MESOSCALE DYNAMICS OF THE RECORD-BREAKING 10 NOVEMBER 1998 MID-LATITUDE CYCLONE: A SATELLITE-BASED CASE STUDY

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Abstract

On 10 November 1998, a cyclone deepened rapidly as it passed through the upper Midwest, bringing with it damaging winds and record-setting low pressures. An examination of meteorological satellite imagery over the upper Midwest during the height of the storm showed an area of drier air curving cyclonically behind the cold front. This dry intrusion forked into two distinct paths near the low-pressure center, with the lowest tropopause heights (~ 600 mb) near the southern fork of the dry intrusion. The main finding of this work is that the surface reports of damaging winds were very closely linked in time and space to the location of the southern fork of the dry intrusion. The possibility of improved nowcasting of extreme winds on very fine space and time scales using satellite imagery is discussed. The satellite signatures of this storm are discussed in relation to other damaging windstorm events, such as the 1979 Fastnet yacht race cyclone and the 1975 Edmund Fitzgerald *cyclone.*

1. Introduction

On 10 November 1998, an intense mid-latitude cyclone passed through the upper Midwest region (Fig. 1), deepening approximately 30 mb in only 18 hours. Albert Lea and Austin, Minnesota, reported state record low pressures of 963 mb as the cyclone passed through the region around 1800 UTC 10 November. Spencer and Estherville also set record low pressures for the state of Iowa with pressures near 966 mb between 1300 and 1500 UTC (Iowa state climatologist Harry Hillaker, personal communication).

Widespread gusts in excess of 50 kt were associated with this cyclone. These winds led to ten deaths, 34 injuries and at least $40 million in property and crop damages in Illinois, Iowa, Kentucky, Michigan, Minnesota, and Wisconsin. Some of the most intense wind gusts during the afternoon hours of 10 November extended along a path from La Crosse to Wausau, Wisconsin. During this time, La Crosse recorded eight wind gusts of greater than 60 kt. Pilot reports (PIREPS) of turbulence were also widespread throughout the upper Midwest. The significance of PIREPS to this case is explained later.

None of the wind-related events listed above, on the ground or in the air, were associated with reports of significant convective activity. As will be shown, the intense winds over Wisconsin occurred beneath the dry stratospheric intrusion (Browning 1997) of the cyclone. Satellite imagery from this storm, combined with surface and aviation observations in addition to analysis of forecast model output, is used to take a closer look at how and why this extreme windstorm event took place.

2. Data Sources

In this study, several types of weather-related data were used. Satellite data included GOES-8 8 km, 6.7-μm water vapor imagery from the Unisys Weather Web site and 2.66 km water vapor imagery. Also, 1 km multi-spectral imagery from the GOES-8 Imager obtained from NOAA/NESDIS was employed to resolve small-scale features.

RUC-2 forecast model output with 40 km resolution was analyzed to diagnose the collocation of surface and upper-air features associated with this cyclone. The RUC-2 is an operational version of the Mesoscale Analysis and Prediction System (MAPS) run at the NOAA/NWS/National Centers for Environmental Prediction (NCEP) (Benjamin et al.. 1998). PIREPS of turbulence were also used to verify the locations of strong winds and vertical motion aloft. Backward trajectories from the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model from the NOAA Air Resources Laboratory were also examined.

Individual storm reports regarding low pressures, damaging winds, fatalities, injuries, and property damages were obtained from the NOAA/NESDIS/National Climatic Data Center. (URLs to data sources used in this research are listed at the end in a section titled, "Sources of Storm Data and Model Information".)

3. Synoptic-Scale Analysis of Cyclone Peak

a. Observations

The purpose of this case study was to examine the mesoscale events that took place over southwestern Wisconsin on 10 November 1998 during the mid-afternoon hours. In order to understand the small-scale features within this cyclone, it is necessary to explore briefly some aspects of the synoptic-scale structure of the cyclone leading up to the intense wind gusts.

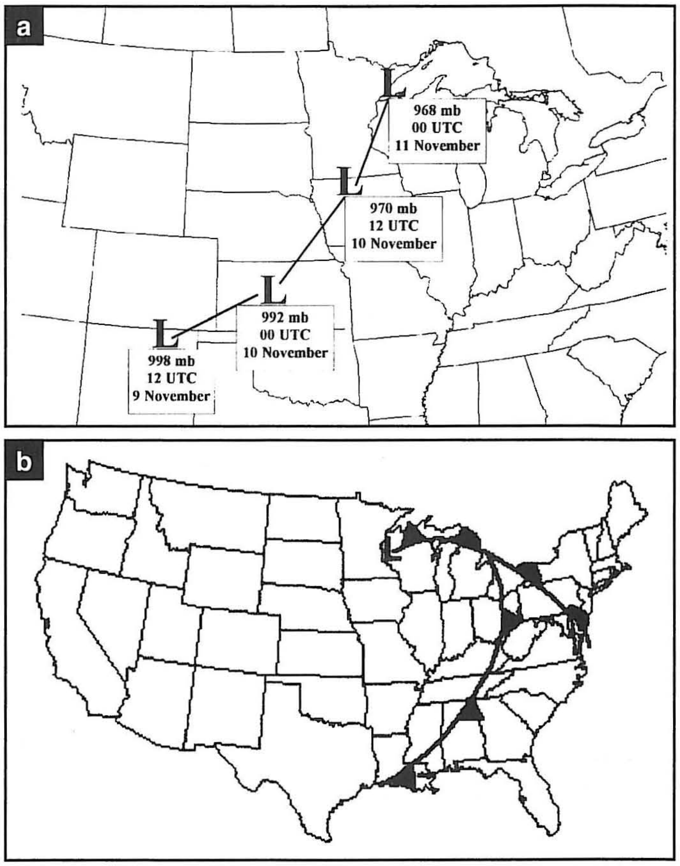

Fig. 1. a) Approximate locations and intensities of the low-pressure center from 1200 UTC 9 November 1998 to 0000 UTC 11 November 1998. b) Low-pressure center at 1800 UTC 10 November 1998 with surface fronts.

