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An Operational Technique Used to Detect "Mountain Wave Signatures": A Forecast Methodology for Severe Westerly Winds in the Mountains of West Texas

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ABSTRACT

Occurrences of extreme winds in the mountains of west Texas have historically posed significant forecast challenges for the region's operational meteorologists. Public impacts from such events have increased since the 1930s, when surface weather observations began at Pine Springs in the Guadalupe Mountains and with the construction of a world-class astronomical research facility in the Davis Mountains. Guadalupe Mountains National Park, including a portion of U.S. Highway 62/180 through Guadalupe Pass, is notorious for the hurricane force westerly winds that frequently occur there during the cool season. These events threaten the safety of park visitors, motorists and aircraft, and aggravate critical fire weather conditions. Synoptic patterns that favor severe mountain winds in the region have long been recognized, but pattern recognition-based forecasts and warnings have traditionally been short-fused and lack specificity with regard to timing and magnitude of anticipated wind events. Improved resolution and performance of operational weather prediction models during recent years has allowed forecasters to refine mountain wind forecasting methods, and improve upon the generalized predictions of the past. Prognostic model signatures that correspond to severe winds associated with vertically-propagating mountain waves have proven operationally useful in producing detailed and accurate forecasts and warnings for hazardous mountain winds. Incorporating a "mountain wave signature" (MWS) methodology, utilizing North American Mesoscale (NAM) model cross-sections of vertical motion and potential temperature, has allowed for longer range forecasts and warnings that accurately predict the onset of severe mountain winds, their magnitude and duration.

1. Introduction and History

The topography of west Texas is characterized by rugged terrain with two small but dominant mountain chains, the Guadalupes (extending north into southeastern New Mexico) and the Davis Mountains (Fig. 1). Despite the region's arid climate, with peaks up to 2,667 m MSL, these mountains are susceptible to extreme weather conditions. Severe westerly winds, defined by the National Weather Service (NWS) local High Wind Warning criteria as sustained speeds equal to or greater than 18 m s^{-1}, or instantaneous gusts of 26 m s^{-1}, frequently occur in the mountains of west Texas during the winter and spring seasons. Wind gusts typically exceed 45 m s^{-1} along the mountain peaks a few times each year.

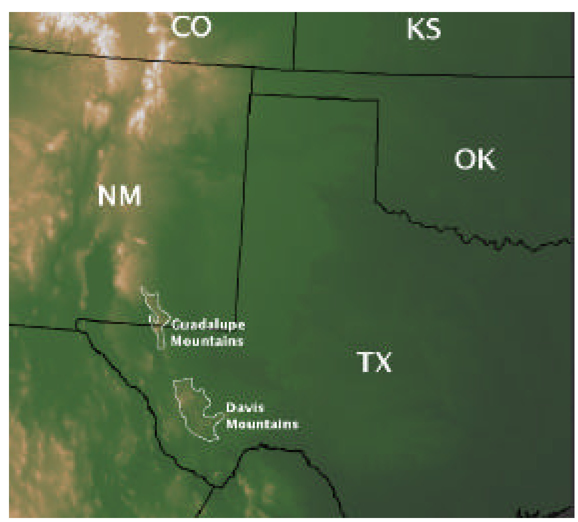

Fig. 1. Map of west Texas and surrounding areas outlining the Guadalupe and Davis Mountain ranges.

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The frequency of severe mountain winds in the region has been understood by operational meteorologists since the 1930s, when the recording of official weather observations began at Pine Springs in the Guadalupe Mountains, and when construction of a world-class astronomical research facility, the McDonald Observatory, began in the Davis Mountains. Since that time, the public impact of such events has increased due to both increased population and the founding of recreational areas such as state and national parks. Guadalupe Mountains National Park, including a stretch of U.S. Highway 62/180 through Guadalupe Pass, is particularly vulnerable to dangerous westerly winds (Cain and Murdoch 1999). High winds are commonplace there during the cool season, and gusts as high as 57 m s^{-1} have been measured near the pass during extreme mountain wind events (NOAA 1996). Such winds have damaged property, threatened the safety of park visitors, motorists, and aircraft, and have directly contributed to at least two fatalities since 1960 (Bomar 1983, and NOAA 2003).

Forecasters in west Texas have long recognized large scale weather patterns that favor severe mountain winds in the region. Typically, westerly high wind events in the Guadalupe and Davis Mountains are associated with increased middle tropospheric height gradients and winds related to the passage of shortwave troughs or middle latitude cyclones (Mead 1997). Using simple recognition of these features in synoptic scale model prognostications, or satellite and upper air analyses, forecasters have traditionally issued short-fused forecasts and warnings prior to occurrences of severe mountain winds. These techniques were most successful in the short-term forecast periods, and contained no specificity with regard to the timing of anticipated severe winds, or their duration and magnitude. Instead, past forecasts typically conveyed general information about the likelihood of severe mountain winds through broad time ranges, usually on the order of 24 to 36 hours, as "favorable" synoptic scale weather features affected the region (Murdoch and Deberry 1999).

