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FORECAST CHALLENGES AND IMPACTS OF SEVERE DOWNSLOPE WIND EVENTS

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1. INTRODUCTION

The coupled mountain wave, downslope wind and rotor circulation system pose significant impacts to the aviation and public service communities. Owens Valley, California is ideally situated for the development of these terrain-induced phenomenon due to the north-south orientation of the Sierra Nevada (one of the steepest mountain barriers in the United States) and the prevailing westerly flow aloft. The National Weather Service Forecast Office (NWSFO) in Las Vegas, NV, has forecast and warning responsibility for this geographic region. The dynamics governing wave induced wind storms have been documented and understood for some time (Klemp and Lilly, 1975). However, due to a very limited set of surface observations and spotter reports, the frequency, strength and localized enhancement of downslope wind events in the Owens Valley was previously, poorly understood.

The NWSFO in Las Vegas, NV provided operational forecast support to the Terrain-induced Rotor Experiment (T-REX) during March and April of 2006. The main task of NWSFO Las Vegas was to provide local knowledge and operational experience to the forecast process and provide interpretation of various models on local, regional and global scales. This effort was an enhancement to the level of operational support that was provided during the initial phase of T-REX, also referred to as the Sierra Rotors Project (SRP), which took place during the spring of 2004. During T-REX, the NWSFO Las Vegas provided detailed, daily weather discussions through the internet and via tele- and video conferences.

The operational experience gained by supporting the Sierra Rotors Project (2004) and the Terrain-Induced Rotor Experiment (2006) has had immediate and significant impact on the level of service that we provide to the aviation, ground transportation, emergency management and general population communities.

The Naval Research Laboratory (NRL) provided access to their nested 2/6/18-km Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS) model to aid in operational forecast support during the SRP and T-REX. Following the SRP, it was evident how valuable a non-hydrostatic mesoscale model could be in the forecasting of mountain waves, downslope winds and rotors. The NWSFO in Las Vegas began to run a 4-km Non-hydrostatic Mesoscale Model (NMM) core of the Weather and Research Forecasting (WRF) system in 2006 February.

The population of Las Vegas has continued to grow and expand particularly over the past twenty years and is now moving into areas that are more susceptible to severe downslope wind events. The occurrence of a severe downslope wind event five years ago along portions of the western valley would be a relatively “low impact event”. Today, and increasingly so in the future, these downslope wind events are more likely to become “high impact” events. We are now running a second 4-km WRF-NMM domain over the Spring Mountains in southern Nevada to improve forecast support of these high impact downslope wind events in the Las Vegas Valley.

The forecasting and verification of downslope wind events continues to be extremely challenging. In this paper, we will briefly discuss lessons learned from T-REX, provide a downslope wind event case study, detail our use of local mesoscale models and some of the results we have seen, and discuss the results of a climatology of downslope wind events over the past few years.

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2. LESSONS LEARNED FROM T-REX

Mountain wave and downslope wind events were much more common and localized than previously understood. In particular, the 25 March 2006 event near Independence provided significant ground truth to the strength and variability of these events. Wind damage occurred at the Independence airport, while just a mile to the south winds were light. This variability is due in part to the terrain. One area of local enhancement occurs as the flow goes through the Kearsarge Pass and down the Onion Valley before reaching the valley floor in Independence.

As was the case during the Sierra Rotors Project in 2004, the COAMPS model continued to provide higher sensitivity to the mountain wave and downslope wind events. This tendency continued during T-REX. The NWSFO Las Vegas 4-km WRF-NMM model was less sensitive to mountain waves in particular, but in many instances provided a more accurate depiction and timing for the moderate to strong downslope wind events. The availability and use of non-hydrostatic mesoscale models provided a significant enhancement to both the understanding and predictability of mountain waves and downslope wind events.

Climatologically, there is a favored time frame in the late afternoon around 0000 UTC for downslope wind and rotor events. This may be due to the expanded boundary layer that occurs with maximum daytime heating. On multiple occasions during T-REX and during the Sierra Rotors Project, the models (particularly COAMPS) would portray a downslope wind event in the evening or overnight hours. Many times the event began earlier around the climatologically favored time of 0000 UTC or would intensify significantly during an ongoing event.

