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AN OBSERVATIONALLY BASED HYPOTHESIS FOR SIGNIFICANT TORNADOGENESIS IN MOUNTAIN ENVIRONMENTS

by

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1. INTRODUCTION

Low relief characterizes the topographic environments beneath the great majority the convective storm-type associated with most significant tornadoes, the supercell thunderstorm. In the Rocky Mountains and Appalachians of North America, the European Alps and other mid-latitude regions characterized by complex topography, the potential is large for landforms to disrupt low-level flows beneath supercells and perhaps preclude tornadogenesis in instances that might otherwise yield tornadoes over flatter terrain. Although generally not explicitly stated in studies on tornado climatology, rough terrain is therefore viewed as an inhibitor of tornado occurrence in mountain environments.

Research attention and modeling studies on supercells and tornadogenesis accordingly have tended to allocate little attention to supercell-landscape interactions. On rare occasions, however, large, intense (F2-F4) and long-lived tornadoes have been documented to form from supercells propagating over regions characterized by high topographic relief. Two such events in the Northeastern United States are examined in detail in companion presentations at this conference (by Bosart et al. and LaPenta et al.). The present study aims to identify common characteristics of these and other comparable events towards developing a hypothesis explaining the process of significant tornadogenesis within mountain environments.

2. CASES EXAMINED

This study is restricted to events documented in published studies and reports where supercells both form and travel across mountainous terrain and produce tornadoes that attain strong-violent intensity ($\geq$F3). A dramatic example was detailed by Fujita (1989), who analyzed an exceptionally large and intense F4 tornado in forested mountainous terrain in the Teton Wilderness of northwest Wyoming on 21 July 1987. This tornado traveled 39 km, crossed the North American continental divide at an elevation of 3,070 m above mean sea level (MSL), and destroyed an estimated 1 million trees across a damage swath covering 61 km^2. Cases reported elsewhere within the Rockies show that the Teton tornado was not unique for the region. Three significant ($\geq$F2) tornadoes have been documented in the Big Horn mountains, also in Wyoming (Evans and Johns, 1996), including a 13-km track F3 tornado that destroyed forest at approximately 3,000 m MSL on 21 July 1993. A few weeks later another F3 tornado occurred in the Uinta Mountains in northeastern Utah on an intermittent 28 km path that reached a maximum altitude of 3,260 m (Storm Data, 1993). Some lesser intensity events in the Rocky Mountain region are also noteworthy. To our knowledge, the highest altitude that a tornado has been documented is a ~2 km track tornado of undetermined intensity which was observed at approximately 3,475 m elevation on Longs Peak (4,345 m) in the Colorado Rockies on 17 August 1984 (Nuss 1986). A tornado that caused forest damage at 2,700 m MSL near Divide, Colorado on 12 July 1996 was produced by a thunderstorm that displayed relatively conventional supercell structure on Doppler radar (WSR-88D), providing confirmation that tornadic supercells are not restricted to lesser elevations and/or low relief terrain environments (Bluestein 2000).

The northeastern United States appears to be a favored region for major tornadogenesis in rough terrain environments. The 56-km-track Worcester, Massachusetts, storm in 1953 that caused 94 fatalities has been post-rated as F4 by Grazulis (1993). More recently, an F4 tornado along the border of New York and Massachusetts on 28 August 1973 caused 6 fatalities (Storm Data, 1973; Grazulis 1993), and an F4 tornado struck Windsor Locks, Connecticut on 3 October 1979 killing 3 people and causing $200 million damage (Riley and Bosart 1987). The longest-track tornado (103 km) of the 31 May 1985 violent tornado outbreak formed and moved across the axis of the Appalachians in Pennsylvania. This tornado attained F4 intensity and 1 km width in densely forested hilly terrain, destroying trees at a rate estimated to have reached 1000 sec^{-1} (Forbes 1998; Forbes 2002, personal communication). On 10 July 1989 a large, long-lived supercell crossed the entire breadth of the Appalachians in New York and Connecticut, producing long damage tracks from both tornadoes and severe mesocyclonic winds with widespread devastation and two associated fatalities (Grazulis 1993; Seimon and Fitzjarrald 1994). On 31 May 1998, New York's Hudson Valley witnessed an outbreak of several supercells that produced a series of large, intense tornadoes, including one that reached F3 intensity in hilly terrain at Mechanicville in the foothills of the Adirondack Mountains (Storm Data, 1998; LaPenta et al. 2004).