Murdoch and Deberry (1999) noted that the newly deployed Advanced Weather Interactive Processing System (AWIPS) provided forecasters the ability to interrogate the atmosphere using "non-conventional methods". They stated that the use of AWIPS may eventually permit the development of better quantified high wind forecasting techniques for the west Texas region.

Although, mountain winds and downslope wind storms in the central Rockies and inner-mountain west of the U.S. are well-documented, studies of the sub-synoptic processes associated with severe mountain winds in the southern Rockies and adjacent ranges are largely absent from literature. With improved performance and increasingly higher resolution of deterministic weather prediction models made available in the operational AWIPS environment during recent years, namely the North American Mesoscale (NAM) model, meteorologists in west Texas have worked to refined forecasting methods for severe mountain winds in the region.

Forecasters at the NWS, Weather Forecast Office in Midland, Texas, have implemented a "mountain wave signature" (MWS) method for detecting patterns in prognostic NAM solutions that correspond to occurrences of mountain wave systems and severe westerly wind events in the west Texas mountains. These patterns, observed in model forecast cross-sections of vertical motion and potential temperature, were identified prior to 34 westerly wind cases studied between 2003 and early 2006. Recognition of the MWS has proven to be a vitally important operational technique utilized to improve the accuracy of temporal and intensity forecasts for hazardous mountain winds in the region, and the method has enhanced forecaster awareness in the High Wind Warning decision-making process.

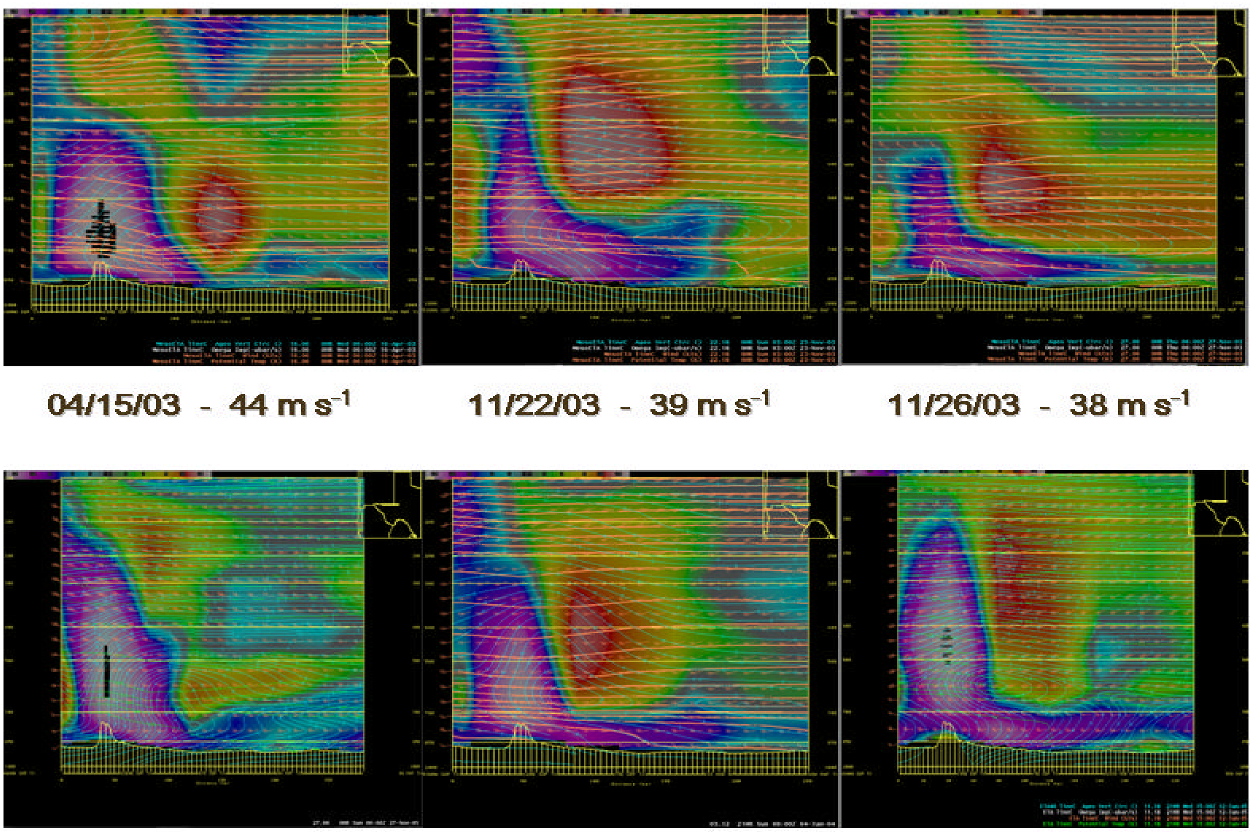
2. Forecasting Methodology

A MWS methodology is used by operational forecasters in west Texas to interrogate the "40NAM" (deterministic NAM solution viewable in AWIPS using a 40 km grid-spacing displayed at three hour forecast intervals) graphical output for conditions conducive to the development of vertically-propagating mountain waves in the vicinity of the Guadalupe and Davis Mountains. Such mountain wave activity occurs as fast statically stable cross-barrier flow over the southern Rockies, including the west Texas mountain ranges, is subject to terrain blockage (Vieira 2004). Numerical modeling of mountain wave systems has suggested that the presence of a critical level, or flow reversal, is a possible sub-mesoscale contributor to severe mountain winds through reflection (Clark and Peltier 1984).