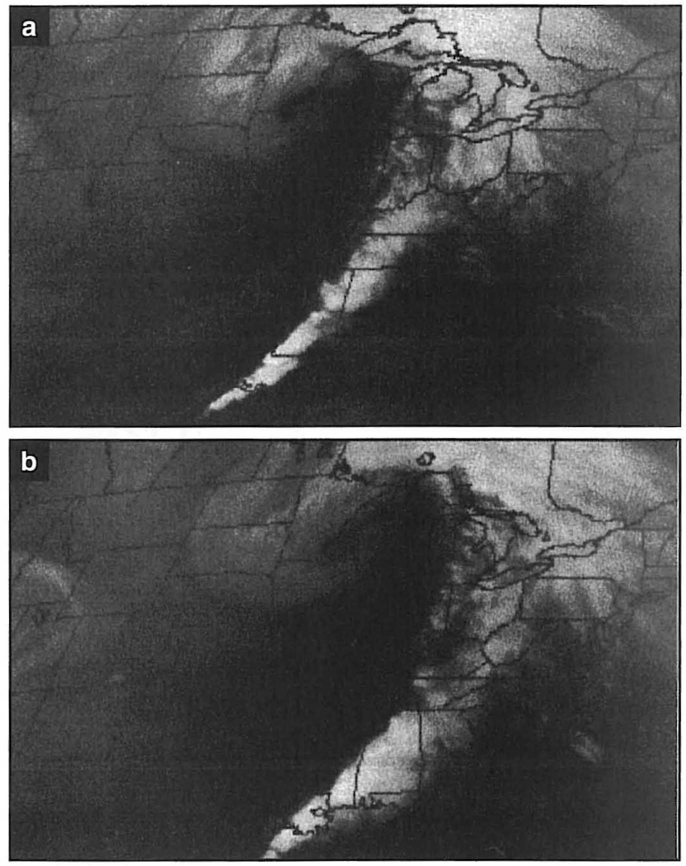

Fig. 2. Water vapor imagery at a) 1515 UTC and b) 1815 UTC 10 November 1998. In a), two distinct tongues of dry air over the Upper Midwest are visible. In b), the southern hook of dry air around the low is becoming better defined while the northern tongue of dry air is becoming less distinct.

1) Dry intrusion

At 1500 UTC on 10 November, water vapor imagery revealed an area of dry air (dark regions) that was forked into two separate tongues and rotating cyclonically around the intense cyclone (Fig. 2a). One of these tongues of dry air stretched to the north-northwest into northeastern Minnesota, in the direction of the 500 mb jet stream as indicated by RUC-2 model analysis. The other tongue of dry air reached west towards the low-pressure center near the Iowa-Minnesota border.

Imagery three hours later at 1800 UTC on 10 November (Fig. 2b) showed that the dry intrusion propagated to the north and west while the low-pressure center was located in eastern Minnesota.

2) Tropopause heights and absolute vorticity

At 1500 UTC, the RUC-2 model analysis estimated tropopause pressures near the low-pressure center to be 530 mb (not shown). However, 200 km northeast of this reading the tropopause height was approximately 190 mb. This was indicative of a deep tropopause fold or what Bithell et al. (1999) refers to as PV "tubes" in stratospheric intrusions. At the same time, RUC-2 model output showed a 500-mb absolute vorticity maximum of greater than 40 x 10^{-5} s^{-1} along the Iowa-Minnesota border. This vorticity maximum was located near the exit region of the 130-kt, 500-mb jet core within the dry intrusion of the cyclone.

Three hours later, at 1800 UTC, RUC-2 analysis indicated a northeastward propagation of the 500-mb jet core, which now extended from Lake Michigan southward into eastern Missouri. The 1800 UTC tropopause pressure was in excess of 560 mb compared to much lower tropopause pressures elsewhere (Fig. 3).

b. Discussion

Water vapor imagery indicated a cyclonically curved area of dry air, which coincides with the location of the 500-mb jet streak during the life of the cyclone. The dry regions appear dark due to a lack of emitters in the upper atmosphere. In this case, it is believed that air from the stratosphere had descended due to the vertical circulation in and near the jet streak causing the satellite to detect water vapor from lower down in the troposphere, which is warmer (Kidder and Vonder Haar 1995, p. 150; Browning and Reynolds 1994).

A discontinuous transition between the tropopause levels above various air masses can be explained by the three dimensional circulation that occurs around jet streams (Djuric 1994, p. 132). Curved jet streaks tend to exhibit a two-cell pattern as opposed to the tra-