It is noteworthy that all of the cases listed above featured large, long-lived and intense tornadoes that occurred over hilly terrain amid landforms exhibiting topographic relief $\geq$150 m at some point along their track. Some characteristics of these selected mountain-area tornadoes recorded in the United States (US) from 1985-1998 that formed in complex terrain and went on to produce damage of F3-F4 intensity are compared in Table 1. Elevation differences, rather than absolute elevations, are used to discriminate between what we consider to be mountain versus non-mountain tornado events. This filter is therefore inclusive to Appalachian tornadoes in the eastern US while it excludes intense tornadoes that occur over the Midwestern High Plains region, which, although elevated above all but the highest summits of the Appalachians, is characterized by low topographic relief.

The data in Table 1 demonstrate that strong and violent tornadoes in rough terrain environments occur with some regularity, with a well-documented event being recorded in the United States roughly once every two years. Such recurrence warrants attention due both to the hazard represented to human interests, and because these tornadoes raise challenging questions concerning how such storms are able to develop and reach great intensity in supposedly unfavorable topographic environments. In particular, the question arises whether large, intense mountain tornadoes are the product of certain supercells overcoming topographic interference, or whether these tornadoes actually are related to topographic influences upon certain supercells.

In contrast to studies conducted in the Midwest US it is noteworthy that studies on tornadoes in California and in central Europe often relates supercell occurrence and tornadogenesis with topographic influences. Orogenic channeling of ambient low-level flows are shown in several case studies to provide both enhanced moisture transport and vertical shear profiles that support supercell development. The recurrence of supercells and tornadoes in association with prominent linear landforms, such as the Po River Valley in Italy (Costa et al. 2000), the Rhine Valley in Germany (Hannesen et al. 1998; Hannesen et al. 2000; Dotzek 2001) and the Jura mountain region in northern Switzerland (Piaget 1976) suggest that such environments may actually enhance the likelihood of supercell and tornado occurrence within otherwise unfavorable topographic domains. Similar findings have been reported in California for the Los Angeles basin (Blier and Batten, 1994) and the central and northern San Joaquin Valley (Monteverdi and Quadros, 1994), where the channeling of flows by topography creates preferred areas for tornado occurrence. Another notable topography-related tornado frequency anomaly is found near Denver, Colorado where an orogenic mesoscale circulation, the Denver Cyclone, promotes locally favored areas of tornado occurrence (e.g., Szoke et al. 1984).

3. A TENTATIVE HYPOTHESIS ON MOUNTAIN TORNADOGENESIS

The cases assembled for this study collectively suggest that large and intense tornadoes in mountain environments are more than merely statistical outliers, but perhaps an unusual class of tornado produced from a common set of environmental circumstances. We put forth here a tentative hypothesis on significant mountain tornadogenesis based upon initial case studies that we aim to develop further in future work.

Analysis presented in a companion presentation (by Bosart et al., 2004 from the 1995 Great Barrington, MA tornado listed in Table 1) offers considerable evidence supporting a hypothesis that terrain influences play a deterministic role in significant mountain tornado occurrence. We find that tornadogenesis in the GBR storm was supported by, if not actually attributable to, orogenic modifications of boundary-layer storm inflow and outflow as the parent supercell traversed a series of prominent topographic landforms (Fig. 1). In a second case study, LaPenta et al. (2004), determine that convective response to topographic channels play a supporting role in tornadogenesis of the long-lived F3-intensity tornado at Mechanicville, New York.

The two case studies allow us to begin to build a hypothesis to examine in future work. The available evidence identifies that that rather than acting as inhibitors, terrain influences may actually play a role in promoting significant mountain tornado occurrence. We hypothesize that three contributing factors must coexist to overcome the topographic inhibition that usually precludes major tornadogenesis over mountainous terrain: (1) A mesoscale environment strongly supportive of supercell thunderstorm development, according to conventional indicators of wind shear and static stability; (2)

Modifications to the low-level wind field by topographic configurations that create local orographic enhancements to tornadogenesis potential; (3) Arrival of a channeled outflow surge, originating from either the supercell or other nearby convection, beneath the mesocyclone of a mature supercell to provides the catalyst to overcome frictional disruptions by topography for tornadogenesis.

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Table 1: Selected US mountain-area tornadoes of >F3 intensity reported from 1985-1998

Tornado event	**Date**	**Damage F Intensity**	**Length (km)**	**Width (km)**	**Topographic variation (m)**		**Highest damage (m ASL)**	**Reference**
					Torn.	**Sprcll**		
Moshannon Forest, Pennsylvania	31 May 1985	F4	103	1.0	530	530	700	Forbes 1998
Watsontown, Pennsylvania	31 May 1985	F4	34	0.85	455	455	595	G. Forbes 2002 pers. comm.
Teton Mts, Wyoming	21 July 1987	F4	39.2	2.5-4.0*	712	1,400	3,070	Fujita 1989
Schoharie, New York	10 July 1989	F3	67	1.2	450	1,000	650	Seimon and Fitzjarrald 1994
Litchfield-Hamden, Connecticut	10 July 1989	F4	100	1.0-4.0*	650	1,200	650	Seimon and Fitzjarrald 1994
Iraan, Texas	1 June 1990	F4	35	1.13	220	300	920	Storm Data 1990
Big Horn Mts, Wyoming	21 July 1993	F3	12.9	0.8	600	2,000	3,020	Evans and Johns 1996
Uinta Mts, Utah	11 Aug 1993	F3	27.4	0.8	N.A.	N.A.	3,290	Storm Data 1993
New York State - Great Barrington, Massachusetts	29 May 1995	F3	50	1.0	500	1,200	550	Bosart et al., submitted
Mechanicville, New York	31 May 1998	F3	48	0.9	150	150	200	LaPenta et al. (in review)