A cross-sectional slice of the atmosphere is used operationally to examine vertical motion and potential temperature along a two-dimensional plane bisecting the Guadalupe and Davis Mountains. The MWS is most pronounced when the deep layer cross-barrier flow is normal to the mountain ridgelines. Therefore, this typically requires the cross-section to be directionally oriented east-to-west when near-zonal flow is expected over the west Texas mountain ranges.

Forecasters have found a repetitive signal in prognostications of these parameters, or MWS, that develops during model-forecast periods when severe westerly mountain winds and perceived mountain wave activity are ultimately observed (Fig. 2). As the model-generated cross-section is examined forward in time through the forecast cycle, the evolution of the signature can be used to predict the approximate time that severe winds will commence, the general timeframe and magnitude of maximum gusts, as well as the approximate duration of an impending wind event.

The operational MWS is characterized by a quasi-symmetrical couplet of upward and downward vertical motions and a separation of the isentropes immediately downstream of the flow-blocking terrain. Both the forecasted horizontal circulation, as represented by the vertical motion couplet, and the terrain's influence on the deep layer flow, evidenced by the isentropic perturbations, frequently extend vertically through the 200 hPa level and a horizontal distance of less than 150 km over the leeward plains. Forecasted subsidence over the mountain peaks can be intense in association with the MWS. Values of model-forecasted omega (vertical motion) up to 50 μb s^{-1} have been observed on the west side of the model-derived circulation. The downstream portion of the circulation is usually depicted with weaker upward vertical motions.



04/15/03 - 44 m s^{-1} **11/22/03 - 39 m s^{-1}** **11/26/03 - 38 m s^{-1}**

11/27/05 - 49 m s^{-1} **01/04/04 - 46 m s^{-1}** **01/12/05 - 45 m s^{-1}**

Fig. 2. 40NAM model-forecasted cross-sections of vertical motion (displayed as an image; cool colors=subsidence warm colors=ascent) and potential temperature (orange contours) bisecting the Guadalupe Mountains. Similar patterns, or MWSs, are evident prior to six severe wind episodes. The event date and the peak intensity of maximum observed winds are included.

Development of the horizontal circulation detected in forecasted vertical motion fields is the most operationally useful aspect of the MWS, and appears to correspond to the eventual onset of severe mountain winds when observed in 40NAM model-forecast cross-sections. The addition of ageostrophic vertical circulation streamlines to model cross-sections aid the forecaster's visualization of the mesoscale circulation. When the model-depicted horizontal circulation is well-developed, a closed "rotor" is present in the ageostrophic vertical circulation streamlines downwind of the flow-obstructing terrain. The streamlines are related to vertical motion (denoted as "ω" in Eq. 1) by the ageostrophic continuity equation,

$$\partial V_{ag}/\partial y + \partial U_{ag}/\partial x = -\partial \omega/\partial z. \qquad (1)$$

A summarization of the MWS methodology employed as an operational technique for forecasting severe mountain winds in west Texas includes the following steps performed in the AWIPS workstation environment: 1) use of the baseline tool feature and the "HiRes Topo Image" map to generate a cross-section bisecting the mountains along the azimuth of greatest cross-barrier flow normal to the ridgeline (i.e. east-to-west for the west Texas mountain ranges in near zonal flow) and extending horizontally at least 200 km; 2) display omega as an image within the cross-section; 3) display potential temperature; 4) load the ageostrophic vertical circulation, and 5) advance through the forecasted time-period to monitor for evidence of a MWS circulation as described. It also is useful to display winds in the cross-section (Fig. 3). This allows forecasters to examine the magnitude and direction of cross-barrier tropospheric flow relative to the topographical ridgeline, and assists in determining the nature of subsequent terrain blockage.

3. Case Studies

This study will briefly review the operational utility of 40NAM-derived vertical motion and potential temperature cross-sections, and the MWS detected within, by correlating the evolution of these signatures to observed wind gusts during two high wind events in the mountains of west Texas. Given the vulnerability of the Guadalupe Mountains to extreme wind events, and the magnitude of observed winds and model-derived MWS noted there, these cases will focus on that particular mountain range. Only the Texas portion of the mountain chain will be discussed per the availibity of observational data. Both of the 40NAM solutions shown here were initialized within 24 hours of each event's respective maximum winds. Similar signatures, however, have been observed to contribute to increased skill in severe mountain wind forecasts up to 60 hours prior to anticipated high wind events.