Strong downslope wind events occur frequently just ahead or during the passage of a trough when the stability at ridge top increases. This was particularly evident in the event on the evening of 25 March 2006 (Czyzyk and Runk, 2006)

3. CLIMATOLOGY OF DOWNSLOPE EVENTS

The Desert Research Institute (DRI) deployed a 16-station surface observation mesoscale network in the Owens Valley in support of SRP and T-REX in March 2004 (Fig. 1), hereinafter referred to as DRI-mesonet. The DRI-mesonet consists of three cross-valley transects in close proximity to the town of Independence, CA. Both the DRI-mesonet and the continually-expanding Mesowest database are relied upon heavily by the NWSFO Las Vegas to provide ground truth for downslope wind and rotor events. This ground truth provides valuable feedback that enables the operational staff to continue to improve the forecast and warning process.

In developing our climatology, we have analyzed the complete dataset that is available from the DRI-mesonet and have supplemented additional observations from the Meoswest database. A downslope wind event strength rating was developed and is strongly correlated with the high wind watch/warning/advisory criteria established at the NWSFO in Las Vegas. The criteria for a wind advisory is the occurrence of a wind gust at or above 18 m s^{-1} (40 mph) at elevations below 1524 m (5000 feet) MSL and wind gusts at or above 26 m s^{-1} (58 mph) for elevations above 1524 m MSL. The criteria for a high wind watch/warning is a wind gust at or above 26 m s^{-1} at elevations below 1524 m MSL and wind gusts at or above 31 m s^{-1} for elevations above 1524 m MSL. The strength rating is divided into three categories moderate, severe and extreme events.

A surface observation was considered representative of a downslope wind event if the wind direction was between 240 and 300 degrees and the associated wind gust was a minimum of 18 m s^{-1} for stations below 1524 m MSL in elevation and a minimum of 26 m s^{-1} for stations above 1524 m MSL.

Strength Rating

Moderate

Wind gusts greater than 18 m s^{-1} (40 mph) at stations below 1524 m (5000 feet) MSL.

Wind gusts greater than 26 m s^{-1} (58 mph) at stations above 1524 m (5000 feet) MSL.

Severe

Wind gusts greater than 26 m s^{-1} (58 mph) at stations below 1524 m (5000 feet) MSL.

Wind gusts greater than 31 m s^{-1} (70 mph) at stations above 1524 m (5000 feet) MSL.

Extreme

Wind gusts greater than 36 m s^{-1} (80 mph) at any station

Using the above criteria, since March of 2004, there have been 10 extreme events in the Owens Valley. An extreme downslope wind event has occurred at least once in every month from September through February and one in April (an event on 2006 Mar 25 was 0.2 m s^{-1} below the extreme threshold).

The following is a list of the observation sites that recorded wind gusts in excess of 36 m s^{-1} for each of the ten extreme events. Included in the list are two RAWS (Remote Automated Weather Stations) observations from the Mesoswest database.

# of events observed		– elevation (site)
9/10	–	1736 m (Stat. 1 – DRI Mesonet)
5/10	–	1575 m (Stat. 7 – DRI Mesonet)
4/10	–	1440 m (Stat. 8 – DRI Mesonet)
3/10	–	1417 m (Owens Valley RAWS)
2/10	–	1476 m (Stat. 2 – DRI Mesonet)
1/10	–	1480 m (Oak Creek RAWS)

In addition, there have been 18 recorded severe downslope wind events (surface winds speeds of 26 m s^{-1} or greater). Combining both the severe and extreme downslope wind events from March 2004 through May 2007, we get a total number of 28 events. This equates to an average of 9 severe/extreme downslope wind events that occur in the western foothills of the Owens Valley annually.

