Appeared in: Preprints, *17^{th} Conf. on Severe Local Storms*, Saint Louis, Missouri (4-8 October 1993), Amer. Meteor. Soc., 173-177. **Note**: references have been updated to show page numbers for publications appearing since this preprint paper appeared.

EXTREME WINDS IN HIGH-PRECIPITATION SUPERCELLS

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1. INTRODUCTION

Supercell thunderstorms produce the complete spectrum of hazardous weather associated with atmospheric convection: tornadoes, large hail, strong "straight-line" winds, lightning, and flash floods. Over the years, a significant amount of attention has been paid by the research and operational communities to the problem of determining environments which are favorable to the generation of supercells. In particular, a major focus has been on the forecasting of tornadoes and tornadic storms. Recently, Cummine et al. (1992) described a storm which inflicted major damage to the Pakwash forest in Northwest Ontario, Canada. Approximately 1500 km^2 of trees were blown down by winds that reached in excess of 50 m s^{-1}, but there was no evidence of any tornadic activity. The damage path was roughly 20 km wide and 75 km long.

We have identified several other storms that have generated damage similar to the Pakwash storm in the past 20 years, with peak winds on the order of 50 m s^{-1}, and long damage paths approximately 10-30 km wide. In addition, these storms had, at most, minor tornadic events. Where possible, we have attempted to determine the environmental conditions in the vicinity of the storms by looking at rawinsonde and surface data. The thermodynamic and wind environments of the various storms are similar in many important respects. Specifically, low levels are extremely moist, there is a significant amount of storm-relative helicity, and, particularly in comparison to significant tornado-producing supercells, the environments have weak storm-relative mid-level winds.

We believe that these "Pakwash-type" storms are high-precipitation (HP) supercells (Moller et al. 1990) that generate extremely strong surface winds on the south side of the mid-level mesocyclone. The mechanism of generating the strong winds, in the absence of a well-organized low-level mesocyclone, is consistent with the conceptual model of the relationship of low-level mesocyclones to supercell storms proposed by Brooks et al. (1993). Here, we will review the observational evidence of the environments of these storms and then discuss a relevant numerical simulation. We close with comments about some of the particular problems these storms for operational meteorology.

2. ENVIRONMENTAL OBSERVATIONS

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We have examined the upper air conditions associated with the Pakwash storm and four other events of similar or greater magnitude. These other events were the 25 May 1976 Graham, Texas storm (Moller et al. 1990), the 4 July 1977 northern Wisconsin storm (mentioned in Fujita et al., 1981), the 19 June 1990 Wichita, Kansas "inland hurricane" (Inglish 1990), and the 8 July 1992 Concordia, Kansas storm (Smith 1993). For each of these cases, we took the nearest upper air sounding in space and time as a starting point and modified the thermodynamic conditions with later surface observations if the surface conditions were significantly different. In the case of the Pakwash storm, we also considered the next upstream sounding site at Saint Cloud, in addition to that at International Falls.

The resulting soundings share some similar characteristics. The Topeka sounding from 0000 Z on 20 June 1990 (associated with the Wichita storm) illustrates these characteristics (Fig. 1). In particular, we emphasize the large amount of instability and high low-level moisture content from the thermodynamic profile. Although the Wichita case represents the most moist and unstable of the five environments (Table 1), the others are also quite unstable and have low-level mixing ratios of at least 17 g kg^{-1} (equivalent to a dewpoint of ~22 C). The wind profile shows significant storm-relative curvature in low levels, leading to high environmental helicity, with weak storm-relative winds in mid-troposphere.

