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THE ROCKY MOUNTAIN FRONT WIND STORM OF JANUARY 4, 2001: A CASE STUDY

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Introduction

Wind events of 25 ms^{-1} or greater are common along the Rocky Mountain Front of Montana, occurring several times a year, most frequently during the winter months (December through February). For the winter of 2000-2001, winds of greater than 25 ms^{-1} occurred on 7 days at Cut Bank, Montana (Fig. 1). These events are usually well forecast using a variety of tools: current National Centers for Environmental Prediction (NCEP) model output, local rules of thumb, and other diagnostic procedures developed locally and based on model output or observations.

The most notable wind event of the 2000-2001 winter took place on the morning of 4 January, when winds greater than 50 ms^{-1} occurred in the town of Choteau and the surrounding area. Wind events of this magnitude are infrequent, occurring roughly once every 5 years. Like most rare meteorological occurrences, these dangerous wind events (DWE) of 50 ms^{-1} or greater are seldom forecasted. Because they occur on a much smaller scale than high wind events with speeds of 20 to 30 ms^{-1}, current NCEP models do not predict these occurrences. Additionally, because the events are so rare, local rules of thumb have not been adequately developed to anticipate these situations.

One of the local tools used to aid in forecasting wind speed is the regression equation based on previous wind events developed by a former lead forecaster. The surface pressure pattern and the 700 mb geostrophic wind at various locations and times are used as predictands (Oard, 1993). This equation does a good job of forecasting synoptic scale wind events. However, even the author acknowledges that this tool will not forecast the most extreme wind events, especially under the synoptic conditions observed in this case. For the 4 January case, and in past occurrences where winds greater than 50 ms^{-1} were reported, the peak surface wind observed was greater than any wind forecast by the numerical models at 700 mb (or higher), by a factor of 2 or 3. In these cases, any method that attempts to predict the surface wind based on the winds aloft will fail. The purpose of this study is to develop a procedure where a DWE can be anticipated. Most high wind events generally only prove to be a nuisance to travelers, and usually cause little damage, while DWEs almost always cause some damage and make travel dangerous for high profile vehicles. For this case, total damage along the Rocky Mountain Front (RMF) was estimated to be $100,000. So for the purpose of fulfilling the National Weather Service mission of "the protection of life and property," more attention should be given to forecasting these occurrences. In this study, model output from the Eta, Aviation (AVN), and Rapid Update Cycle (RUC) models was examined to determine if the damaging winds could have been anticipated. Models with better resolution could also be used, but the purpose of this study is to help forecast these events better, with as much lead time as possible. Since these three models are currently readily available to forecasters, they were exclusively utilized for this study.

The Forecast

Due to the frequency of strong downslope winds in the Great Falls forecast area, methods of predicting these winds is well known to local forecasters. The terrain along the RMF descends towards the northeast, so the most favorable direction for a downslope wind is from the southwest. A synoptic pattern that produces such winds includes a strong pressure gradient oriented towards the northeast, a strong 700 mb flow from the southwest or west, and a vigorous short wave at mid-levels that passes over the RMF or southern Alberta.

The synoptic pattern of January 3-4 was that of a typical high wind event with a long wave upper ridge over the Western U.S. The axis of the ridge at 500 mb propagates east through the RMF about 9 hours ahead of the damaging winds, as a weak, but fast moving shortwave flattens the ridge (Fig. 1). The bulk of the shortwave energy stayed in southern Alberta, however, even as far south as Great Falls, the wave had the effect of backing 700 mb winds from northwest (315°) to west (260°). This is important because the Continental Divide runs along a 340-160 axis, nearly perpendicular to the 700 mb wind that developed with the shortwave. At 700 mb, the wind was forecast by the models to be 25 to 30 ms^{-1} between 0000 UTC and 1200 UTC over the RMF (Fig. 2). At the surface, a cold pool of air was entrenched west of the Continental Divide, creating an area of high pressure. East of the Divide, pressures were much lower, creating a pressure gradient favorable for southwest winds. However, the pressure gradient was not forecast to be strong enough to generate high winds by itself. Forecasters also look at the isallobaric gradient in potential high wind cases. Only very small pressure falls (< 0.6 mb hr^{-1}) were forecast along the RMF, with pressure rises forecast after 0900 UTC (Figure 3). Pressure falls were also forecast west of the Continental Divide, so the pressure gradient was not expected to increase much during the time where high winds were expected.