We have observed two classes of downslope wind events that are correlated with the passage of a mid level trough. Those events which are not associated with the passage of a trough are labeled Type 1 and those associated with the passage of a trough are labeled Type 2 events. The ten extreme events from the climatology are all classified as Type 1 events and have been composited using the NCEP/NCAR reanalysis data. Type 1 events are generally "longer duration events" with the upper level jet maximum located to the north across northern California (Fig. 2). The main moisture and instability remain well north of the region with the 500 hPa trough axis located along the Pacific Northwest coast (Fig. 3). This pattern allows for an extended period of sufficient cross barrier flow (Fig. 4) and places the central Sierra and Owens Valley in the right exit region of the upper level jet (Fig. 2). Subsidence and higher static stability associated with the indirect transverse circulation of the upper level jet streak (Uccellini and Johnson, 1979) also provide ideal conditions for the development and sustainment of a mountain wave and downslope wind event. Type 2 events are generally "short duration events" and occur within close proximity to the passage of the mid level trough. Four events were used in the Type 2 composite and were all severe downslope wind events (2005 Mar 28, 2005 Apr 13, 2005 Jun 06 and 2006 March 26). Type 2 events sometimes occur near the end of a Type 1 event. The composite upper level jet is located over the central Sierra (Fig. 5) and slightly weaker than the Type 1 events. The 500 hPa trough is more amplified and located just to the west of the central Sierra crest (Fig. 6). The 600 hPa wind speed composite (Fig. 7) depicts similar flow to Type 1 events with the mid level jet axis located over the central Sierra. The trough passage, pressure jump, and short duration are evident in the plots of surface pressure, wind gust and wind direction (Fig. 8 a-l) from sensors in the DRI-mesonet. The abrupt change in pressure, wind gust and in some cases wind direction (two events had west winds prior to the passage of the trough) occurs simultaneously.

Unlike the Type 1 composite, the Type 2 composite depicts a strong surface pressure gradient (Fig. 9) aligned with the orientation of the central Sierra. The relatively weak surface pressure gradient in the Type 1 composite is also present in many of the individual events and is not solely a factor of smoothing from the composite process or the coarse reanalysis.

Summary of Type 1 and Type 2 composites

Type 1

300 hPa Jet to the north	40-45 m s^{-1}
600 hPa Jet overhead	20-25 m s^{-1}

500 hPa trough axis along Pacific NW coast

Type 2

300 hPa Jet overhead	35-40 m s^{-1}
600 hPa Jet overhead	20-25 m s^{-1}

500 hPa trough axis just west of Sierra crest

4. PREDICTION OF TERRAIN-INDUCED PHENOMENON

To aid in determining whether conditions would favor trapped waves or vertically propagating waves, the 1.6 rule was utilized (UCAR's COMET Program). Trapped lee waves are likely to occur when significantly increasing forward wind shear exists or when airmass is unstable. The 1.6 rule states that if the wind speed at 2000 m above the ridge top level is greater than 1.6 times that of the wind speed at ridge top level then trapped waves would be favored over vertically propagating waves. Operationally, we use 625 hPa and 500 hPa which is a difference of approximately 1500 m. 500 hPa was chosen due to its availability as a standard level in upper air radiosonde data and 625 hPa (which is below the highest peaks of the Sierra - Mt. Whitney at 4421 m), but it is reasonable representation of an average ridge top level.

The climatology of extreme wind events provides a mean value of 1.25 for the ratio of 500 hPa to 625 hPa and 1.37 for severe events. This makes sense, with extreme events indicating the presence of weaker shear and more conducive to the development of a self induced critical level, breakings waves, and enhanced downslope winds. (Note: Utilizing only two levels for an assessment of wind shear for downslope wind events is not sufficient).

As was identified by Colle and Mass (1998) during the study of windstorms along the slopes of the Washington Cascades, there are four significant factors associated with the development of major downslope wind events. These include:

1) strength of the cross-barrier flow
2) magnitude of the cross barrier pressure gradient
3) presence of a critical level
4) stable layer near ridge crest with lower stability above

Two of these factors, sufficient cross-barrier flow (13 m s^{-1}) and a stable layer near ridge crest with lower stability above are present in each of the extreme and severe downslope events.