Location	*Date*	*Q*	*CAPE*	*H*	*Min Wind*	*Source for environment*
Graham, TX	25 May 76	17.0	3200	330	6.7	1200 UTC SEP, Surface obs
Wisconsin	04 Jul 77	19.6	3200	360	6.5	1200 UTC STC
Wichita, KS	20 Jun 90	20.0	4500	240	0.0	0000 UTC TOP
Pakwash, ON	18 Jul 91	17.0	2400	220	5.5	1200 UTC INL, STC, Surface obs
Concordia, KS	08 Jul 92	18.5	2300	430	2.2	0000 UTC (09 Jul) TOP
Red Rock, OK	26 Apr 91	16.2	3900	370	14.3	2300 UTC Lamont Profiler
Purcell, OK	02 Sep 92	--	--	220	10.7	2300 UTC Purcell Profiler
Tulsa, OK	24 Apr 93	--	--	520	15.2	0000 UTC (25 Apr) Haskell Profiler

Table 1: Environmental conditions in vicinity of extreme non-tornadic wind events with recent selected tornadic events included for comparison. *Q* is maximum boundary-layer water vapor mixing ratio in g kg^{-1} from sounding or nearby surface observations. *CAPE* is convective available potential energy as defined by Weisman and Klemp (1982), using a parcel mixed over the lowest 50 mb of the atmosphere as the lifted parcel. *H* is 0-3 km storm-relative helicity in m^2 s^{-2}, with storm motion estimated from observations and damage reports (Davies-Jones et al. 1990). *Min Wind* is the minimum magnitude of the storm-relative environmental winds in the 2-8 km layer. Wind information for tornadic events (in italics: Red Rock, Purcell, and Tulsa) from hourly wind profiler data. Red Rock thermodynamics from the OUN sounding at 0000 UTC (27 April).

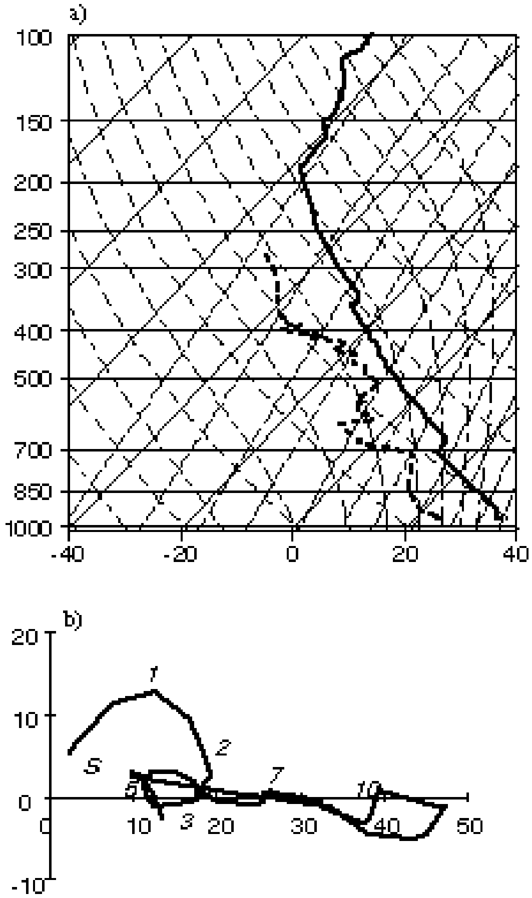

Fig. 1. a) Skew-T plot of thermodynamic conditions from 0000Z 20 June 1990 TOP sounding. Solid line is temperature and dashed line is dewpoint. b) Hodograph from same sounding. Axes are labelled in m/s and italicized numbers represent heights above ground level in km. Approximate storm motion for first 2 hours of damage was from 270° at 20 m/s.

The features in the hodograph are of particular interest in comparison with tornadic storms. We have included information in Table 1 about three recent tornadic events that were well-sampled by the Profiler Demonstration Network. (Because of the precipitation on 2 September 1992 and dryline passage on 24 April 1993, there are no representative soundings for those days.) While the helicities are similar in the tornadic cases and extreme wind cases, the storm-relative winds are much weaker in the extreme wind cases.

