aspect of this event was the fact that the storms were low-topped (est. 7.5-9.0 km (25-30K ft) MSL), had reflectivities generally not exceeding 50 dBZ, and were initiated and remained stationary without any obvious focusing mechanism. As a result of the shallow nature of the convection and the fact that it occurred at a significant distance from the radar, estimates of the storm total precipitation by the radar were too low (Fig. 1a).

These thunderstorms developed within an environment of minimal instability (CAPE=100-300 J/kg) and moderate shear (0-6km $\Delta V = 15\ ms^{-1}$). A closed upper-level low pressure circulation was directly over the area, with a low-level trough and surface low pressure center to the west. This rather anomalous arrangement of atmospheric features led to moderate (5-10 ms^{-1}) surface flow from the southeast, with very light mid-to upper-level flow out of the north-northwest over the storm area. The mean cloud-level wind was very light from the south, with the low-level wind shear vector from the north.

There were no frontal boundaries or pre-existing thunderstorm outflows near the storm, and no thermal or moisture gradients of any significance were noted in the area. The lack of any such features suggests that the reason for the quasi-stationarity of this system was largely controlled by the favorable environmental shear profile. Note, that the presence of the closed upper-level circulation made the horizontal extent of shear profiles conducive to stationarity quite limited. The observations suggest that new cells were being continually regenerated along the outflow on the southern (downshear) flank of the storm, and very slowly advecting to the north and raining out over the flood area.

B. The 30 May 1996 supercell hail/tornado/flash flood event.

A visually-striking supercell thunderstorm formed south of Rapid City during the evening of 30 May. Copious amounts of large hail, several weak tornadoes, and extremely heavy rain fell from this storm which remained virtually stationary for 90 minutes along the eastern edge of the Black Hills. WSR-88D rainfall estimates of greater than 15 cm (6 inches) were supported by reports in the area (Fig. 1b). This rainfall caused significant flash flooding along Spring Creek, and sent water over the primary highway leading south out of Rapid City (Searles and Bailey 1997).

As in the previous case, the large scale environment for the 30 May storm did not conform to the flash-flood producing storm models as presented by Chappell (1986). Rather, the atmospheric environment was conducive to severe (tornadic), progressively moving thunderstorms; with copious instability (CAPEs of 2000-3000 J/kg), and a significant amount of shear (0-6km ΔV of 19 ms^{-1}). The observed motion of other storms in the area at this time were between 210-230° at ~12 ms^{-1}, in good agreement with the estimated storm motion from the shear profile. The thunderstorm investigated here was one of several severe thunderstorms in the area this day, but was the only storm to exhibit quasi-stationary behavior.

Though the storm was very close to the radar, no boundaries (on any scale) were discerned to which one could attribute its stationarity. Given the environmental shear which would support significant movement, a likely alternative explanation is that some topographic effect was favoring continued re-development of the storm on its southwest flank. The study of Searles and Bailey (1997) indicated that there may have been some storm-scale outflow interaction with the Black Hills which may have promoted stationarity. It should be noted, however, that this case was not primarily forced by any larger scale upslope flow.

C. The 14 June 1996 supercell / cell-merger flash flood event

Late in the afternoon and evening of 14 June 1996, greater than 25 cm of rain fell along Alkali Creek (east of Sturgis, SD) from a nearly stationary multicell/supercell storm, which eventually was overtaken by a convective line which moved in from the west. The KUDX radar estimated 39 cm (15.5 inches) of rain between 22Z and 02Z on 14-15 June (Fig. 1c); damage surveys indicated the radar estimates were likely quite accurate. The flooding which occurred in this area was the worst on record, causing the typically tiny creek to swell and engulf numerous structures.

Environmental conditions for the storm were favorable for the development of severe thunderstorms, with CAPE around 2000 J/kg, 0-6km $\Delta V=17\ ms^{-1}$, and precipitable water ~125% of normal. The shear profile indicated storm movement to the northeast at 5-8 ms^{-1}. Like in the previous two cases, there were no stationary fronts, or any type of persistent mesoscale boundary in the immediate area.

The storm which produced the flash flooding was hypothesized to be the result of multiple convective regeneration over a convergence zone downwind of the Black Hills (Bunkers 1997), similar to that observed in Akaeda *et al.* (1995). Very heavy rainfall fell as the supercell storm continuously re-developed in the same location on the northern flank of the Black Hills, essentially remaining stationary for over three hours. The storm finally moved off to the east when a line of convection moved in from the west and merged with the system, briefly forming a bow echo which rapidly dissipated and moved off to the east.

D. The 1 June 1997 severe hail/flood event

Over 20 cm of rain fell in south-central South Dakota from a quasi-steady severe thunderstorm event which occurred between 23Z and 02Z on the evening of 01-02 June, 1997. In addition to the torrential rainfall, this storm also produced damaging large hail (over 7 cm in diameter) and very strong downburst winds. The 1 June storm was initiated (and persisted) along a stationary frontal boundary. With time, additional thunderstorms were initiated along the front, eventually forming a short-lived MCS. Numerous reports of flooding were received from areas along and to the north of the frontal position where 10-12 cm rainfall totals were also reported. The most severe flooding and heaviest rainfall totals, however, were associated with the quasi-stationary thunderstorm described above which preceded the development of the MCS.

