Abstract

During the overnight hours of 22-23 April 1999 (23 April case) a damaging downslope windstorm occurred west of the Park Range (3000-3700 m MSL) in northern Colorado. Although downslope windstorms are known to be common in the eastern foothills of the Colorado Rockies, only recently has this phenomenon been documented on the West Slope of the northern Colorado mountains. The strong east winds toppled numerous pine trees and damaged at least six homes in the vicinity of Steamboat Springs (SBS; 2100 m MSL). The lower and middle tropospheric wind flow during the windstorm was atypically east-to-west, similar to the 25 October 1997 Routt National Forest blowdown. The NWS National Centers for Environmental Prediction (NCEP) guidance predicted strong synoptic winds over northern Colorado, but did not indicate a downslope windstorm. To supplement the NCEP guidance, an operational version of the Regional Atmospheric Modeling System (RAMS) was employed to explore the mesoscale processes of the downslope windstorm. Forecasts of cross-barrier sea-level pressure gradient and near-surface winds nearly equaled the observed values of these parameters. Cross-sections of wind and potential temperature indicated strong cross-barrier easterly flow and a mountain wave pattern. The potential temperature pattern also depicted a favorable stability profile, with a layer of instability in the middle troposphere overlaying a stable crest-level layer. Comparisons to the 25 October 1997 forest blowdown were conducted in order to find common characteristics of this rare phenomenon. In both cases, strong cross-barrier easterly winds, favorable stability profile, and a critical level had occurred. The 25 October 1997 event had stronger cross-barrier flow, and much colder temperatures than the 23 April case. A strong cross-barrier pressure gradient was observed in the 23 April case but not the 25 October 1997 event.

1. Introduction

During the overnight hours of 22-23 April 1999 wind gusts to 40 m s⁻¹ occurred west of the Park Range (3000-3700 m MSL) in north central Colorado (Fig. 1) topping numerous pine trees and damaging at least six homes in the vicinity of Steamboat Springs (SBS; 2100 m MSL; Fig. 2). The lower and middle tropospheric wind flow during the windstorm was atypically east-to-west. This event showed similarities to the 25 October 1997 Routt National Forest blowdown event where 13,000 acres of old growth forest were devastated by wind gusts in excess of 50 m s⁻¹. Meyers et al. (2002) detailed the nature and possible mechanisms responsible for this destructive storm. The research presented here will detail the synoptic and mesoscale environment of the 22-23 April 1999 windstorm through analyses of various NWS National Centers for Environmental Prediction (NCEP) models, Regional Atmospheric Modeling System (RAMS) forecasts, and observed conditions. Comparisons will be made to the 25 October 1997 Routt National Forest devastation and post-storm research in an attempt to aid operational meteorologists in forecasting these rare events.

2. Background

Although the effects of mountain waves are commonly observed east of mountain barriers, such as the Colorado Front Range, due to the prevailing westerly flow at mid-latitudes, for the same reason mountain windstorms are observed far less frequently west of mountain barriers (e.g., Santa Ana (Svejkovsky 1985) and Croatian Bora (Smith 1987)). In fact, the bulk of the theoretical and observational research pertaining to mountain wave formation has focused on westerly lower and middle tropospheric wind flow. Lilly and Zipser (1972) conducted a thorough survey of a mountain wave event near Boulder, Colorado on 11 January 1972, which has been the focus of several subsequent studies and model comparisons (e.g., Klemp and Lilly 1975; Clark and Peltier 1977; Peltier and Clark 1979; Clark and Farley 1984; Durran and Klemp 1987; Doyle et al. 2000). Other research studies have also examined other Colorado Front Range windstorms (Lee et al. 1989; Brown et al. 1992; Cotton et al. 1995). More recently, Meyers et al. (2002) described a high wind event resulting from easterly winds traversing the Continental Divide. Colle and Mass (1998) investigated 55 western Washington windstorms and describe several common characteristics found in these and other studies on downslope windstorms:

1) Strong cross barrier flow with weak vertical shear above it, where the upper-tropospheric winds are not excessively strong.
2) Magnitude of cross-barrier sea-level pressure gradient.
development of larger amplitude mountain waves creating an environment where breaking waves (Clark and Peltier 1977) are more likely.