3. CONCEPTUAL MODEL

The distinctive characteristics of the environments associated with the extreme windstorms make it appealing to construct a simple conceptual model of the evolution of the storm leading to these winds. Brooks et al. (1993) proposed a simple model of the generation of low-level mesocyclones in supercell thunderstorms which sheds light on this issue. Their model builds on the work of Rotunno and Klemp (1985) and Davies-Jones and Brooks (1993), which stressed the importance of baroclinic generation of vorticity in the evaporatively-cooled air in downdrafts of supercells as the source of vorticity at low levels. A second effect of the evaporation is the generation of cold outflow air.

Brooks et al. hypothesized that the two primary mechanisms transporting precipitation horizontally in supercells are the environmental winds, blowing precipitation away from the updraft, and the mid-level mesocyclone circulation, which tends to wrap precipitation around the updraft. A balance between those two processes is necessary in order to generate long-lived, low-level mesocyclones. If little rain gets wrapped around to the rear of the updraft to be evaporated, baroclinic generation in the rear flank region will be slow, if it occurs at all. On the other hand, if evaporation is very large, the cold outflow generated may be so strong as to cut off the inflow into the storm rapidly, killing the storm. In simplest terms, the model focuses on the issue of the location and magnitude of evaporation in the vicinity of the updraft of the storm.

Applying the model to the environmental conditions associated with the extreme wind cases, we start with the large low-level absolute humidity and the associated large CAPE.[1] The high moisture content of the boundary layer represents a large source of possible rain for the storm, and, hence, potentially a large amount of evaporation. Weak storm-relative winds in mid-levels imply that the rain would not be blown a long distance from the updraft. The high helicity in the environment suggests that any strong storms in the environment will rotate at mid-levels (Davies-Jones et al. 1990). As a result, we would expect that a large amount of the rain would be wrapped around the updraft as it falls. Then, since the thermodynamic profile is not saturated, evaporation and the associated cooling would be very strong. We hypothesize that the cooling is so strong in these cases that the dominant effect is to produce a very strong outflow on the south side of the updraft. It is possible that the outflow might cut off the initial storm, but that convection may redevelop on the leading edge of the outflow and the process repeat itself. The lifetime of individual cells in this kind of environment is an unanswered question at this point, but it appears likely that each would be rotating, pulling rain around to rear side of the updraft and producing a swath, with a width on the order of the size of the individual storm, of very high surface winds extending over a distance much longer than it is wide. Associated with the winds, we would expect to see significant drops in temperature and absolute humidity. An illustration of that effect is seen in the automated observations taken at Concordia in association with the 8 July 1992 storm (Smith 1993).

4. NUMERICAL SIMULATION

In order to examine the hypothesized storm structure, we carried out a numerical simulation of the Wichita "inland hurricane" case. This case was selected because it had less of an inversion than the other four cases, which meant that the thermodynamic profile required less modification in order to generate a storm. The model used was developed by Wicker and Wilhelmson (1990). The model is similar to that of Klemp and Wilhelmson (1978), but has improved numerics and includes the ice-phase microphysics of Straka and Anderson (1993). The horizontal domain was 70 x 70 km with a grid spacing of 1 km. The vertical domain was 16 km, with a "stretched" grid such that the lowest levels had a spacing of 200 m and the highest levels were approximately 700 m. The simulation was run out to 9000 s, with a large time step of 5 s and a small time step of 1.25 s. The environmental conditions used to initialize the model are shown in Fig. 1, although the high surface moisture layer was deepened slightly and the dry adiabatic boundary layer temperature profile was changed slightly (to raise the Richardson number above 0.25 in low layers to limit the growth of gravity waves in the model). A storm was started in the model by imposing a warm bubble, located in the middle of the domain, centered at 1400

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[1] We note in passing that a large value of CAPE implies a great deal of information about the humidity profile in the atmosphere. High CAPE requires steep lapse rates in the low-to-mid-troposphere, implying dry air at those levels, with high absolute humidity at low levels, so that the parcel is lifted along a very warm pseudo-adiabat.

m altitude, and with a maximum potential temperature perturbation of 8 K. While the perturbation is admittedly large, smaller perturbations failed to generate long-lived storms. While we have not had an opportunity to investigate this question fully, it is likely that it is related to the relatively high level of free convection in the sounding. Issues concerning modelling of storms in such environments are discussed in Brooks (1992).