Unlike the other three cases presented in this study, the 1 June 1997 case could be considered a ‘classic’ frontal-type flash flood event (Chappell 1986). There existed a quasi-stationary frontal boundary (with very strong convergence along it), weak environmental shear, and deep atmospheric moisture with up to 3.3 cm

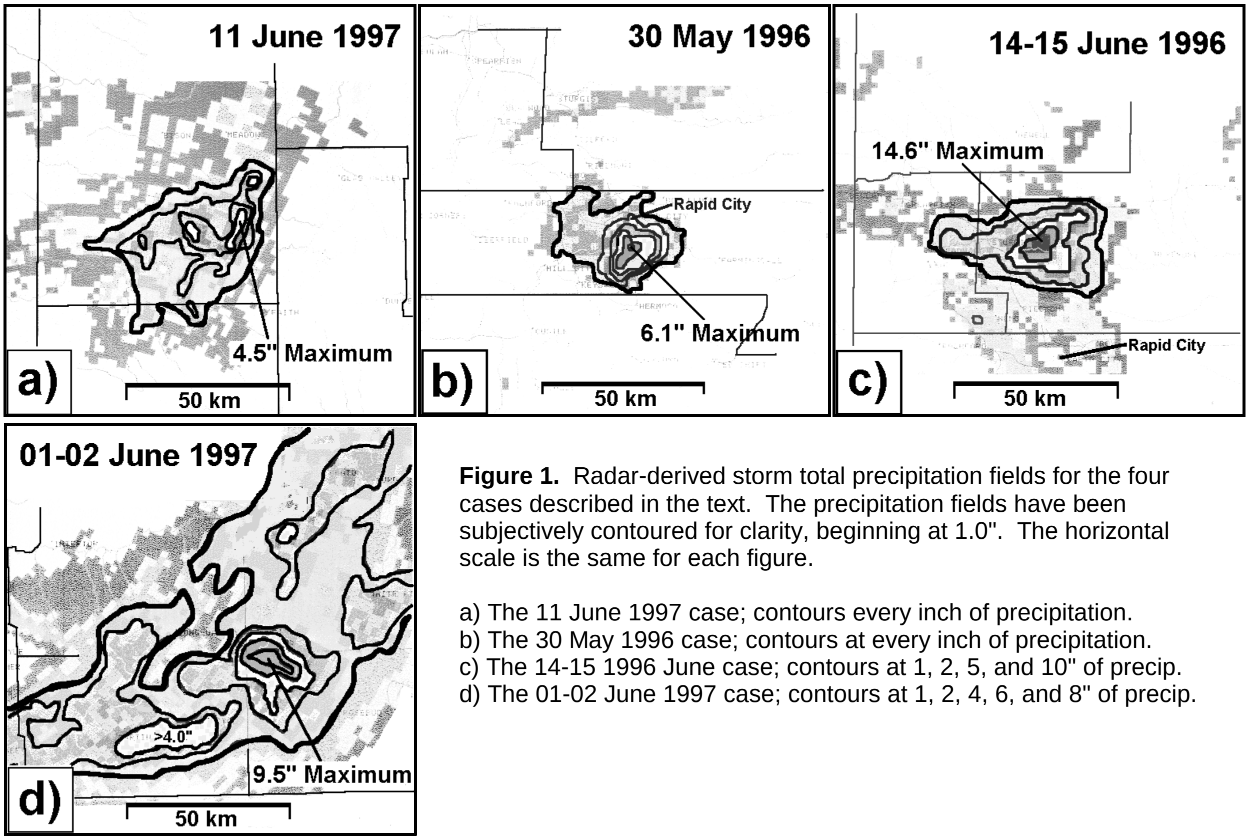

Figure 1. Radar-derived storm total precipitation fields for the four cases described in the text. The precipitation fields have been subjectively contoured for clarity, beginning at 1.0". The horizontal scale is the same for each figure.

a) The 11 June 1997 case; contours every inch of precipitation.
b) The 30 May 1996 case; contours at every inch of precipitation.
c) The 14-15 1996 June case; contours at 1, 2, 5, and 10" of precip.
d) The 01-02 June 1997 case; contours at 1, 2, 4, 6, and 8" of precip.

of precipitable water (204% of normal). Of particular interest, however, was the one storm which remained nearly stationary for almost 90 minutes prior to becoming engulfed by the other storms forming along the boundary. Though it is unclear at this time why this storm was initiated earlier, and persisted longer than the other convective elements along the line, it emphasizes the importance of recognizing and understanding the storm-scale aspects within a larger-scale convective situation. Convection along frontal boundaries is never homogeneous - understanding the reasons for this variability is a great challenge given the resolution of our current observing systems.

4. SUMMARY AND CONCLUSIONS

The nature of four small, but damaging flash flood events have been briefly described. The analyses have shown that storm-scale processes, though not obvious, can have a great influence on storm motion and evolution. It is clear that all convective events (of any scale) will have localized regions of most intense and heavy rainfall. This is the very nature of convection. However, accurate forecasts of flash-flood events require an understanding those conditions which may promote stationarity of convective elements under a wide variety of conditions.

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