A critical level prevents the gravity wave energy from continuing upward and acts to deflect and redirect the gravity wave back toward the surface. This process of redirecting packets of concentrated wave energy downward is why it is possible to produce surface wind speeds at the base of the mountains far exceeding wind speeds observed at any level in the free atmosphere (Colle and Mass, 1998).

A mean-state critical level is typically defined as a point in the atmosphere where the cross-barrier flow goes to zero. This can be a place where the winds become very light, or where the winds become parallel to the barrier. In ideal situations, it occurs in a region where a wind direction reversal takes place in the vertical (e.g., going from easterly to westerly flow).

A mean state critical level appears to be extremely rare in the Owens Valley. A mean state critical level was not evident in any of the downslope wind events in the Owens Valley since March 2004. However, in many of the stronger events, weak or negative shear was present which would aid the production of a self-induced critical level. It is surmised that a self-induced critical level is occurring in many of these severe and extreme downslope wind events. This is in agreement with the observations and findings of Lilly (1977) from the analysis of a severe downslope wind event in Boulder, CO during January 1972. This self-induced critical level is depicted in the WRF-ARW during the 2006 Nov 14 event in which the cross barrier flow above the valley is reduced to zero (Fig. 10). The result is wave breaking and an extreme downslope wind event in both the WRF-ARW output and in the surface observations.

A strong cross-barrier pressure gradient is present in several of the severe and extreme downslope wind events, but it is not always observed. The downslope wind event that occurred during the afternoon of 2004 Apr 28 in which a wind speed of 36 m s^{-1} was observed, the pressure gradient between Bishop, CA (KBIH) and Fresno, CA (KFAT) was approximately 1 hPa. During an extreme event on 2007 Feb 25 in which multiple sensors reported wind gusts of 38 m s^{-1}, the pressure gradient from KBIH to KFAT was in excess of 15 hPa.

5. T-REX CASE STUDY – 25 MARCH 2006

a) 23 March 2006

A Hovmoeller diagram (Fig. 11) from the 1200 UTC run of the COAMPS was indicating strong cross barrier flow beginning at 0600 UTC 25 March. The local 4km WRF-NMM run from 1200 UTC 23 March was depicting a strong mountain wave signature (Fig. 12) and 30-35 m

s^{-1} of cross barrier flow at ridge top, increasing to 45 m s^{-1} of cross barrier component at 500 hPa at 0000 UTC 26 March. A sounding also at Independence at 0000 UTC 26 March depicted a stable layer between 600 and 700 hPa (Fig. 13). A similar depiction (although slightly weaker) was indicated in a Bishop sounding (not provided).

b) 24 March 2006

The COAMPS run at 1200 UTC depicted significant mountain wave activity in cross-section centered on Independence and strong downslope winds along the eastern Sierra and into Owens Valley peaking at 0300 UTC 26 March (Fig. 14). The local WRF-NMM run at 1200 UTC continued to depict strong mountain waves and a significant downslope wind event peaking at 0000 UTC 26 March (Fig. 15). A sounding from the WRF-NMM near the Sierra crest west of Independence at 0300 UTC 26 March indicated a stable layer between 650 and 550 hPa and 25 m s^{-1} of cross barrier flow at ridge top (Fig. 16). The surface wind forecast from the WRF-NMM showed 30 m s^{-1} along the Sierra crest at 0000 UTC 26 March 26 (Fig. 17) and easterly flow along the east side of the valley, hinting at the presence of a rotor circulation.

c) 25 March 2006

The 1200 UTC COAMPS run showed downslope flow in excess of 40 m s^{-1} along the eastern Sierra and nearing the center of Owens Valley at 0300 UTC 26 March (Fig. 18). A GPS dropwindsonde from the National Center for Atmospheric Research (NCAR) Gulfstream-V aircraft, at 2220 UTC 25 March, (3-4 hours prior to the onset of the downslope wind event) indicated an inversion near 600 hPa and 12 m s^{-1} of ridge top cross barrier flow with strong forward shear (Fig. 19). A sounding from the (NCAR) Multiple Antenna Profiler (MAPR) taken at Independence at 0202 UTC 26 March, just prior to the onset of the downslope wind event, depicted an expansion of the stable layer/inversion between 600 and 500 hPa (Fig. 20), a backing of the wind and a reduction in the forward shear with the approach of the trough.