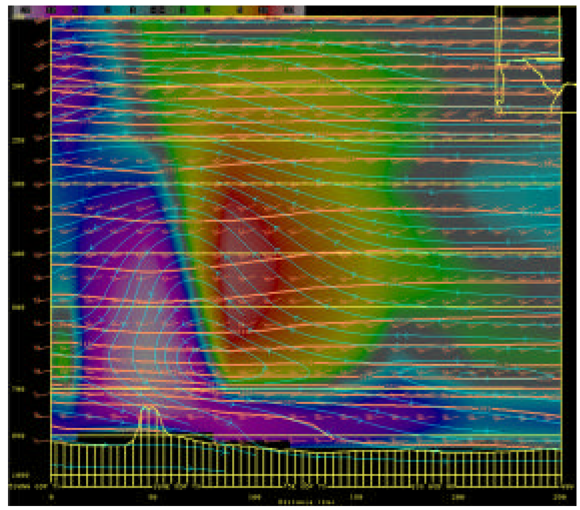


Fig. 3. 40NAM forecast cross-section bisecting the Guadalupe Mountains ridgeline (east-to-west) shows a MWS in model-forecasted omega (image; cool colors=subsidence warm colors=ascent), potential temperature (orange contour), ageostrophic vertical circulation (cyan streamlines), and wind (orange barbs).

a. 6-7 January 2005

A severe mountain wind event occurred in west Texas on 6-7 January 2005. The duration of the event, including the onset of severe winds, the time of maximum winds, and cessation of severe gusts in the Guadalupe Mountains will be examined here (Fig. 4).

The vertical motion and potential temperature cross-section through the Guadalupe Mountains initialized by the 6 January 2005 1800 UTC 40NAM solution depicted no evidence of a MWS, with downward motions of only 4 $\mu\ s^{-1}$ over the mountain peaks (Fig. 5a). At that time, sub-severe wind gusts of 16 m s^{-1} were measured by the Remote Automated Weather Station (RAWS) site located near "The Bowl", located 300 m below the ridgeline on the eastward slope at an elevation of 2364 m MSL. By 7 January 2005

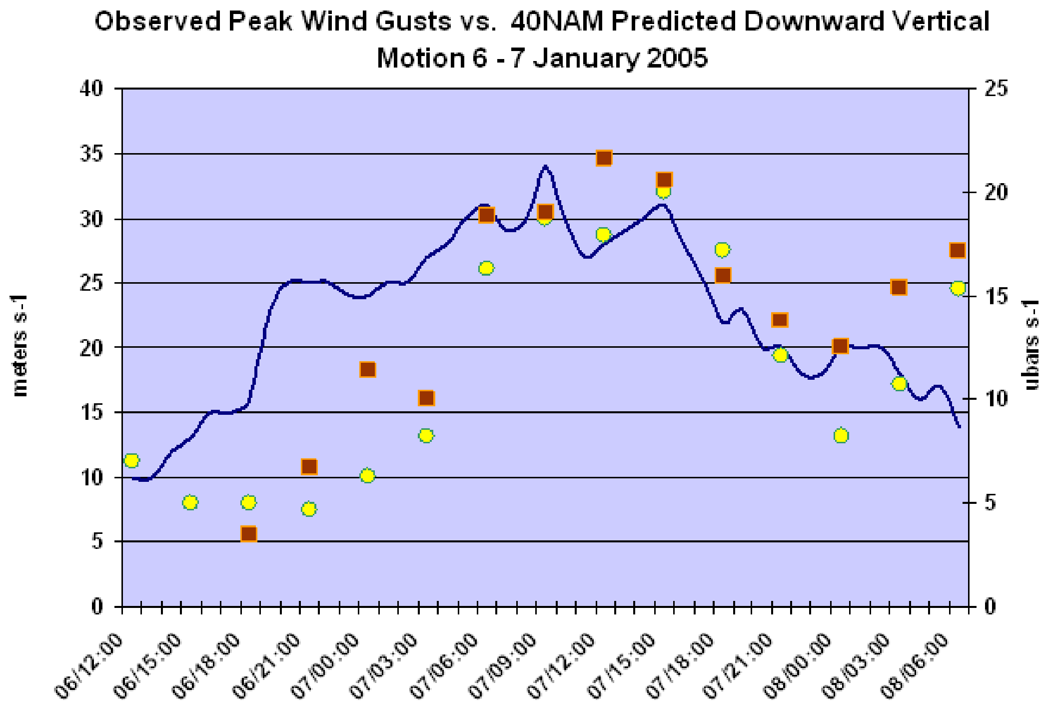


Fig. 4. A plot of observed maximum wind gusts (blue line) in the Guadalupe Mountain versus corresponding values of model forecasted downward vertical motions from the 40NAM runs initialized at 0600 UTC 6 January 2005 (yellow circles) and 1800 UTC 6 January 2005 (red squares).