3. Observations and Storm Overview

During the overnight hours of 22-23 April 1999 devastating winds affected Steamboat Springs (SBS) and vicinity damaging trees and personal property. This storm also produced up to 1.0 m of snowfall along the Front Range of Colorado east of SBS. The predominate wind direction in the lower and middle troposphere was from the east. Although damage was not as extensive, this event showed similarities to the 25 October 1997 Routt National Forest blowdown event (Meyers et al. 2002) where 13,000 acres of old growth forest were devastated by wind gusts in excess of 50 m s\(^{-1}\). In both cases, a devastating snowstorm occurred on the Front Range of Colorado. In the 1997 storm up to 1.5 m of snowfall accumulated along the Front Range of Colorado (Poulos et al. 2002).

a. Local observations

Reports of downed trees and power lines in the vicinity of SBS were received from the Colorado State Patrol around 0900 UTC 23 April 1999. Wind gusts were estimated as high as 40 m s\(^{-1}\) by local law enforcement, and downed trees fell in an east-to-west pattern. The Dry Lake Remote Automated Weather Station (RAWS), located 8 km northeast of SBS at an elevation of 2430 m MSL, recorded wind gusts from the east at 30 m s\(^{-1}\) at both the 1100 UTC and 1200 UTC 23 April observations. Local damage reports from county officials placed the Dry Lake RAWS in an area of enhanced damage stretching from SBS to 16 km northeast of SBS (Fig. 2). Within this damage swath, 6 homes were damaged, 2 sheds were destroyed, 12 power lines were downed and numerous trees were toppled.

Additional wind and temperature data were provided by Storm Peak Laboratory (SPL), a facility operated by the Division of Atmospheric Sciences of the Desert Research Institute (Borys and Wetzel 1997). The SPL provided continual monitoring of the event from Mt. Werner (7 km southeast of SBS - elevation 3210 m MSL). The 5-minute average wind plot in Fig. 3a showed that sustained winds ranged from 15 to 19 m s\(^{-1}\) between 1000 UTC and 1600 UTC 23 April. The 5-minute average wind gusts (Fig. 3b) during this 6-h period routinely topped 22 m s\(^{-1}\), with a peak of nearly 24 m s\(^{-1}\) at 1550 UTC 23 April. The corresponding wind direction ranged from 085 to 105 degrees (not shown).
Wyoming (RIW) occurred during the 12-h period. Windsitations from Cheyenne, Wyoming increased dramatically between the wind became southerly, a direction parallel to the south central Wyoming and the Platteville wind profiler (PI'L) at both the Medicine Bow wind profiler (MBW) in Colorado during this 12-h period. Slightly stronger winds cally stacked and deepened significantly area denotes time of observed wind damage. (Data provided by Drs. Randy Borys and Melanie Wetzel)

b. Synoptic and mesoscale environment

Upper-air analyses of 0000 UTC 23 April 1999 (Fig. 4) depicted a nearly vertically stacked closed low near Las Vegas, Nevada. (LAS). The cut-off low moved closer to LAS over the next 12 hours (Fig. 5) became more vertically stacked and deepened significantly (30 m at both 500 and 700 mb). As a result of the tightened gradient, 700-mb height rises of 50-70 m at Bismarck, North Dakota (BIS), Denver, Colorado (DEN), and Riverton, Wyoming (RIW) occurred during the 12-h period. Winds (Fig. 6) at both the Medicine Bow wind profiler (MBW) in south central Wyoming and the Platteville wind profiler (PTL) in north central Colorado showed easterly winds during this 12-h period. Slightly stronger winds (20 m s⁻¹) occurred at MBW than at PTL. The presence of a critical level was evident at -5 km MSL at PTL where the wind became southerly, a direction parallel to the Park Range.