The stability increased at ridge top level, the flow became more perpendicular to the terrain and the strong forward shear was removed with the passage of the trough. The high winds began to develop over the northern portions of the Owens Valley in and around Bishop by 2200 UTC where the wind gusts reached 21 m s^{-1} at 2205 UTC at the Bishop Airport. From north to south down the Owens Valley, the occurrence of strong downslope winds progressed and reached Independence between 0200 and 0300 UTC. Six sites from the DRI-mesonet reported wind gusts in excess of 30 m s^{-1} with a maximum of 36 m s^{-1} at station 2 between 0200 UTC and 0300 UTC.

This case demonstrates the local variability that occurs with many downslope wind events. Two observations (sites 2 and 5) from the DRI-mesonet reported a wind gust difference of 15 m s^{-1} over the distance of 10 km and a difference of elevation of just under 300 m. Station 2 with a wind gust of 36 m s^{-1} is just west of Highway 395 near the base of the foothills (elevation of 1476 meters) and station 5 is just to the east of the highway in the base of the valley (elevation of 1145 meters).

6. MESOSCALE MODELING

The main method for NWS operational meteorologists to view and assess numerical weather prediction is via the Advanced Warning Interactive Processing System (AWIPS). Currently, the NCEP 12-km NAM (WRF-NMM) is the highest resolution model that is available in AWIPS and this resolution is insufficient to properly resolve downslope wind events and rotor circulations. Therefore, there continues to be a need to locally run non-hydrostatic mesoscale models.

Following the SRP and having access to NRL's COAMPS, it was evident how valuable a non-hydrostatic mesoscale model could be in the forecasting of mountain waves, downslope winds and rotors. In preparation for T-REX the NWSFO in Las Vegas began to run a 4-km domain of the WRF-NMM over the central Sierra and Owens Valley, CA. The model domain is 101 km x 109 km with 4-km grid spacing and 31 vertical levels. The COAMPS and 4-km WRF-NMM were run twice daily at 0000 UTC and 1200 UTC. The COAMPS was run through 48 hours and the WRF-NMM was run out to 60 hours. Both models showed skill during T-REX and heavily utilized by the operational meteorologists at NWSFO Las Vegas.

Results obtained from the real-time forecasts show the WRF-NMM divergence-damping effect reduced the amplitude of vertically propagating waves considerably more so than did the ARW upper-layer sponge scheme (Koch, 2006). In order to determine whether the WRF-ARW would consistently offer significant improvement over the WRF-NMM in the forecast of vertically propagating waves and downslope wind events in the Owens Valley, the NWSO Las Vegas began running a 4-km WRF-ARW domain with an identical 4-km WRF-NMM in September 2006. Both models are run on a single workstation with a dual processor and are run consecutively. The WRF-NMM requires approximately 3 hours to produce a 60-hour forecast (download time, run time and transfer time into AWIPS). The WRF-ARW with an identical configuration takes approximately 6.5 hours to produce a 36-hour forecast, which severely reduces it operational usefulness.

However, there have been significant differences in the depictions of vertically propagating waves and downslope wind events between the WRF-NMM and WRF-ARW, some of which have been mentioned previously.