The basic synoptic ingredients discussed previously for strong surface winds along the Rocky Mountain Front were well forecasted by the operational models. Strong winds were expected, but whether high wind warning criteria would be met was in doubt. This was primarily due to two factors: (1) the short wave was not very strong, and (2) the peak winds would occur at night, so solar heating would not aid vertical mixing.

There were some reservations about issuing a high wind warning, but one was issued at

2230 UTC (3:30 pm LT), calling for winds to barely exceed the 58 mph (25 ms^{-1}) needed to verify the warning (Fig. 4). High winds did not begin until 0400 UTC over the RMF, quite a bit later than was expected based on the forecast pressure changes. The peak of the event was at 10 UTC, and it was over by 1400 UTC. Time series of data from Browning and Cut Bank are provided (see Table 1 and Fig. 4). These are the only locations along the RMF where time series were available. The peak wind at these locations met high wind criteria for at least 6 hours in a row. However, the speeds were significantly less than the 52 ms^{-1} that was recorded at the Choteau Airport between 0930 and 1000 UTC. Some damage occurred to the hangar and power lines were blown down in Choteau and Valier.

The most unusual aspect of this case was that the surface winds were much stronger than the winds aloft up to 500 mb. While it is not noteworthy for downslope surface winds to exceed winds aloft, the magnitude to which they were exceeded in this case is rarely observed. Additionally, there was very little cold air advection associated with this system. So, the only synoptic scale feature to develop mixing was the weak mid-level short wave trough. Given the sparsity of strong wind reports, one would expect mesoscale and even microscale mechanisms to be at work here.

Mountain Wave Theory

The surface wind observed at Choteau was over twice that of the 700 mb wind. Given that the event occurred overnight, and only a weak short wave was in place, the winds at Cut Bank and Browning were also unusually high. An acceleration of this magnitude could not have been caused by downslope/compressional warming alone. Additionally, the variability of wind speeds across the area suggests that a more complex process, involving mountain waves, occurred during this event.

Mountain waves are a well studied phenomena that occur when a strong cross-barrier flow develops. Cases of mountain waves have been documented in northern Arizona (Tesar and Keighton, 1997) and downwind of the Wasatch range in Utah (Dunn, 1999). The most studied mountain wave cases have occurred along the Front Range of the Rockies in Colorado (e.g. Clark and Hall, 1994, and Jones et al, 2000). Many times when a sufficient west to southwest flow is observed in Montana, these waves are evident in the modeled potential temperature cross-section east of the Rocky Mountains. Extreme wind speeds in the lee of a mountain range have been theorized to be the result of vertically propagating gravity waves (Durran, 1986). These waves are reflected back towards the surface from a "critical level", generating a speed in excess of that found anywhere upstream of the mountain. The generation of mountain waves requires a strong cross-barrier flow and a critical level just above the height of the barrier. The critical level can be formed by a layer of stable air topped by a layer of less stable air, typically separated by an inversion. The critical level can also be defined by reverse or weak forward shear in the cross barrier component of the wind. A combination of both is ideal. In examining model output for this case, there is evidence that both of these aspects existed to some degree.