The cross-barrier, sea-level pressure (SLP) gradient increased dramatically between 1800 UTC 22 April and 1400 UTC 23 April (not shown). Surface METAR observations from Cheyenne, Wyoming (CYS) and Craig, Colorado (CAG) were chosen to measure the cross-barrier SLP difference. CYS and CAG lie 169 km east and 72 km west of the Park Range crest, respectively. The SLP at CYS increased from 1009.0 to 1026.8 mb, while measurements at CAG showed an increase from 1004.1 mb to 1010.0 mb. Thus, the cross-barrier SLP difference increased from 0.020 mb km⁻¹ to 0.070 mb km⁻¹ in 20 hours across a distance of 241 km. Colle and Mass (1998) found a common factor among the strongest west Cascade wind events to be a SLP difference of > 0.047 mb km⁻¹ between Seattle and Yakima (169 km). Similarly, a cross-barrier SLP difference between RIW and SLC (320 km) of > 0.025 mb km⁻¹ is typically enough to generate gap winds on the west slope of the Wasatch (Dunn 1999).

4. Numerical Guidance

The synoptic conditions predicted by various models of the NCEP suite available to the operational forecaster were all quite similar for this event. The 1200 UTC 22 April 1999 and the 0000 UTC 23 April 1999 model output also showed excellent run-to-run consistency. Therefore, only the 1200 UTC 22 April Eta model (Black 1994) products are shown. To complement the NCEP guidance, the 0000 UTC 23 April RAMS forecasts are also presented.
Fig. 5. Same as in Fig. 4, except analyses valid at 1200 UTC 23 April 1999.

a. NCEP guidance

The 1200 UTC 22 April 1999 NCEP forecasts gave strong indications to the possibility of strong winds in northern Colorado and adjacent areas. A plan view of both the 500-mb level and 700-mb level height contours and grid-point winds (Fig. 7) indicated that the forecasts compared quite well to the observations shown earlier. The forecast cross-section of potential temperature and wind (Fig. 8) showed crest-level winds of 20 m s\(^{-1}\) and a critical layer around 500 mb near SBS. The potential temperature profile also showed a stable lower troposphere and a decrease in stability aloft. The cross-section also shows a strong stable layer up to 500 mb with a less stable layer up to the tropopause. NCEP guidance from the 0000 UTC 23 April forecasts (not shown) showed little change from the 1200 UTC 22 April forecast indicating good continuity between runs.

A typical measure of the upstream blocking and the potential for non-linear behavior is expressed by the dimensionless quantity called the Froude number

\[
Fr = \frac{U}{NH}
\]

where \(U\) is the upstream wind speed, \(N\) is the square root of the Brunt-Väisälä frequency representative over the mountain depth \(H\) (Carruthers and Hunt 1990). There are some concerns based on the applicability of \(Fr\) in the real atmosphere (Durran 2002). However using the same caveats and assumptions used by Meyers et al. (2002), \(U\) is approximated by 12 m s\(^{-1}\) and \(N\) is approximated by 0.015 s\(^{-1}\). Assuming an effective barrier height of 2000 m, a Froude number of 0.4 was measured for the north central portion of Colorado during this time. This value corresponds to blocked flow, and non-linear flow behavior, including acceleration to the lee of the barrier, and possible wave breaking (e.g., Klemp and Lilly 1975; Poulos et al. 2000).

The wave-like structure of the \(\theta\) and \(w\) fields (not shown) observed in previous research was not seen in the NCEP forecasts. This was most likely due to the coarse resolution and smoothed terrain surfaces of the model. Thus, we used the RAMS forecast to complement the Eta model output and hopefully provide even more evidence of possible mountain wave formation.