In comparison with the WRF-ARW, the WRF-NMM generally produces less amplified mountain waves, weaker downslope flows and generally does not produce a self-induced critical level. In many instances, the WRF-NMM does not depict downslope winds down to the valley floor. The WRF-NMM regularly depicts an unrealistic forecast of potential temperature, in which there is a dramatic folding of the surfaces. In general, this folding of the potential temperature occurs when mountain waves/downslope winds were expected or did occur. It is conjectured that this folding of potential temperature is the WRF-NMM's way of representing "wave breaking". This type of "wave breaking" depiction is evident in many downslope wind events and can be seen in a forecast of the 2007 February 26 downslope wind event. A WRF-NMM 60-hour forecast cross-section centered on Independence, CA depicts the folding of potential temperature surfaces between 400 and 700 hPa over the crest of the Sierra (Fig. 21). This folding or "wave breaking" was also present in the WRF-NMM in the 15-hour forecast of the 2006 November 14 event. The folding of potential temperature is evident between 500 and 700 hPa over the crest of the Sierra (Fig. 22). For comparison purposes a WRF-ARW forecast for the same time and location is provided in Fig. 10. In this figure, the lines of potential temperature are not producing any folding over the crest of the Sierra. However, wind speeds in excess of 36 m s^{-1} are depicted along the eastern slopes of the Sierra. This forecast of an extreme downslope wind event did in fact verify. Although the run time of the WRF-ARW is less than ideal, its depiction and forecast of vertically propagating waves and downslope wind events still provides value to the operational meteorologist at NWSFO Las Vegas.

Other Applications of Local Modeling

The use of local modeling has not only aided in the forecast process, but has added to the understanding of, and enhancement of the conceptual model associated with mountain waves, downslope winds and rotor circulations.

Approximately 6000 new residents move into the Las Vegas Valley each month. New communities continue to encroach onto areas that are more prone to severe downslope wind events, in particular, along the eastern foothills of the Spring Mountains. The Spring Mountains are located along the western side of the Las Vegas Valley, with the highest peak of Mt. Charleston reaching 3633 m. The Spring Mountains provide a sufficient topographic barrier for the development of vertically propagating mountain waves and severe downslope winds. Severe downslope wind events that occurred in the past were relatively "low impact" events. Today, and increasingly so in the future, these downslope wind events have the potential to become "high impact" events.

Early in 2007, we began to run a third WRF domain (WRF-NMM) in order assess its value over a more densely populated and aviation-critical portion of our County Warning and Forecast Area (CWFA). The WRF-NMM domain is centered over the Spring Mountains and is also 101 km x 109 km with 4-km grid spacing and 31 vertical levels. In addition to having an improved conceptual model, our use of the WRF-NMM has already begun to have an impact on our ability to forecast downslope wind events in the Las Vegas Valley.

At 00 UTC 2007 February 25, conditions appeared to be favorable for the development of a downslope wind event along the western portions of the Las Vegas Valley between 12 UTC February 26 and 00 UTC February 27. Output from the initial run of the WRF-NMM on 2007 February 26 did indicate the presence of a mountain wave (Fig. 23) but in a much more subtle way than with the 4-km WRF-NMM domain over the central Sierra. Enhanced downslope flow was evident in the lee of the Spring Mountains on a cross section at 09 UTC

2007 February 27 (Fig. 23). The downslope wind event was depicted in the surface wind speed along the west side of the Las Vegas Valley, shown on a plan view in Fig. 24, also at 09 UTC 2007 February 27. The morning sounding from Desert Rock (KDRA), NV, which is slightly upstream of the Spring Mountains is a reasonable representation of the air mass in place during the downslope wind event (Fig. 25). An inversion is located just above ridge top level between 600 and 650 hPa. The flow at ridge top was strong (25 m s^{-1}) and an area of negative shear was found between 500 and 600 hPa where the flow went from 36 to 29 m s^{-1}. Surface observations verified the strength and timing of the WRF-NMM forecast at multiple locations including 28 m s^{-1} at Red Rock Canyon, NV (1146 m) and 24 m s^{-1} at Indian Springs, NV (955 m). The NWSFO in Las Vegas highlighted the potential for a downslope wind event along the western portions of the Las Vegas valley with wind gusts up to 27 m s^{-1} and provided a 10-hour lead time. This initial model run from 2007 February 26 also produced a forecast of a weaker downslope wind event on the following night, 2007 February 28. A weak downslope wind event did occur with wind gusts of 18 m s^{-1} at Red Rock Canyon, NV. The WRF-NMM did not produce any folding of the potential temperature surfaces with either of these events. This potentially enabled a more accurate depiction of surface wind speed during the downslope wind event.