* damage also attributed to microburst activity and/or intense mesocyclone circulations
N.A. = not available

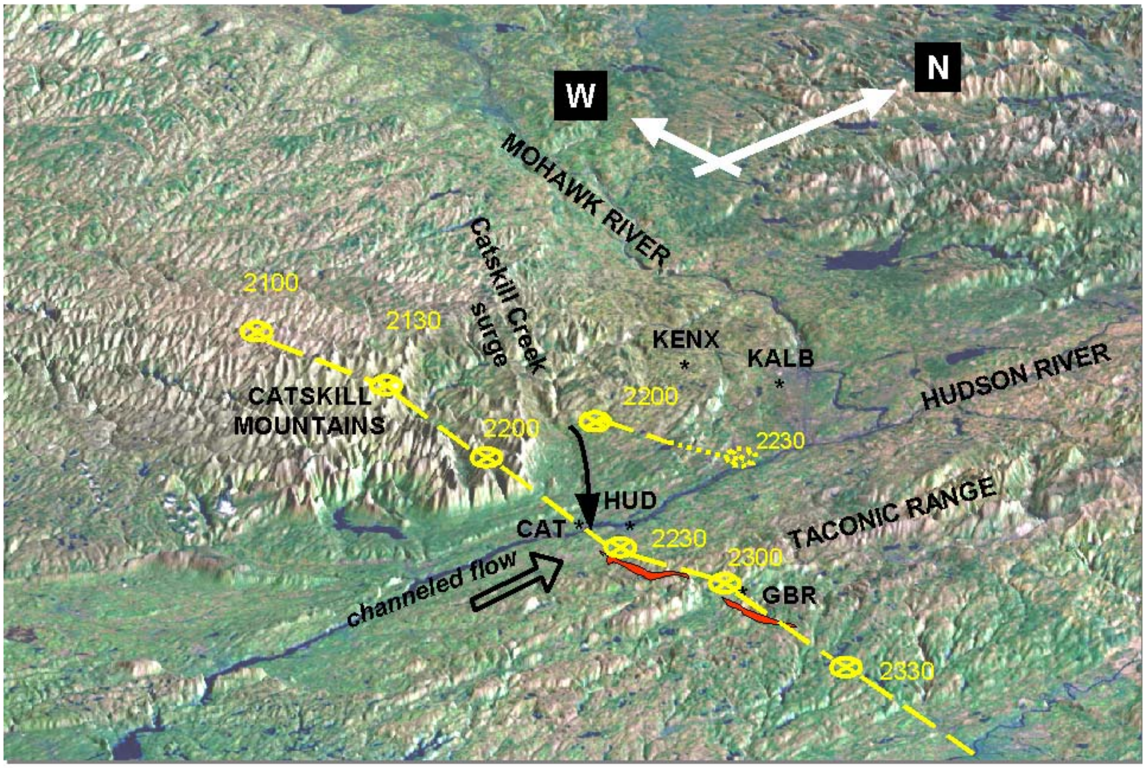

Figure 1: On 29 May 1995 a long-lived supercell traversing the complex landscapes of eastern New York State and western Massachusetts produced a large tornado that tracked for almost continuously for 50 km over terrain with 500 meter altitudinal variation; this case is detailed in the companion presentation by Bosart et al. in this collection (paper 5.3). Analysis incorporating WSR-88D Doppler radar data from East Berne, New York (KENX) and landscape morphology provides compelling evidence that the supercell's interaction with its underlying topography was instrumental in tornadogenesis. Displayed here are the mesocyclone (yellow) and tornado damage (red) tracks derived from Doppler velocity data and aerial surveys, respectively, with mesocyclone locations indicated at 30-minute intervals in UTC. The landscape representation is a simulated oblique aerial perspective looking northwest centered upon the central Hudson Valley region of New York. The background image is a cropped section of LANDSAT imagery draped over a high-resolution (90-m) digital elevation model derived from C-Band Interferometric radar data from the Shuttle Radar Topography Mission (Source: http://photojournal.jpl.nasa.gov/catalog/PIA02757). The vertical relief is amplified 5x.