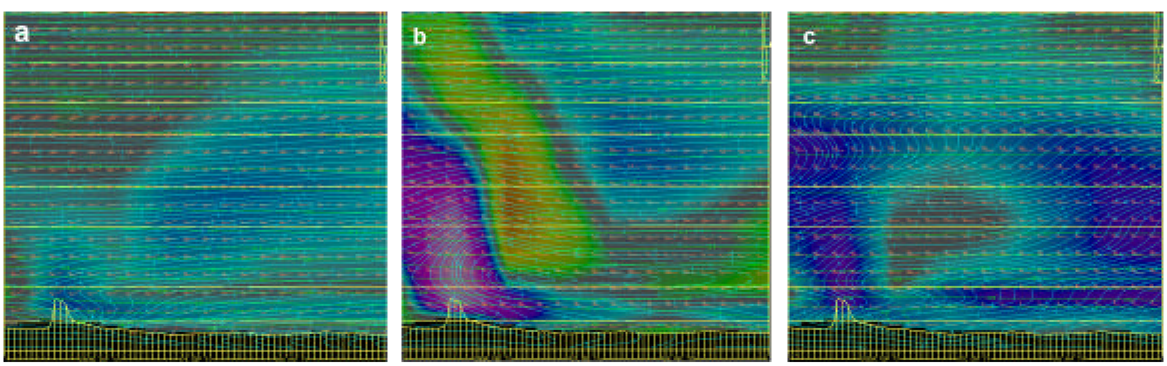


Fig. 5a-c. The evolution of a severe mountain wind event on 6 - 7 January 2005 as depicted in 6 January 1800 UTC 40NAM-forecasted cross-sections of vertical motion (image; cool colors=subsidence warm colors=ascent) and potential temperature. The observed period of maximum winds corresponded to the well-developed MWS seen in Fig. 5b.

1500 UTC, the same 40NAM model run depicted a strong and nearly symmetrical MWS, with a separation of the isentropic surfaces and downward vertical motions of 21 μ s^{-1} (Fig. 5b). This corresponded to peak winds of 31 m s^{-1} at the same observation site. The 40NAM-depicted MWS quickly dissipated by 7 January 2005 2100 UTC, with the horizontal circulation previously seen in the vertical motion field no longer evident, and downward motions of only 13 μ s^{-1} (Fig. 5c). Observed winds reflected the same trend, with sub-severe gusts of 20 m s^{-1}.

b. 26-27 November 2005

A long-lived episode of severe westerly winds resulted in extreme gusts in the Guadalupe

Mountains of west Texas on 26-27 November 2005. The evolution of 40NAM-forecasted vertical motion and potential temperature cross-sections will be examined here along with their correlation to observed wind speeds through the peak of the event (Fig. 6).

The initialization of the 26 November 2005 1800 UTC 40NAM solution depicted a developing MWS, with evidence of sloping insentropes and downward vertical motions of approximately 16 μ s^{-1} over the highest mountain peaks (Fig. 7a). At that time, severe wind gusts of 30 m s^{-1} were ongoing at The Bowl RAWS site. The MWS was depicted to be very intense per the same 40NAM 15-hour forecast at 0900 UTC on 27 November 2005, with a well-developed circulation evidenced by the ageostrophic vertical circulation streamlines and strong downward motions of 45 μ s^{-1} (Fig. 7b) over the mountain ridgelines. The Bowl RAWS site recorded extreme wind gusts of 49 m s^{-1} at 0900 UTC. The MWS weakened by 28 November 2005 0000 UTC, with the horizontal circulation previously depicted in model predicted vertical motion less-defined, and decreased downward motions of 17 μ s^{-1} (Fig. 7c). Observed wind speeds reflected the same pattern, with marginally severe gusts of 27 m s^{-1} observed at that time.