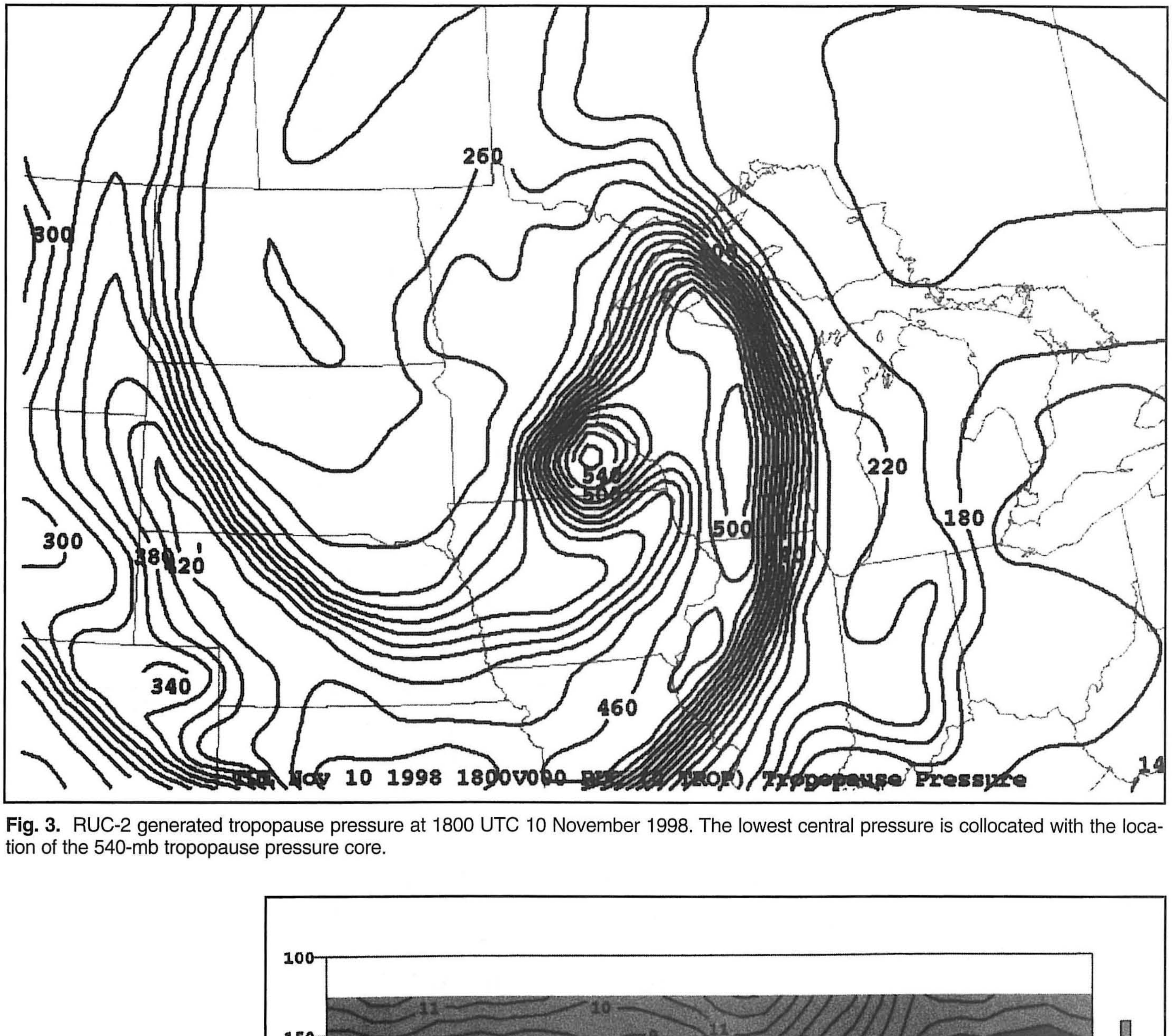

Fig. 3. RUC-2 generated tropopause pressure at 1800 UTC 10 November 1998. The lowest central pressure is collocated with the location of the 540-mb tropopause pressure core.

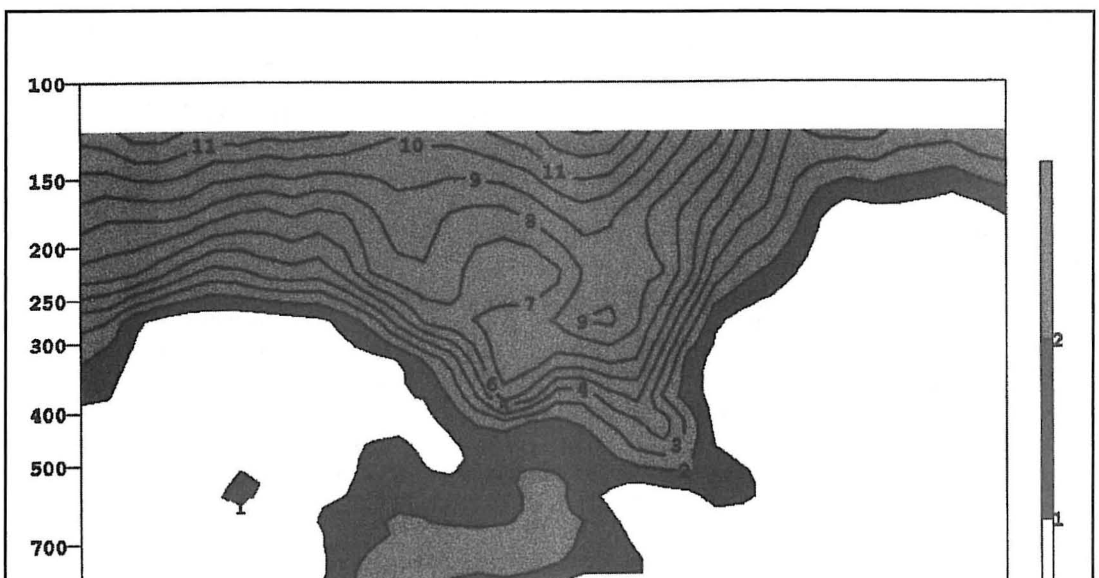

Fig. 4. A northwest-to-southeast vertical cross-section of potential vorticity centered on La Crosse, Wisconsin (LSE), as determined from the 2100 UTC 10 November 1998 RUC-2 analysis. Potential vorticity is contoured in "PV units" (1 PV unit = 10^{-6} m^2 s^{-1} K kg^{-1}) with values between 1 and 2 in dark shading and values above 2 in light shading. See text for the interpretation of these PV unit values.