b. Local-area model

RAMS is a local mesoscale model which was run once a day at 0000 UTC during the 1998-99 winter season at
both Colorado State University (CSU) and the NOAA Forecasts Systems Laboratory (FSL). The operational RAMS forecasts were supported through funding provided by the Cooperative Program for Operational Meteorology, Education, and Training (COMET), operated jointly in cooperation with the National Weather Service (NWS), CSU, and FSL. A nested-grid version of RAMS (Pielke et al. 1992) provided by CSU was utilized for this research. The CSU model utilizes parallel processing for the interactive nested-grid version of the model. The model includes two interactive, nested grids. The coarse grid covers the western United States with 48 km horizontal grid spacing; and the fine grid encompasses all of Colorado and portions of Wyoming, Utah, South Dakota, Nebraska, and Kansas at 12-km grid spacing. Both grids utilize 26 vertical levels beginning at 250-m grid spacing near the surface, gradually stretching to a maximum of 1000 m. One distinct advantage of RAMS is the more advanced physics employed compared to that of the NCEP model suite. RAMS includes a mixed-phased microphysical scheme described by Walko et al. (1995). Another distinct advantage of this high-resolution model is the improved representation of complex terrain, which is invaluable especially over mountainous regions.

The RAMS forecasts initialized at 0000 UTC 23 April 1999 were employed for this research. All forecast fields discussed here are valid at 0800 UTC 23 April, which approximates the start of the severe wind event. The forecast of MSL pressure is shown in (Fig. 9). The RAMS forecast shows a tightening pressure gradient between CYS and CAG with a cross-barrier difference of 0.063 mb km⁻¹. This value is similar to the observed cross-barrier pressure difference of 0.070 mb km⁻¹. A plan view of winds (Z=2) in (Fig. 10) shows 26 m s⁻¹ easterly flow west of the higher terrain of the Park Range and to the north of SBS. This spatial location of higher winds, which is displaced...
west of the higher terrain of the Park Range compares well with the damage area shown in (Fig. 2). Several cross-sections were generated in this forecast, running along an axis from FCL to just south of SLC (approximated by the 40.5 N latitude). The wind and θ fields in (Fig. 11) clearly show the mountain wave pattern with descending easterly winds of 28 m s⁻¹ west of the Park Range. The enhanced damage area is located almost directly below this wind maximum. The θ pattern also depicts a less stable layer in the middle troposphere from 5000-10,000 m MSL overlaying a stable layer above crest-level. The RAMS cross-section of the w component of the wind (Fig. 12) shows a wave structure similar to those described in earlier literature discussed in section 2. Three distinct downward maximums could be seen west of the Colorado Front Range with a downward velocity maximum of 0.5 m s⁻¹ displaced above SBS. Special note should be made of the intense downward velocity seen west of the Wasatch Front (far left, Fig. 12). Just prior to the valid time of the RAMS forecast, a gust to 51 m s⁻¹ was recorded near Brigham City, Utah. This mark established a new record for lower elevations in the state of Utah (Dunn 1999).

The model guidance provided by RAMS closely resembled the findings of previous observational and theoretical research. Several important mesoscale factors appeared to have come together in the SBS vicinity, to create these damaging winds. Crest-level flow was strong, and isentropes illustrated a mountain wave pattern and favorable stability profile. RAMS also displayed strong downward descent of the mountain wave in the w field, and the cross-barrier SLP gradient was significant. Finally, a critical layer was evident in the middle troposphere. The use of RAMS, in concert with other NCEP guidance, showed a strong potential for a downslope windstorm west of the Colorado Park Range.

5. Comparison to the 25 October 1997 Forest Blowdown

The Routt National Forest blowdown of 25 October 1997 is the only other mountain wave event occurring west of the Continental Divide in the northern Colorado
Rockies that has been examined in detail (Meyers et al. 2002). This event produced wind gusts in excess of 50 m s⁻¹, which downed 13,000 acres of old growth forest in the Park Range. The toppled trees fell in a swath several miles wide and 20 miles long. The findings of various studies pertaining to this devastating blowdown will be discussed here and compared to those of the 22-23 April 1999 event.