Stability

The peaks of the Continental Divide average anywhere from 8,000 to 10,000 feet above mean sea level, or about 750 to 700 mb in the standard atmosphere. So between 600 and 700 mb would be an appropriate height for a critical level to have an impact on the flow over the Northern Rockies. The nearest upper air site upstream of the RMF is at Spokane, Washington. The 1200 UTC 4 January sounding from Spokane indicates an inversion at 650 mb, however this is too late to have impacted mountain wave formation near the RMF (Figure 6). The 0000 UTC 4 January sounding shows no such inversion, or even an increase in stability above mountain-top level. It is possible that this inversion formed shortly after 0000 UTC, which would have impacted mountain wave formation, but it is impossible to tell from the two soundings.

One can look at model output to get an indication of when the inversion formed. For this study, Kalispell, Montana, was chosen as a representative location of the upstream characteristics of the flow. Kalispell is about 40 miles upstream of the Continental Divide (Fig. 1). Model soundings from Kalispell (Fig. 7) show a descending inversion towards the end of the period of high winds. At 18 UTC, this inversion has moved below 700 mb, where it has no influence on the cross mountain flow. To better illustrate the vertical changes in stability, a profile of the Brunt Vaisala frequency is shown for the same times (Fig. 8). Brunt Vaisala frequency, N, is defined as

$$N = \sqrt{\frac{g}{\theta}\frac{d\theta}{dz}}$$

where g is the gravitational force, q is potential temperature, and z is height.

A parcel displaced vertically will have an oscillation period of 2p/N (Holton), so increasing values of N correlate to increasing stability. The maximum in stability below 700 mb is indicative of the cold air mass near the surface. The feature of importance is the sharp stability gradient at 500 to 600 mb at 1200 UTC. By 1800 UTC the gradient has decreased to what it was at 0600 UTC, but there is still a decrease in stability with height above the mountain top. The decreasing stability above 700 mb for the duration of the high wind event is consistent with mountain wave formation. With a 700 mb flow of 20 to 30 ms^{-1}, it would take approximately 2 hours for a parcel over Kalispell to make it to the RMF. So the peak of the stability gradient occurs a little later than the strong winds, although a gradient does exist throughout the event.

Cross-Barrier Shear

The shear in the cross-barrier component of the wind is easy to analyze. An assumption is made here that a 250° wind is perpendicular to the Continental Divide. This was determined by making a linear fit of the Divide from just west of Helena to the Canadian border. For the northern extremes of the RMF, a 230° to 240° wind would be perpendicular to the Divide itself. However, the ridges of the Rocky Mountains in this area still yield a perpendicular wind from 250°.

The Eta model was once again used to determine if any reverse shear existed above 700 mb. Figure 9 shows the cross-mountain component of the wind 20 miles upstream of the Continental Divide. At 0600 UTC, there is some reverse shear that appears over the RMF. The magnitude of the reverse shear is very weak, but even weak forward shear has been observed in mountain wave cases, so this may be enough to aid in generating a mountain wave. The RUC 6-hour forecast for 0600 UTC shows more pronounced reverse shear. By 1200 UTC, the reverse shear disappears, although there is still weak forward shear. The timing of this aspect is a little early in the high wind event, complementary to the timing of the stability gradient.

Model Discussion

For this case, the Eta revealed the critical level factors more than AVN. This is somewhat surprising due to the inherent problems with the Eta coordinate near unusual terrain. The RUC did about as well as the Eta. The main weakness of the Eta in this case was failing to identify the layer of reverse shear until the 0000 UTC 4 January run, after the high wind warning issued. The stability gradient was well forecast with sufficient lead time to allow a warning to be posted at least 12 hours before the event.

The synoptic features were also well forecast by both models. The short wave that moved across southern Alberta was slightly stronger than forecast. The sea level pressure pattern was well forecast on the synoptic scale. There were significant pressure falls (>1 mb hr^{-1}) along the RMF when the wave-generated winds occurred, due to compressional warming that could not be forecast by the models.