The initial storm splits and the left-mover moves out of the north side of the domain. The right-mover grows and develops rotation rapidly at mid-levels. Soon, rain falls out and a strong cold pool forms with a maximum potential temperature perturbation of approximately 10 K by 3600 s. As a result of the cold air, strong outflow develops. At the leading edge of the outflow, shear vorticity is generated, but nothing resembling a significant rotational circulation develops at low levels. Ground-relative wind speeds at 100 m above the ground (lowest model level) at 3600 s reach more than 40 m s^{-1} over a small region within a relatively wide swath of more than 25 m s^{-1}. (Although not shown here, the initial development of the winds is on the south side of the updraft, with the leading edge of the high winds then moving ahead of the updraft.) Given that the model storm motion is 260 deg/20 m s^{-1}, the westerly component of the wind depicts most of the features of the low-level flow (Fig. 2). The cold outflow cuts off the inflow of buoyant air into the storm and the initial updraft dies. Secondary updrafts develop on the leading edge of the outflow and go through a similar evolution to the initial storm except that the lifetime of the secondary updrafts is shorter.

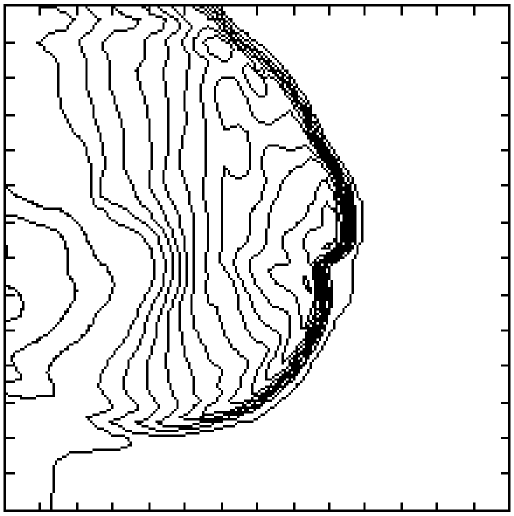

Fig. 2. Westerly component of ground-relative wind at 100 m above the ground at 3600 s in the Wichita simulation. Contour interval is 3 m/s. Dashed contours are negative and zero contour is suppressed. Tick marks are spaced 5 km apart. Peak value is 40 m/s.

We can approximate the maximum wind speed that would be seen at locations on the ground as the storm moves by calculating the 100-m AGL wind at every point in the model domain and translating the computational domain to a ground-based coordinate system. Data for this purpose were saved every 30 seconds for a 12,000 s simulation and the pattern of winds reveals significant features of the storm's behavior (Fig. 3). Within the area of winds associated with initial right-moving storm, a small concentrated area of more than 40 m s^{-1} (indicated by the arrow in Fig. 3 located at maximum of velocity in Fig. 2) is seen. There is an narrow swath (on the order of 5-10 km) of winds greater than 25 m s^{-1} extending eastward from the wind maximum for approximately 100 km.