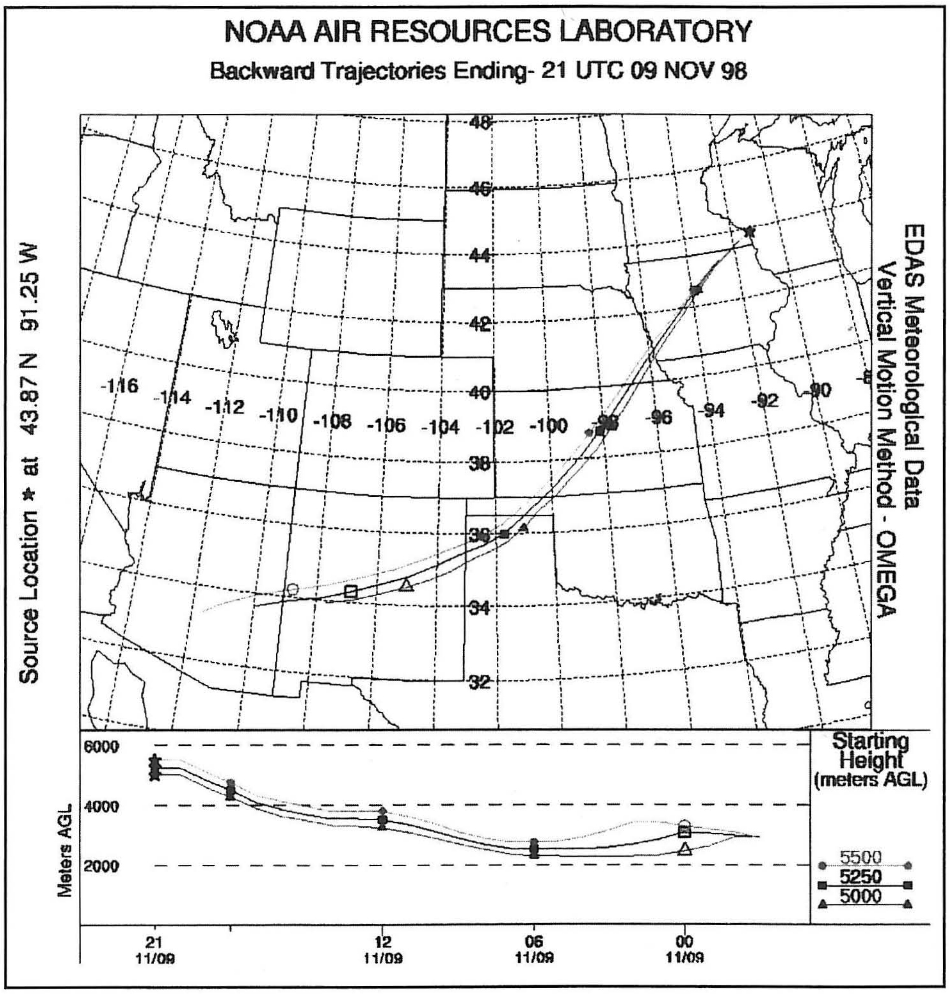

Fig. 5. Generated HYSPLIT backward trajectories obtained from the Air Resources Laboratory Web site (see "Sources of Storm Data and Model Information" section at the end of this article for URL) from La Crosse, Wisconsin. This run of the HYSPLIT model shows the 5000 m, 5250 m, and 5500 m above ground level. This figure shows air ascending over time as it approaches La Crosse.

ditional four-cell model (Cunningham 1997, p. 3). In the two-cell model, curved jet streaks are associated with much stronger vertical motion than straight jet streaks due to increased vorticity within the concave area of the curved jet streak. The RUC-2 model output (not shown) indicated a cyclonically curved jet accompanying a much stronger-than-average absolute vorticity maximum. However, the curvature of this jet was not pronounced in the RUC-2 output. The RUC-2, with 40-km resolution as opposed to the 8-km resolution of water vapor imagery, may not have resolved the location and curvature of this jet streak as well as it has been by satellite data. This suggests that the mesoscale features of this cyclone are best understood qualitatively by analyzing high-resolution satellite data.

4. Mesoscale Analysis of Cyclone Peak

a. Satellite imagery and model diagnosis

The area of dry air indicated on water vapor imagery split into two separate paths near the low-pressure center. One of these followed the expected path of the curved 500-mb jet. However, the second path of advecting dry air, to the south of the first, took a markedly different path than would be expected, curving around the center of the cyclone in a mesoscale hook-like pattern. For the remainder of the paper, we focus on this "mesoscale dry hook."

By 1800 UTC, the southerly fork of the dry slot became significantly more distinct while the northerly fork became less distinct. Assuming that the dark areas on water vapor imagery were regions of dry air, and the stratosphere is a nearby source of dry air, this may indicate sinking motion in the southern mesoscale dry hook. The tropospheric fold relative to the low-pressure center also supports this idea. A northwest to southeast cross-section, centered on La Crosse, Wisconsin, of RUC-2-analyzed potential vorticity at 2100 UTC indicated high ($\geq$ 2 PV units) values below 500 mb (Fig. 4). These high values of potential vorticity are well known to be tracers of stratospheric air (Hoskins et al. 1985; Olsen et al. 2000).

At first glance it would be easy to assume that this dry air was sinking and directly causing the extreme wind events at the surface (Browning and Reynolds 1994). However, dry slots can also be caused via horizontal dry air advection. In addition, Bader et al. (1995, p. 94) state that, while the dry intrusion is formed by rapidly descending air from the upper troposphere and lower stratosphere, air actually ascends in the dry slot that hooks around the low-pressure center. Backward trajectories from La Crosse using the NOAA Air Resources Laboratory HYSPLIT model confirm that the near-cyclone air was ascending (Fig. 5). If stratospheric air is descending beyond the tropopause it is happening on scales smaller than the resolution of the HYSPLIT model run with EDAS (Eta Data Assimilation System) output. Olsen et al. (2000) also infer from satellite-based ozone data that stratospheric descent was confined to levels above 600 mb in this particular cyclone; high values in the lower troposphere were diabatically generated. Thus, it is difficult to use satellite imagery by itself to diagnose vertical motions.

b. PIREPS of turbulence

Pilots should experience moderate turbulence while in the air if strong small-scale vertical motions are present (Lester 1994, p. 1-13). PIREPS of turbulence provided some support of water vapor imagery features on the 10th. Several flights encountered moderate to severe turbulence while flying through the dry intrusions of the 10 November cyclone. Between 1400 and 1600 UTC on 10 November, a significant number of turbulence reports were found below the region of the dry intrusion, including the mesoscale hook-like area that was beginning to wrap around the vorticity maximum (Fig. 6). Turbulence PIREPS during this storm suggested that satellite imagery was correctly resolving features of dynamical importance at small scales. Therefore, in the following section, we examine the evolution of the mesoscale dry hook and its relation to extreme surface wind gusts.