Analyses at 0000 UTC 25 October 1997 (Meyers et al. 2002) indicated a deep, closed low in northeast New Mexico which produced lower and middle tropospheric easterly flow of 15-20 m s⁻¹ across northern Colorado. This closed low was much farther east than that observed in the April 1999 event. Froude number calculations for both events were quite similar, with values falling in the non-linear flow regime (~0.5). Surface observations during the 1997 event indicated a cross-barrier SLP difference of only 0.026 mb km⁻¹ between CYS and CAG. This value was far less than the 0.070 mb km⁻¹ difference observed in the April 1999 event. Another observed parameter that varied greatly between the two mountain wave events was lower tropospheric temperature. Meyers et al. (2002) showed how deep, very cold lower tropospheric air enhanced mountain wave formation during the 1997 blowdown. Mountain top temperatures of -4 °F were recorded in the 1997 event, whereas readings of around 16 °F were recorded during the 1999 event. Also, surface temperatures at the mid-point of each wind event were taken from METAR observations at nearby Hayden, Colorado (HDN, Fig. 2). Surface temperatures of the 1997 event were 14 °F colder than those observed in the April 1999 event (23 °F in 1997 vs. 37 °F in 1999). The much colder lower tropospheric air present in 1997 may have been a significant factor in the magnitude of that event. The cold air may have also generated a stability structure to the lee of the Park Range, which inhibited the extent of the downslope winds to lower elevations, such as the town of Steamboat Springs, and thus, concentrated damage to the higher elevations.

Investigations of the 1997 event through numerical modeling were conducted using the RAMS model. Findings of these simulations indicated that strong easterly cross-barrier flow with a favorable stability profile was the primary meteorological factor enhancing the mountain wave. Results of the finest- grid RAMS simulations (1.67 km) depicted 28 m s⁻¹ east winds to the lee of the Park Range at the surface (Fig. 13). A cross-section of the u-component of the wind and 0 taken perpendicular to the Park Range showed a 42 m s⁻¹ maximum descending the west side of the barrier along with tight isentrope packing just above crest-level (Fig. 14). A high amplitude mountain wave structure was evident in the isentrope pattern. Additionally, a wave induced critical level was observed in the middle troposphere (~8000 m MSL), characterized by a flow reversal (westerly wind). Despite the varying horizontal grid spatial differences of the two RAMS forecasts (12 km in 1999 and 1.67 km in 1997), the overall structure of the wind and 0 fields were somewhat similar. The difference was the magnitude of the winds.
and amplitude of the mountain wave, some of which may be attributed to the differences in the horizontal and vertical grid resolutions.

6. Conclusions

This research was prompted by the occurrence of a severe mountain wave event west of the Colorado Park Range on 22-23 April 1999, the second such event within a span of two years in that region. Prior to the 25 October 1997 Routt National Forest blowdown little knowledge or literature existed regarding mountain wave events west of the Continental Divide in Colorado. A detailed examination of the mountain wave of 22-23 April 1999 and subsequent comparisons to the 1997 event provide some insight to the synoptic and mesoscale characteristics common to this phenomenon.

NCEP guidance observations served as a good diagnostic tool to infer the potential for strong winds on 23 April 1999. The guidance depicted strong easterly cross-barrier flow and the presence of a mean-state critical level evident in the middle troposphere. However, the NCEP models did not forecast a downslope wind event most likely due to the coarse horizontal resolution and poor representation in the model. A local-area operational model (RAMS) was used in concert with the Eta model to forecast the magnitude and location of the mesoscale phenomena. The 12-km RAMS forecast added good predictive value in forecasting the severe winds. RAMS forecast fields of wind and θ depict the mountain wave pattern and descending winds (28 m s⁻¹) west of the barrier. Forecast profiles of middle tropospheric instability overlaying regions of crest-level stability, and forecasts of downward vertical velocity also gave operational forecasters strong indications of mountain wave formation.