Summary

The combination of reverse shear and decreasing stability above mountain top level has been shown to exist in previous mountain wave cases. These factors were evident in the model output forecast for this case. Forecasters should examine the vertical profile of the cross-barrier wind component and stability in potential high wind cases to determine if damaging winds are possible. Because only one case is being investigated here, one should be cautious about drawing any concrete solutions about the mechanism involved in generating the unusually strong winds from a synoptic pattern that is not uncommon. It is reassuring to see the same mechanisms in the model output that have been found during high wind events at other locations. A deterrent to making a forecast based on recognition of the factors is that some of these events may be missed due to the sparse population along the RMF. Mountain waves are a small-scale phenomena, and with only a few reliable observation sites in this area, it is possible that mountain waves occur without being reported. A dense observation network could capture more of these events, and give forecasters more confidence as to whether mountain wave events are occurring.

References

Clark, T. L. and W. D. Hall, 1994: Two- and Three-Dimensional Simulations of the 9 January 1989 Severe Boulder Windstorm: Comparison with Observations. Journal of the Atmospheric Sciences, 51, 2317-2343.

Dunn, L. 1999: Downslope Windstorm Case Study, Wasatch Front 4/23/99. Western Region Technical Attachment No. 99-9.

Durran, D. R., 1986: Mountain Waves. Mesoscale Meteorology and Forecasting. Amer. Met. Soc. 472-492.

Holton, J. R., 1992: An Introduction to Dynamic Meteorology, Academic Press, Inc., San Diego. pp. 54-55.

Jones, C. N., Colton, J. D., McAnelly, R., and M. P. Meyers, 2000: A Mountain Wave Event West of the Colorado Park Range. Preprints, Ninth Conference on Mountain Meteorology, Orlando, FL, Amer. Met. Soc.

Oard, M. J., 1993: A Method for Predicting Chinook Winds East of the Montana Rockies. Weather and Forecasting, 8, 166-180.

Tesar, B. E., and S. Keighton, 1997: A Localized Downslope Windstorm in Northern Arizona. Western Region Technical Attachment No. 97-19.

Figure 1. Area of interest for this study. Browning, Cur Bank, Valier, and Choteau lie on the Rocky Mountain Front. The Continental Divide is shown by the line just to the west of these towns.

Figure 2. 500 mb height (m) and absolute vorticity (shaded, 10^{-5} s^{-1}) on 4 Jan at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC, (d) 1800 UTC. Output is from the Eta model run of 1200 UTC 3 Jan.

Figure 3. 700 mb height (m) and wind speed (shaded, ms^{-1}) on 4 Jan at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC, (d) 1800 UTC. Output is from the Eta model run of 1200 UTC 3 Jan.

Figure 4. Mean sea level pressure (mb) and average pressure change (dashed, mb hr^{-1}) over the past 6 hours on 4 Jan at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC, (d) 1800 UTC. Output is from the Eta model run of 1200 UTC 3 Jan.

Figure 5. High wind warning issued by NWSFO Great Falls, Montana.

Figure 6. Skew T plot of soundings from Spokane, Washington on 4 Jan at (a) 0000 UTC, (b) 1200 UTC.

Figure 7. Skew T plot of model soundings from Kalispell, Montana on 4 Jan at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC, (d) 1800 UTC. Vertical axis is pressure (mb), horizontal axis is temperature (°C). Output is from the Eta model run of 1200 UTC 3 Jan.

Figure 8. Vertical profile of Brunt Vaisala frequency (10^{-2} s^{-1}) on 4 January at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC, (d) 1800 UTC. Height is pressure (mb). Output is from the Eta model run of 1200 UTC 3 Jan.

Figure 9. Cross section of wind component normal to the Continental Divide (ms^{-1}) on 4 Jan at (a) 0000 UTC, (b) 0600 UTC, (c) 1200 UTC, (d) 1800 UTC. Height is pressure (mb). Output is from the Eta model run of 0000 UTC 4 Jan.