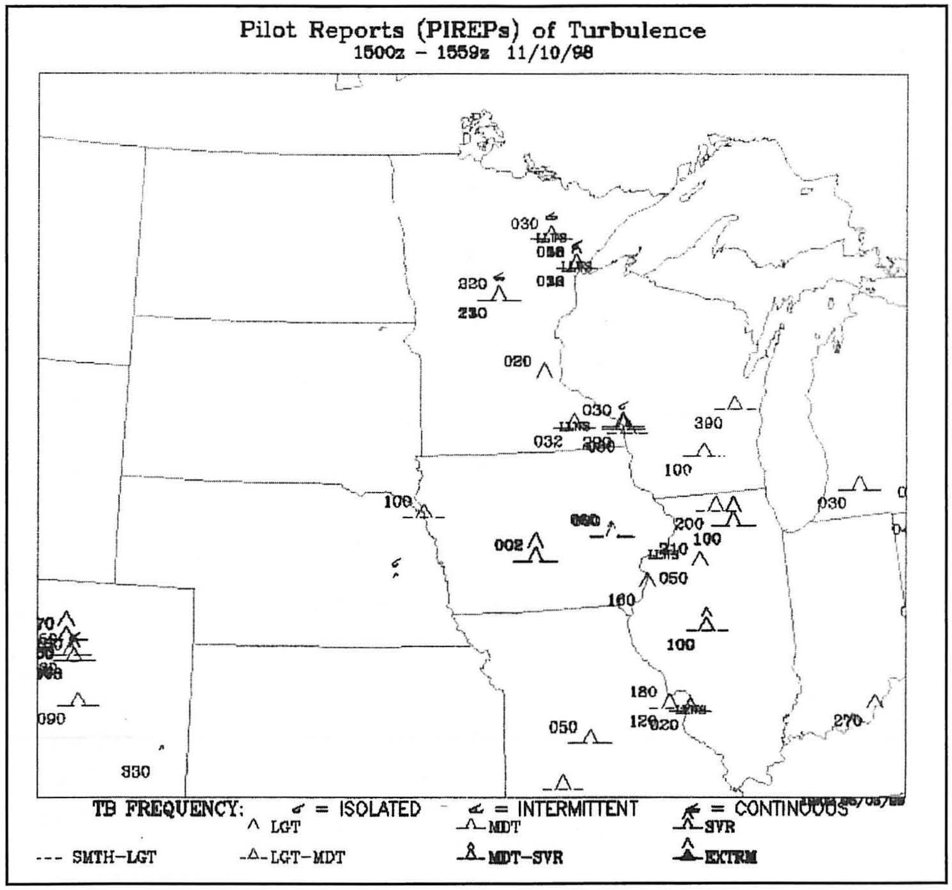

Fig. 6. PIREPS of turbulence between 1500 and 1559 UTC 10 November 1998. Moderate and severe reports of turbulence in the Upper Midwest were located below or within the vicinity of the dry intrusion and the two tongues of dry air, which extend from it. Figure courtesy of Greg Thompson, NCAR/RAP.

5. Evolution of Mesoscale Features and Surface Wind Gusts

a. Observations

By 2100 UTC the mesoscale dry hook had become well defined both in visible and water vapor imagery (Figs. 7 and 8). The higher-resolution imagery in Fig. 7 suggests that the hook folded over into a spiral. Meanwhile, at 2020 UTC, the La Crosse, Wisconsin, National Weather Service Office recorded an impressive 81 kt wind gust from the southwest. Less than an hour earlier, at 1937 UTC, there had been a strong southwesterly gust at the La Crosse office of 63 kt. Both water vapor and visible imagery indicated that the southern portion of the mesoscale hook passed over La Crosse between 1900 and 2200 UTC. Furthermore, storm reports of high winds in western and central Wisconsin from 2020 to 2130 UTC (Fig. 9) formed a hook-shaped path directly underneath the mesoscale dry hook in satellite imagery during the same time period. What is interesting about the arrow in Fig. 9 is that it both represents the direction of development of the mesoscale hook as well as the temporal progression of local storm

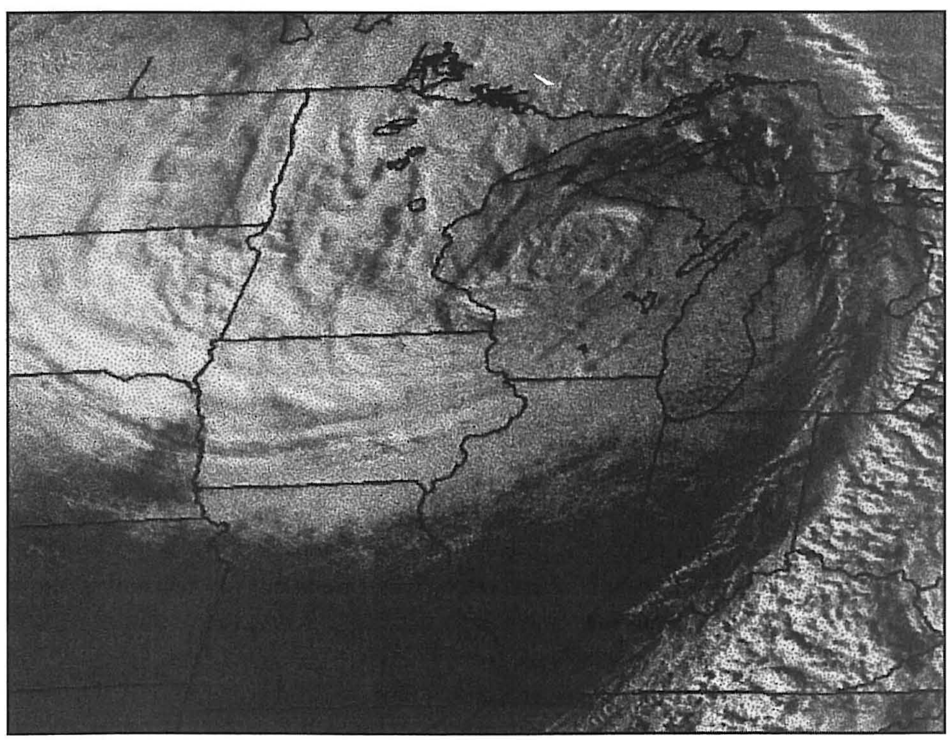

Fig. 7. Mesoscale hook over Wisconsin in GOES-8 multispectral (channels 1, 2, and 4) imagery at 2045 UTC 10 November 1998. Image courtesy of NOAA/NESDIS.