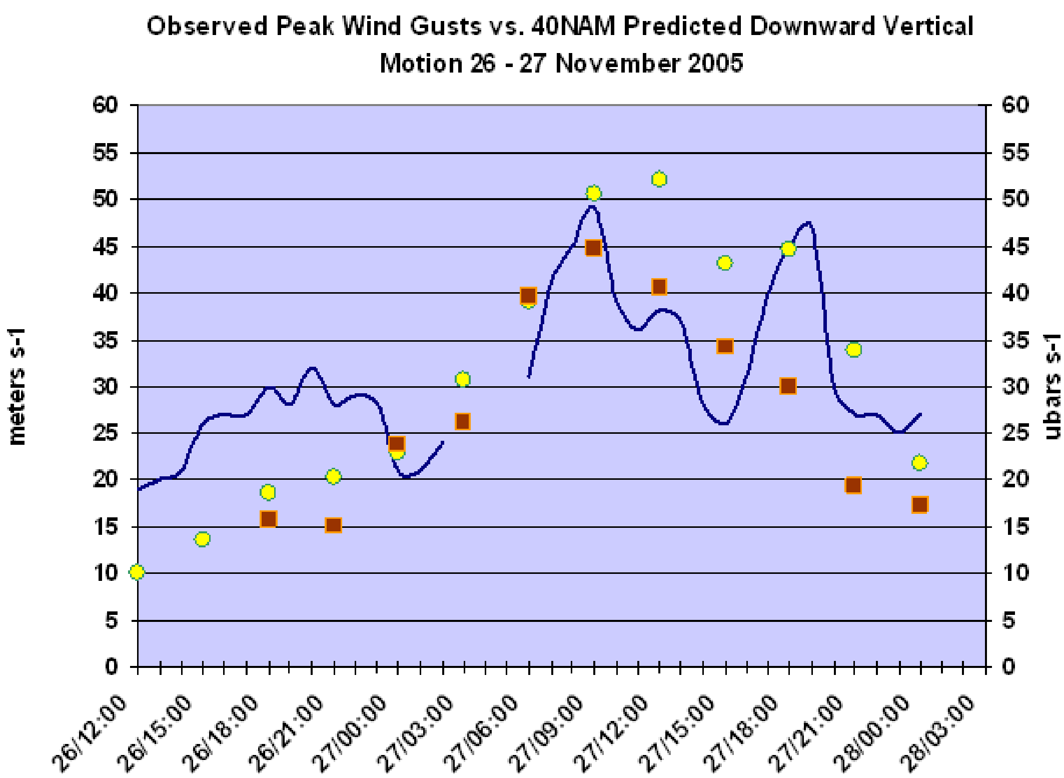


Fig. 6. A plot of observed maximum wind gusts (blue line) in the Guadalupe Mountain versus corresponding values of model forecasted downward vertical motions from the 40NAM runs initialized at 0600 UTC 26 November 2005 (yellow circles) and 1800 UTC 26 November 2005 (red squares). *Note: A communications failure-induced loss of data occurred between 0200 UTC and 0600 UTC on 27 November 2005.*

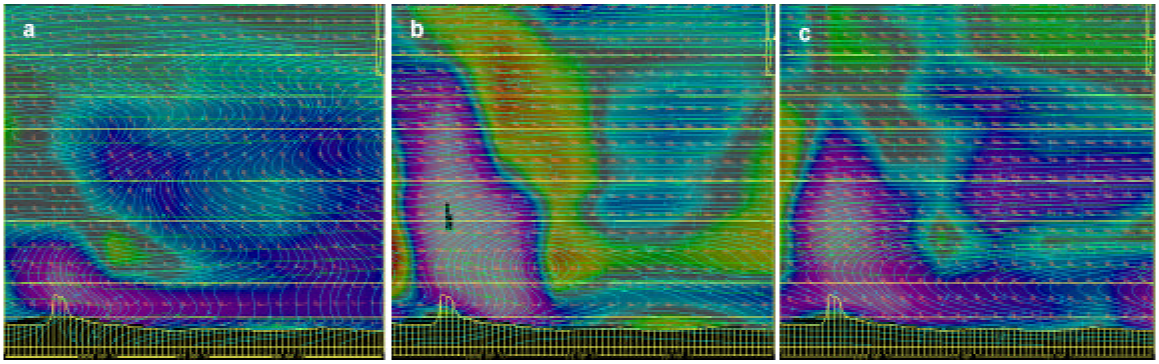


Fig. 7a-c. The evolution of a severe mountain wind event on 26-27 November 2005 as depicted in 26 November 1800 UTC 40NAM-forecasted cross-sections of vertical motion (image; cool colors=subsidence warm colors=ascent) and potential temperature. The observed period of maximum winds corresponded to the intense MWS in Fig. 7b.

4. Relating Mountain Waves to Operational Signatures

Further investigation is required to determine the exact numerical modeling and atmospheric processes that result in the MWS. Its physical relation to mountain waves and severe mountain winds is not well-understood. Although the MWS methodology has proven to be an effective operational technique for forecasting high wind events in the mountains of west Texas, it is not proposed that the signature is in itself a model-derived representation of vertically-propagating mountain waves. It is likely that the MWS is a model artifact resulting from the 40NAM's depiction of large scale circulations within the same terrain-blocked flow that promotes the development of vertically-propagating mountain waves.

The signature used in operational forecasting, however, does display several features common to vertically-propagating mountain wave conceptual models. One such similarity is seen in the conceptual streamlines and their relationship to isentropic surfaces. Air that is forced over terrain barriers in conditions favorable for mountain wave systems, tends to move downward along the lee slopes and then oscillate in a series of waves. In a stable atmosphere, the waves will propagate vertically until breaking at some lower stratospheric height (Durran and Klemp 1983, Whiteman 2000, and NOAA 2004). Since the isentropes approximate streamlines of air flow, subtle but notable evidence of this oscillation and "breaking-wave" pattern can be seen in the 40NAM potential temperature cross-sections in vicinity of suspected vertically-propagating mountain wave activity (Fig. 8).

Another aspect of the MWS that resembles conceptual mountain wave systems is the development of a closed circulation downwind of the blocking terrain seen in ageostrophic vertical circulation streamlines (Fig. 9). Smaller scale lee-side rotors commonly develop in an area of strong low-level turbulence during mountain wave activity (UCAR 2004). These rotors, however, generally have spatial dimensions of 5 to 10 km and are too small to be detected using the currently used operational numerical weather prediction solutions and observations (Doyle and Durran 2002, Grubisic and Kuettner 2003). Since ageostrophic streamlines are used operationally to best visualize vertical motion, the sense of rotation associated with the larger scale model-depicted circulation is opposite that of the smaller physical mountain wave rotors.