7. DOWNSLOPE WIND EVENTS OF 2007 FEB 25 AND 2007 FEB 26 – OPERATIONAL PROGRESS

During the afternoon of 2007 February 25, an extreme downslope event occurred in the Owens Valley with a maximum surface wind gust of 39 m s^{-1} (at elevation of 1736 meters). The NWSFO Las Vegas was able to provide a 34-hour lead time on a high wind watch for locations above 1524 meters, a 22-hour lead time for a high wind warning for elevations above 1524 meters and an 8-hour lead time for a high wind warning for elevations below 1524 meters.

The following afternoon, 2007 February 26, a second extreme downslope wind event occurred in the Owens Valley. The maximum observed surface wind gusts observed was 41 m s^{-1} at 1575 meters. The WRF-NMM was predicting light winds in the valley and wind speeds of under 10 m s^{-1} near 1524 meters. As mentioned previously, the WRF-NMM did depict "breaking waves" in the form of folded potential temperature surfaces. The WRF-ARW produced a mountain wave with downslope winds around 20 m s^{-1} at mid slope and light winds in the valley (Fig. 26). Two upstream soundings (1200 UTC) on 2007 February 26 at Reno, NV (KREV) and Oakland, CA (KOAK) did depict ideal conditions for a second downslope wind event. Both soundings indicated the presence of an inversion just above ridge top level and wind speeds of 20-30 m s^{-1} near ridge top level (Fig. 27 and 28). However, assessing the representativeness of upstream soundings in order to accurately forecast these downslope wind events, continues to be a challenge. The closest upper air soundings are available from Oakland, CA, Reno, NV and Vandenburg AFB, CA which are all 180 to 200 nm from Independence, CA.

The DRI-mesonet provided an excellent example of how the footprint of a rotor circulation can be deduced from surface observations. The satellite imagery on 2007 February 26, displayed a significant rotor cloud down the entire Owens Valley throughout the afternoon. Wind speeds along the eastern foothills of the Sierra and along the western portions of the Owens Valley (from the DRI-mesonet) were blowing from the west in excess of 26 m s^{-1}, while the eastern stations of the DRI mesonet (along the center and eastern portions of the valley) were indicating reversed, easterly flow (Fig. 29) at times in excess of 10 m s^{-1}, a likely representation of the rotor circulation reaching the surface. This reverse easterly flow due to the rotor circulation was also found in Doyle and Durran's high resolution COAMPS simulations (2002). In addition, at 0200 UTC 26 February, station 8 and 9 are indicating a southwest wind of 37 m s^{-1} and an easterly wind at 10 m s^{-1}, respectively. These two stations are just over 2 nm apart.

The prediction and observation of these rotor circulations, as well as vertically propagating mountain waves and downslope wind events are now regularly included in both the public and aviation sections of the Area Forecast Discussion (AFD) from the NWSFO in Las Vegas, NV.

The following is an excerpt from the public and aviation section of the AFD.

2007 Feb 24

Public Section

Main weather concern in the short term is the belt of strong westerly winds expected to impinge upon the Sierras tomorrow. WRF/NMM cross sections show veering winds with height resulting in a much light cross-barrier component aloft by noon. Forecast soundings show an inversion or isothermal layer just above crest level. These factors are favorable for downslope winds and the NMM cross sections show 50+ knots of wind down the mid-slope level during the day. With free air wind speeds near crest level forecast to be close to 100 mph…will issue a high wind watch for the eastern slopes of the southern sierra. Considering the aforementioned reverse shear and temperature profile…will also include the Owens Valley due to the possibility of downslope winds.

Aviation Section

Mountain waves and turbulence can be expected Sunday in the lee of the southern Sierra with ridgetop winds near Bishop approaching 100 knots by 18Z Sunday.