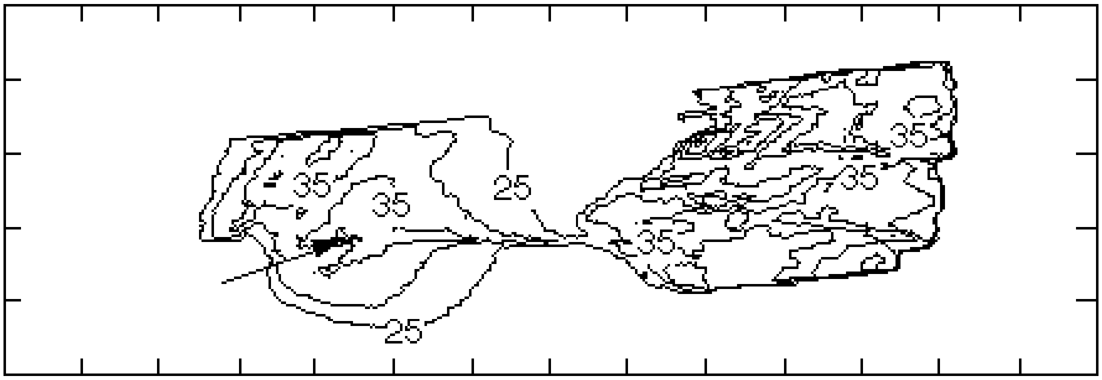

Fig. 3: Maximum ground-relative winds (in m/s at 100 m above the ground in Wichita simulation in ground-based coordinate system. Outer contour is 25 m/s and contour interval is 5 m/s, with selected contours labelled. Tick marks are 25 km apart. Arrow indicates location of maximum westerly wind near center of model domain at 3600 s, as seen in Fig. 2 and discussed in text.

The explosive development of secondary convection on the outflow is marked clearly by the second large area of high winds seen to the east. This wind field in this region is much noisier than the initial, western region. Short-lived, rotating updrafts are initiated at many locations along the initial outflow boundary. Subsequent boundaries lead to new convection, but also provide additional cold air that acts to cut off updrafts. The redevelopment (which has not been observed) represents a serious problem with the simulations, related to the initiation question. In efforts to simulate other events, such as the Concordia or Pakwash storms, the observed inversion at the top of the boundary layer had to be eliminated in order to allow the initial storm in the model to survive. Without the inversion, the problem of frequent redevelopment also occurred, as seen here. The presence of the inversion may act to inhibit redevelopment in the atmosphere. Clearly, the initiation of a single storm, without significant redevelopment of a large number of secondary storms, which appears to be the mode of behavior in the atmosphere, is something that has not been captured in the model and is an important limitation on the results.

5. OPERATIONAL IMPLICATIONS

Extreme winds (greater than 50 m s^{-1}) over an extended distance associated with rotating thunderstorms may represent an high-end example of a severe, non-tornadic thunderstorm (Doswell and Brooks 1993). These storms can produce significant damage over areas on the order of 2000 km^2 or larger. We estimate that perhaps one of these extreme events per year occurs in North America,[2] although lesser events of a similar character may occur with much greater frequency. They present an interesting operational challenge in that warning lead times for an event probably would be on the order of 30-60 minutes at best, similar to tornado warnings. Even though the peak winds are not as strong as violent tornadoes, the relatively wide area associated with the high winds makes public response problematic, since it would be very difficult to get out

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[2] We are also aware of similar storms occurring in Australia. A possible example has been described by Eyre (1992).

of the path of the storm. The winds also tend to move ahead of the updraft and rainfall, so that the area of danger may be in advance of the radar-observable quantities if the storm is far enough away from the radar that the high winds can't be observed directly.

As with any weather phenomenon, operational meteorologists need to anticipate the environmental conditions leading up to extreme-wind HP supercells. Very high surface moisture values, helicity consistent with supercell development and weak storm-relative mid-tropospheric winds appear to be essential ingredients. Note that the winds at 7 km in the "inland hurricane" sounding (Fig. 1b) were 25 m s^{-1}, but that in a storm-relative framework, they were approximately 5 m s^{-1}. Thus, simply considering the ground-relative environmental winds may lead to the incorrect conclusion that the mid-level winds are strong, when in the reference frame of the storm, they are, in reality, weak.