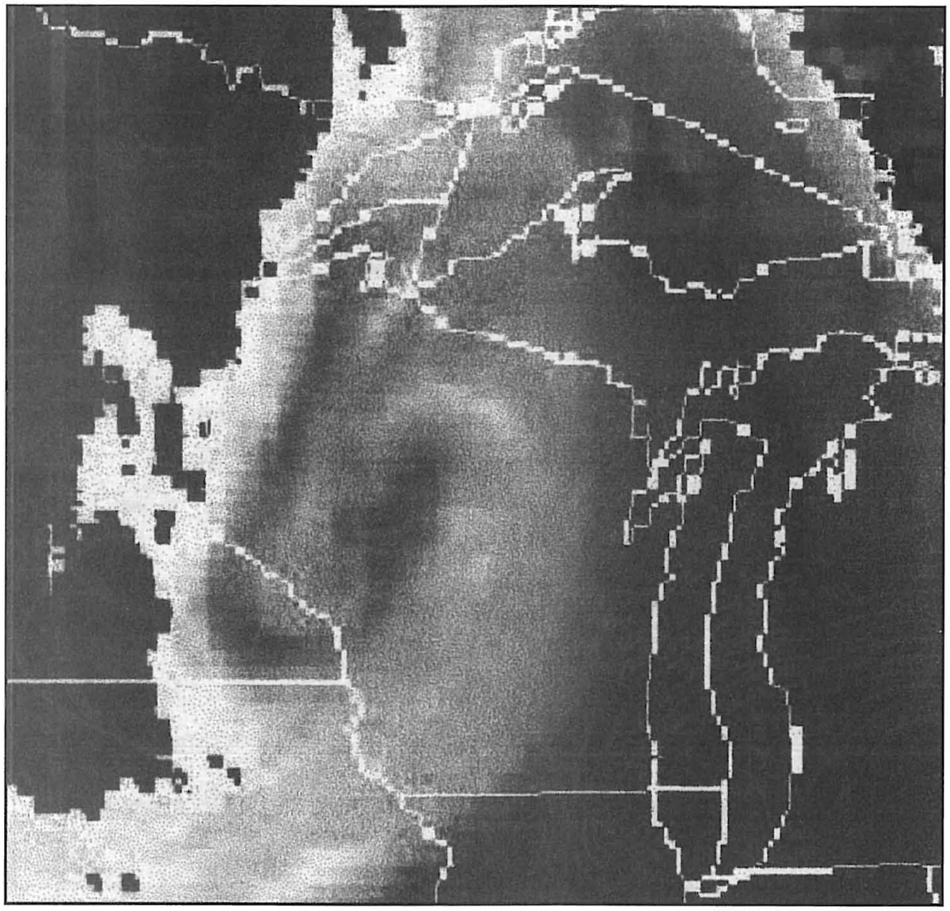

Fig. 8. Close-up of mesoscale dry hook over western Wisconsin and southeastern Minnesota in 8-km water vapor imagery at 2015 UTC 10 November 1998.

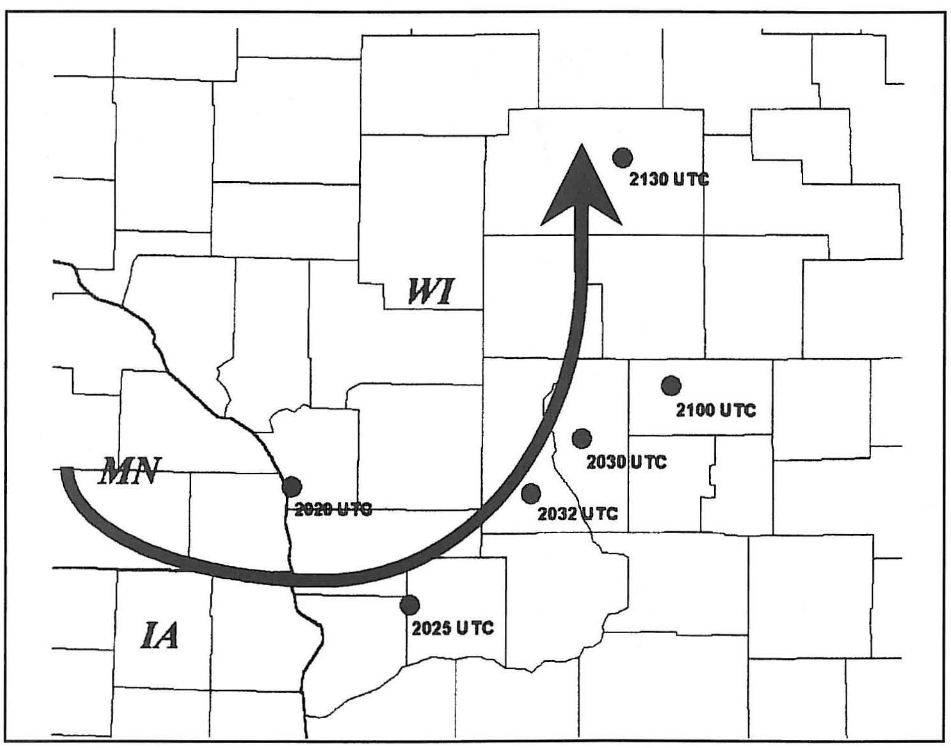

Fig. 9. Reports of non-convective high winds in western and central Wisconsin showing a hook of high winds from 2020 to 2130 UTC. The dark arrow indicates the approximate location and movement of the mesoscale dry hook in water vapor imagery during the same period.

reports. An overlay of 0000 UTC surface isotachs on 2.66 km simulated resolution water vapor imagery at 0015 UTC on the 11th (Fig. 10) once again confirmed that the location of the strongest winds were associated with the southern portion of the mesoscale dry intrusion, now contorted into a V-shape. The extremely close agreement between the surface reports of damaging winds and the satellite signature of the southern fork of the dry intrusion is a major finding of this paper.

b. Discussion

The link between dry intrusions and the forecasting of extreme surface winds has been made previously by Browning and Reynolds (1994). Browning and Reynolds studied a severe wind event in 1991 over the United Kingdom that was linked with a cyclone centered over Scandinavia and correlated hourly wind reports with output from an operational numerical weather prediction model. They inferred that stratospheric air descended to the boundary layer, where shear instabilities transmitted the momentum to the surface. They also stated (p. 254) that the close correspondence between the model potential vorticity features and the wind gusts "suggests a possible method for forecasting damaging surface winds, which might be based on *model* prediction" [emphasis added] with satellite imagery used only for confirmation of the model.

In contrast, the 10 November 1998 wind events occurred near the center of the cyclone; stratospheric air in this case did not descend to the boundary layer under the influence of the jet circulation; and the *satellite*-based methods of identification advocated here appear to permit nowcasting on time and space scales currently unattainable by model-based methods.