Lastly, the ascending portion of the 40NAM-depicted circulation is frequently displaced slightly in height relative to the level of maximum subsidence, so that the circulation's axis of zero vertical motion, or horizontal flow, tilts upwind with increasing height (Fig. 10). This corresponds to the vertically-propagating mountain wave conceptual models that show an oscillating and breaking wave structure that tilts upwind with increasing height (American Meteorological Society 2000 and NOAA 2000).

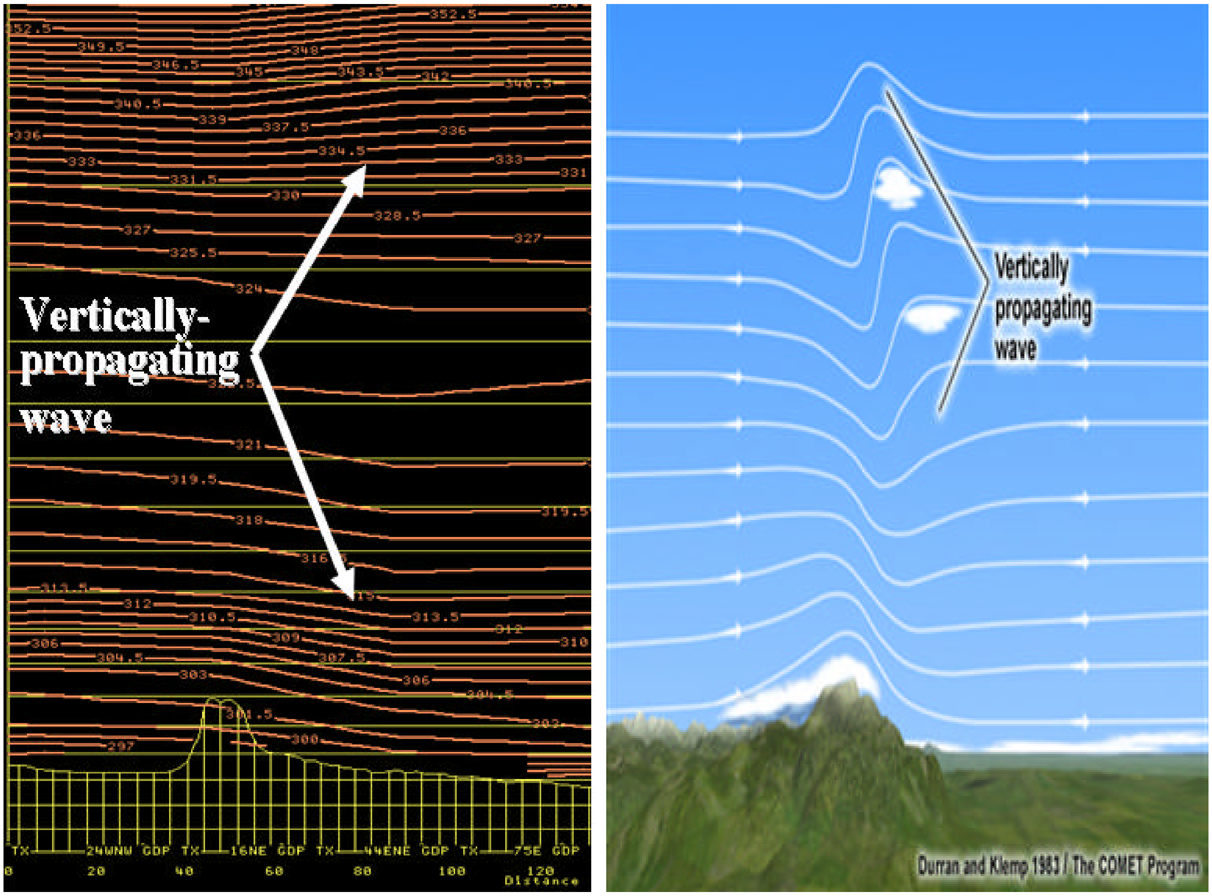


Fig. 8. An example of isentropic perturbations depicted in 40NAM cross-sections (left) associated with perceived mountain waves activity compared to the conceptual model of streamlines for vertically-propagating mountain waves (right) (Durran and Klemp 1983 and NOAA 2000).

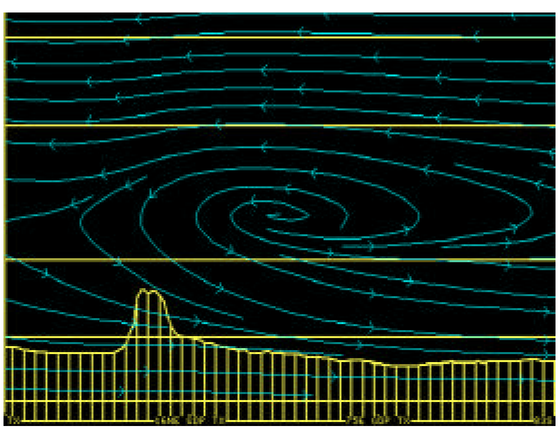


Fig. 9. A closed circulation seen in ageostrophic vertical circulation streamlines downwind of an obstructing mountain as depicted in 40NAM cross-sections during mountain wave activity.