The results qualitatively resembled the overall wind flow structure observed in the RAMS simulation (1.67 km grid spacing) of the 25 October 1997 event. Strong synoptic and crest-level easterly flow, and the presence of a critical level were common to both episodes. In addition, RAMS θ profiles of the 1997 event clearly showed a well-developed mountain wave with a stable layer, and with lower stabilities aloft. Both events occurred simultaneously with a devastating snowstorm along the Front Range of Colorado. Several factors appear to have caused the higher wind speeds forecasted in the 1997 event (42 m s⁻¹ to the lee of the barrier in the 1997 event, whereas a 28 m s⁻¹ maximum was forecast during the 1999 event). First, Meyers et al. (2002) showed how the presence of very cold, lower-tropospheric air modified the stability profile, thereby enhancing mountain wave development by nonlinear effects. Mountain top temperatures in the 1997 event were 20 °F colder than those measured in the 1999 event. Secondly, 700-mb winds were stronger in the 1997 event than in the 1999 event. Contrary to the stability profiles and forecast winds, which favor the 1997 event for higher wind speeds, the cross-barrier sea-level pressure gradient favored the 1999 event. The 1999 episode generated 0.070 mb km⁻¹ pressure gradient between CYS and CAG, a value nearly three times greater than that generated during the 1997 event. A comparison of the Colorado Park Range windstorms indicates that cross-barrier sea-level pressure gradient may not be a good predictor of event severity in that region for certain types of wind events. However, more research needs to be conducted concerning downslope windstorms west of the Continental Divide and the relationship to cross-barrier SLP difference.

Operational forecasters west of a mountain barrier should be attentive to cut-off lows south or southwest of the forecast area that could produce strong synoptic easterly winds. Wind profilers and the velocity azimuth display (VAD) wind profile of the WSR-88D can supplement upper-air reports to determine the presence of embedded wind maxima. This could prove especially helpful in data sparse regions of the west and between radiosonde launch times.

Acknowledgments

The authors wish to thank John Snook and Douglas Wesley for their insights and comments on this research. The authors would also like to thank Dr. Gregory Poulos and Charlie Liles for their thorough review of the manuscript. A special thank you to Drs. Randy Borys and Melanie Wetzel of the Desert Research Institute’s Storm Peak Laboratory (SPL) for graphs and data from SPL and for a thorough review of the research. Also, thanks to NWS Forecast Office Grand Junction Hydrologist Brian Avery and forecaster David Nadler for their assistance with the manuscript. Additional thanks are given to Liz Page and Jonathan Heyl for providing archived data used to examine the event.

Support for this research was provided, in part, by the National Weather Service’s Cooperative Program for Operational Meteorology, Education and Training (COMET) under UCAR Grants S96-71867 and S00-19126. The COMET funding is provided by a cooperative agreement between the National Oceanic and Atmospheric Administration (NOAA) and the University Corporation for Atmospheric Research (UCAR). The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA, its sub-agencies, or UCAR.

Authors

Christopher N. Jones is the Warning Coordination Meteorologist at WFO Riverton, WY. He previously served at four NWS offices: WSFO Cheyenne, WY, WSO Casper, WY, NWSO Paducah, KY, and WFO Grand Junction, CO. He received his B.A. in meteorology from the University of Northern Colorado in May 1995. Chris’ interests include mountain meteorology, public outreach, and operational forecasting.

Jeffrey D. Colton is a Senior Forecaster at WFO Grand Junction, CO. Previously, he served as a journeyman forecaster at WFO Amarillo, TX, and as a Meteorologist Intern at WFO Cheyenne, WY. He received his B.S. degree in meteorology from Metropolitan State College in Denver, CO in May 1992.
Jeff’s interests include mountain meteorology, severe storms forecasting, public outreach and operational forecasting.

Ray L. McAnelly is a Senior Research Associate in the Department of Atmospheric Science, Colorado State University. He received his B.S. and M.S. degrees in Meteorology from Texas A&M University in 1976 and 1980, respectively. His research at CSU has focused on convective storm systems and mesoscale/cloud-scale modeling. He helped develop and continues to maintain the realtime RAMS forecast operations for the Colorado region at CSU. Through the COMET Outreach program, he has collaborated with NWS Central Region forecasters on many case studies.


**References**


AUTHOR INDEX TO VOLUME 26


Christopher N. Jones, Jeffrey D. Colton and Ray L. McAnelly, 2002: An Examination of a Severe Downslope Windstorm West of the Colorado Park Range. Natl. Wea. Dig. 26:3,4, 73-82.


Features in Volume 26:

NWA Bylaws. 26:1,2, 55-56.

NWA Weathercaster Seals of Approval. 26:1,2, 61-64.

Author Index to Volume 26. 26:3,4, 82.