The link between mesoscale dry intrusions in satellite imagery and extreme surface winds has been recently discussed by Pedgley (1997). Pedgley studied an intense mesoscale surface jet that tragical-

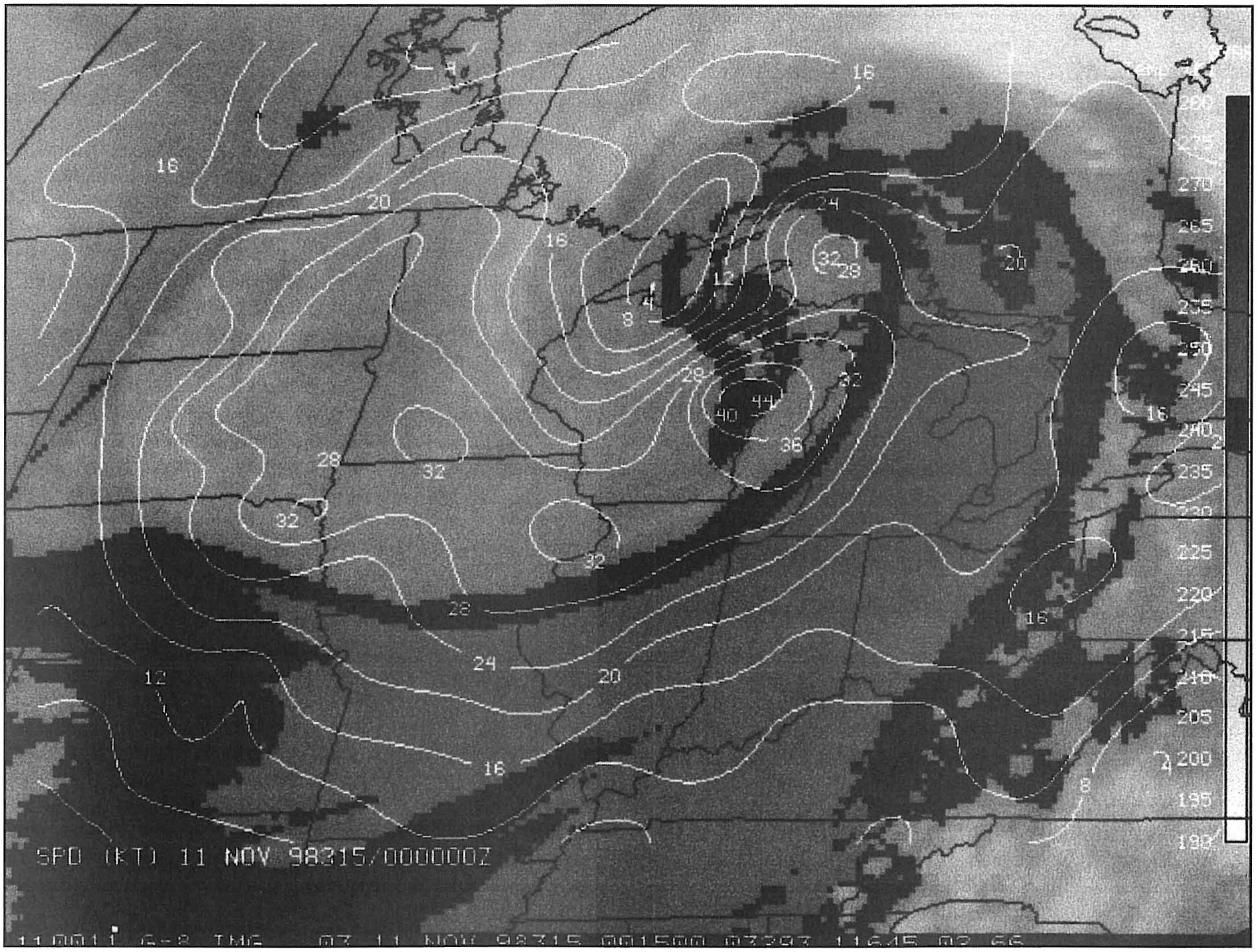

Fig. 10. Overlay of isotachs of highest wind gusts at 0000 UTC on a color-enhanced 2.66 km simulated resolution water vapor image at 0015 UTC on 11 November 1998. The temperature band near 240K in the water vapor imagery has been darkened to highlight the location of the mesoscale dry hook, now in the form of a "V" over eastern Wisconsin.

ly crossed paths with the biannual international Fastnet yacht race in August 1979 while racers were between Scilly, France, and Fastnet Rock, just off the southern coast of Ireland. During the height of the storm, there was an area on the southern side of the depression in which wind exceeded 30 kt over a banana-shaped area.

The 10 November 1998 cyclone exhibited a similar pattern to that of the Fastnet cyclone. A hooked region of highest winds and a mesoscale curl of dry air near the low-pressure center are evident in observations of the Fastnet cyclone (see Fig. 8 in Pedgley 1997). The similarity between the water vapor satellite imagery of these two storms is much closer than the similarity between the 10 November 1998 storm and the Browning and Reynolds case.

It is plausible that stratospheric intrusions far from surface cyclone centers are more likely to reach the lower troposphere or even the surface than those near a cyclone center. Mesoscale sinking motion associated with the jet streak would presumably be opposed by the larger-scale ascent near the cyclone center, as originally depicted in Danielsen (1964). This may explain differences between our case and Browning and Reynolds' example.

Weldon and Holmes (1991) note two different satellite features that are of importance to this study. The first feature is the spiral moisture pattern, which is similar in nature to the mesoscale feature that was observed on 10 November 1998. While this spiral water vapor feature was not necessarily a signature for a deep cyclogenesis, it had also been noted by Weldon and Holmes that stronger cyclones have a much better defined dry intrusion on a southwest-northeast axis. Additionally, spiral moisture features associated with deep cyclones develop much faster than those associated with weaker cyclones.