6. ACKNOWLEDGMENTS

We thank James Cummine and Mike LeDuc for initially sparking out interest in these storms by calling our attention to the Pakwash storm and for providing a videotape of the storm. Erik Rasmussen suggested the Wichita storm as another example of this class of storm. Brian Smith shared ASOS observations from the Concordia storm. The simulations were carried out on an IBM 350H RS-6000 workstation purchased, in part, with funds from the Department of Energy's Atmospheric Radiation Measurement program. Some of the analysis during the course of the project was done at the National Center for Supercomputer Applications.

7. REFERENCES

Brooks, H. E., 1992: Operational implications of the sensitivity of modelled thunderstorms to thermal perturbations. Preprints, *4th Workshop on Operational Meteorology*, Whistler, British Columbia, Canada, Atmos. Environ. Service/Canadian Meteor. and Oceanogr. Soc., 398-407.

______, C. A. Doswell III, and R. B. Wilhelmson, 1993: On the role of mid-tropospheric winds in the evolution and maintenance of low-level mesocyclones. Mon. Wea. Rev., 122, 126-136.

Cummine, J., P. McCarthy, and M. Leduc, 1992: Blowdown over Northwestern Ontario. A Derecho Event - 18 July 1991. Preprints, *4th Workshop on Operational Meteorology*, Whistler, British Columbia, Canada, Atmos. Environ. Service/Canadian Meteor. and Oceanogr. Soc., 311-317.

Davies-Jones, R., and H. E. Brooks, 1993: Mesocyclogenesis from a theoretical perspective. *The Tornado: Its Structure, Dynamics, Hazards, and Prediction* (*Geophys. Monogr.* 79), Amer. Geophys. Union, 105-114.

Doswell, C. A. III, and H. E. Brooks, 1993: Supercell thunderstorms [Comments on "How severe can a 'severe thunderstorm' be?: An investigation into two violent electrical storms in Australia"]. *Weather*, **48**, 209-210.

Eyre, L. A., 1992: How severe can a 'severe thunderstorm' be?: An investigation into two violent electrical storms in Australia. *Weather*, **47**, 374-383.

Fujita, T .T., and R. M. Wakimoto, 1981: Five scales of airflow associated with a series of downbursts on

16 June 1980. *Mon. Wea. Rev.*, **109**, 1438-1456.

Inglish, H., 1990: *Year of the Storms. The Destructive Kansas Weather of 1990.* Hillsboro, Kansas, Hearth Publishing, 120 pp.

Klemp, J. B., and R. B. Wilhelmson, 1978: The simulation of three-dimensional convective storm dynamics. *J. Atmos. Sci.*, **35**, 1070-1096.

Moller, A. R., C. A. Doswell III, and R. Przybylinski, 1990: High-Precipitation supercells: A conceptual model and documentation. Preprints, *16th Conference on Severe Local Storms*, Kananaskis Park, Alta., Canada, Amer. Meteor. Soc., 52-57.

Rotunno, R., and J. B. Klemp, 1985: On the rotation and propagation of simulated supercell thunderstorms. *J. Atmos. Sci.*, **42**, 271-292.

Smith, B. E., 1993: The Concordia, Kansas downburst of 8 July 1992: A case study of an unusually long-lived windstorm. Preprints, *17th Conference on Severe Local Storms*, Saint Louis, Missouri, Amer. Meteor. Soc., 588-592.

Straka, J.M., and J.R. Anderson, 1993: Numerical simulations of microburst producing storms: Some results from storms observed during the COHMEX. *J. Atmos. Sci.*, **50**, 1329-1348.

Weisman, M. R., and J. B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504-520.

Wicker, L. J., and R. B. Wilhelmson, 1990: Numerical simulation of a tornado-like vortex in a high resolution three dimensional cloud model. Preprints, *16th Conf. on Severe Local Storms*, Kananaskis Park, Alberta, Canada, Amer. Meteor Soc., 263-268.