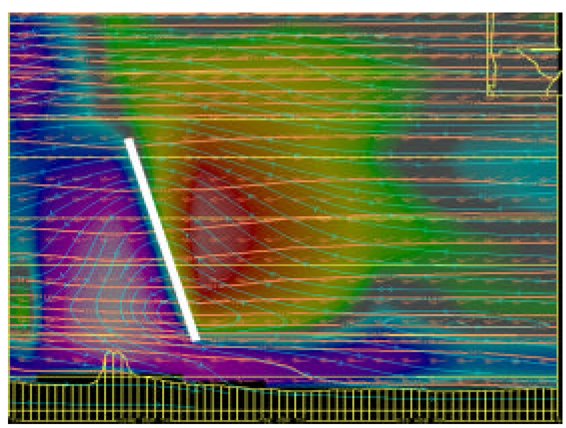


Fig. 10. The MWS depicted in 40NAM cross-sections displays an upwind tilt with height.

5. Conclusion

The use of a MWS methodology has allowed meteorologists to provide more accurate operational forecasts and warnings for severe westerly winds in the mountains of west Texas. This methodology is based on the recognition of several characteristics common to conceptual models of vertically-propagating mountain waves in 40NAM model-derived cross-sections of vertical motion and potential temperature. The MWS was observed in deterministic model-forecasts prior to 34 studied cases of severe westerly winds in the Guadalupe and Davis Mountains, and has proven to be a vital operational tool enhancing High Wind Warning decisions.

The evolution of model-forecasted horizontal circulations in vertical motion fields, and divergence of isentropic surfaces over the leeward slopes, has been observed to correspond temporally with episodes of severe mountain winds. The definition and symmetry of this MWS, and values of forecasted downward vertical motions over ridgelines, enhance the predictability of maximum winds. No statistical analysis is presented, however, the cases shown suggest that model-forecasted omega between 15 and 20 $\mu\ s^{-1}$ may be used to approximate the onset of severe gusts (27 $m\ s^{-1}$), while values that exceed 40 $\mu\ s^{-1}$ have been observed to correlate with extreme winds of at least 45 $m\ s^{-1}$.

In the summer of 2006, the NAM model was replaced in the operational environment with the Weather Research and Forecasting–Nonhydrostatic Mesoscale Model (WRF-NMM) (NOAA 2006). The WRF-NMM provides higher resolution model depiction of both atmospheric and terrain features. Jascourt (personal communication on 19 March 2004) noted that the WRF-NMM has demonstrated increased skill in depicting MWSs over the Appalachian Mountains. Future case documentation using the WRF-NMM will begin during the 2006/07 cool season in west Texas, and additional research correlating the operational signature to actual mountain wave systems is needed.

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REFERENCES

American Meteorological Society, 2000: *Glossary of Meteorology.* 2nd Edition.
Bomar, W, G., 1983: *Texas Weather.* University of Texas Press, 189 pp.
Cain, D., G. Murdoch, 1999: The geography/topography of WFO Midland's county warning area and its influence on weather and climate. Local study, National Weather Service Forecast Office, Midland, Texas.
Clark, T. L., and W.R. Peltier, 1984: Critical level reflection and the resonant growth of nonlinear mountain waves. *J. Atmos. Sci*., **41**, 3122-3134.
Doyle J. D., D. R. Durran, 2003: The dynamics of mountain wave induced rotors. J. Atmos. Sci., **59**, 186-201.
Durran R. D., J. B. Klemp, 1983: A compressible model for the solution of moist mountain waves. *Mon. Wea. Rev*., Vol. 111, No. 12, pp. 2341-2361.
Grubisic V., J. P. Kuettner, 2003: Terrain-induced rotor experiment (T-REX). *AMS 10th Conf. on Mesoscale Processes* 11.3. Portland, OR, Amer. Meteor. Soc., Available on conference CD.
Mead, M., G. Murdoch, T. J. Turnage, 1997: A severe weather climatology for the NWSO Midland, Texas county warning area. NOAA Technical Memorandum, NWS SR-191.
Murdoch, G., J. DeBerry, 1999: Aspects of significant west wind events across west Texas and southeast New Mexico. Local study, National Weather Service Forecast Office, Midland, Texas.
NOAA, 1996: Storm data. January, Vol 38, No. 1, National Climatic Data Center, Ashville, NC.
___, 2003: Storm data. February, Vol 45, No. 2, National Climatic Data Center, Ashville, NC.
___, 2004: Mountain waves and downslope winds. COMET module, University Corporation of Atmospheric Research, National Center for Atmospheric research, Boulder, CO.
___, 2006: Technical implementation notice 05-68. National Weather Service Headquarters, [Available online: http://www.weather.gov/os/notification/tin05-68aab_eta_replacement.txt]
Vieira, A., 2004: Mountain wave activity over the southern Rockies. Local study, National Weather Service, Center Weather Service Unit, Albuquerque, New Mexico.
Whiteman, D. C., 2000: *Mountain Meteorology: Fundamentals and Applications*. Oxford University Press.