The second feature noted in Weldon and Holmes was called the "vorticity-eye" feature. These are sub-synoptic or mesoscale in size and are associated with a dark spot on satellite imagery. Vorticity-eye features on satellite imagery are likely attributed to actively

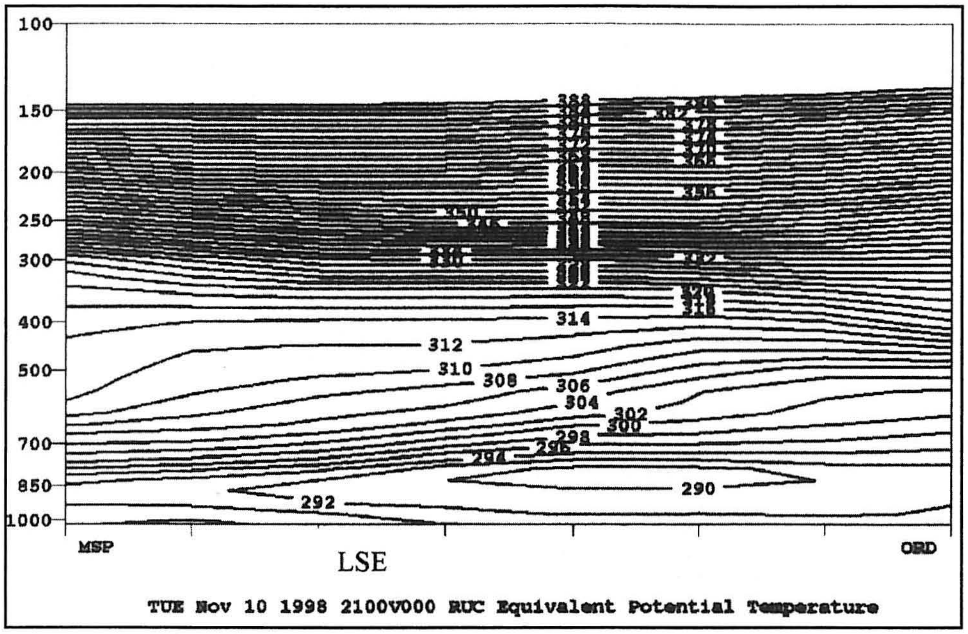

Fig. 11. Cross-section of equivalent potential temperature at 2100 UTC on 10 November 1998 showing a convectively neutral layer from the surface to 750 mb at La Crosse, Wisconsin (just left of center of plot).

sinking upper tropospheric or lower stratospheric air due to their long life of greater than twelve hours, instead of residual dry air, which would be generally be noticeable on satellite imagery for shorter periods of time. The 10 November 1998 cyclone exhibited a combination of Holmes and Weldon's spiral moisture pattern and vorticity-eye feature. Due to the longevity of the feature on 10 November 1998, it is possible that momentum was transported downward through a convectively unstable or neutral layer in the lower troposphere, thereby causing high surface winds in the region of the mesoscale hook. We explore this possibility in the next section.

The comparison of local wind reports and high-resolution imagery indicated that real-time analysis of satellite features could improve the nowcasting of the location and propagation of severe wind events associated with intense cyclones. This improvement could be on an hourly basis as noted by Browning and Reynolds, but also on a time scale of minutes and a space scale comparable to the resolution of water vapor imagery.

6. Possible Mechanisms for Extreme Surface Wind Gusts

Browning and Reynolds (1994, p. 255) claimed that for their 1991 case "vigorous turbulence at the level of the [boundary-layer capping] inversion is thought to have mixed some of this [stratospheric] air into the boundary layer and to have generated strong gusts of wind at the surface." Due to the mid-tropospheric limit on the stratospheric intrusion and the lack of a pronounced inversion in the 10 November 1998 case, another mechanism for the extreme surface wind gusts discussed here must be identified.

One possibility is momentum mixdown due to weak convective stability. A RUC-2 model cross-section of equivalent potential temperature on 10 November 1998 at 2100 UTC from Minneapolis-St. Paul to Chicago-O'Hare (Fig. 11) showed a convectively neutral to convectively unstable layer from 1000 mb to approximately 750 mb ($d\theta_e/dz \cong 0$) in western Wisconsin near La Crosse. Sustained localized descent, along with low-level destabilization from cold advection, could have accounted for the transport of high momentum air toward the surface (Ellrod 1990).

The possible linkage between mesoscale dry hooks and extreme surface winds is more compelling if convection is present on the backside of the cyclone, providing localized regions of downdrafts to transport strong winds to the surface. Exactly 23 years prior to the 10 November 1998 storm, the ore freighter *Edmund Fitzgerald* sank in Lake Superior in high winds and lake-effect snow squalls behind an intense cyclone (Knox and Ackerman 1996, p. 95). Like the *Edmund Fitzgerald*, La Crosse experienced rain and snow when the maximum wind gusts were recorded. This suggests that a combination of water vapor and visible satellite imagery, focused on the detection of stratospheric intrusions combined with localized low-level convection, would be optimal for nowcasting of these extreme wind events.

As a side note, it is possible that the intense winds accompanying the sinking of the *Edmund Fitzgerald* could also be related to mesoscale dry intrusions (Ackerman and Knox 2003); this is the subject of current research.

7. Conclusions

On 10 November 1998, a rapidly deepening cyclone tracked through the upper Midwest region, bringing damaging high surface winds throughout much of the region. The most extreme winds were closely associated with a propagating mesoscale dry hook in water vapor imagery. Satellite imagery resolved the mesoscale hook whereas model analyses, operating on much coarser resolutions, were unable to adequately simulate the feature. This satellite feature has been associated with other damaging windstorms. Operationally, it may be possible to nowcast damaging non-convective winds on the time and space scales of minutes and kilometers by recognizing the importance of this mesoscale feature in satellite imagery.

Sources of Storm Data and Model Information

NOAA Air Resources Laboratory information on the HYSPLIT model
http://www.arl.noaa.gov/ready/hysplit4.html

Background information about the RUC model from the NWS Southern Region Headquarters
http://www.srh.noaa.gov/ftproot/ssd/NWPMODEL/HTML/ruc.htm

COMET Case Study 023: Winter Severe Weather, 08-11 November 1998
http://www.joss.ucar.edu/cgi-bin/codiac/projs?COMET_CASE_023

NOAA/NESDIS/NCDC Storm Event database
http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~storms

Unisys Weather archive of maps and satellite imagery
http://weather.unisys.com/archive/index.html

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John Knox is now an associate research scientist on the Faculty of Engineering at the University of Georgia. He obtained a B.S. in mathematics in 1988 from the University of Alabama at Birmingham and a Ph.D. in atmospheric science in 1996 from the University of Wisconsin-Madison, after which he served as a post-doctoral research fellow at Columbia University and the NASA/Goddard Institute for Space Studies. Following his post-doctoral research, he served as an assistant professor of geography and meteorology at Valparaiso University from 1998 to 2000. His research interests include atmospheric dynamics, aviation hazards, and meteorology education. He is an Associate Editor of the *National Weather Digest*.

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