2007 Feb 25

Public Section

Believe there will be enough downward reflection of momentum to get at least isolated high winds on the west side of the Owens Valley below the canyons. In addition…the NMM and ARW show significant rotor signatures…so there will also be a chance of isolated high easterly winds reaching the surface on the east side of the valley.

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10. ILLUSTRATIONS AND TABLES

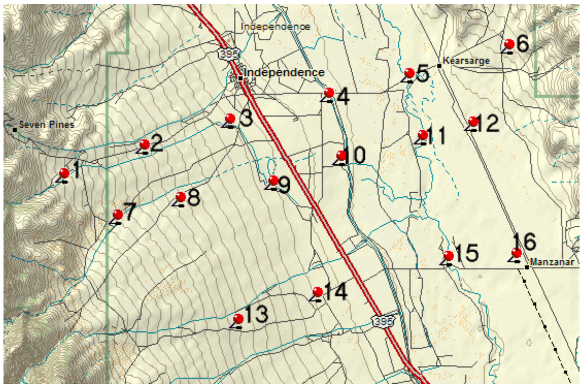

Figure 1. Desert Research Institute (DRI) 16-station surface observation mesoscale network near the town of Independence, CA.

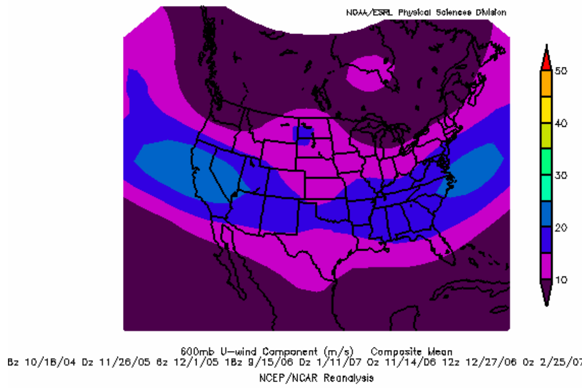

Figure 4. NCEP/NCAR reanalysis composite of the 10 extreme events. The color image depicts the mean wind speed in m s -^{1}at 600 hPa.

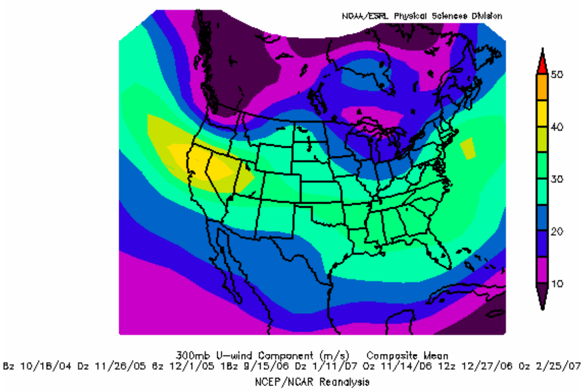

Figure 2. NCEP/NCAR reanalysis composite of the 10 extreme events. The color image depicts the mean wind speed in m s -^{1}at 300 hPa.

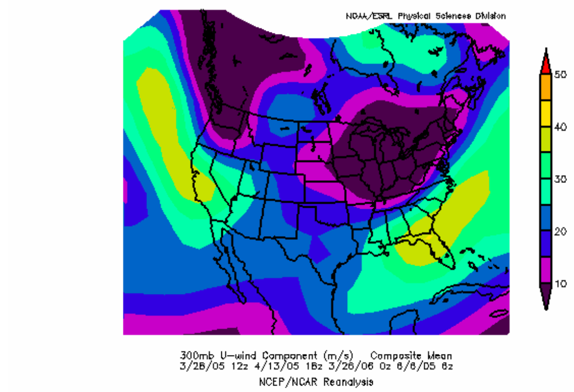

Figure 5. NCEP/NCAR reanalysis composite of 4 Type 2 events. The color image depicts the mean wind speed in m s -^{1}at 300 hPa.

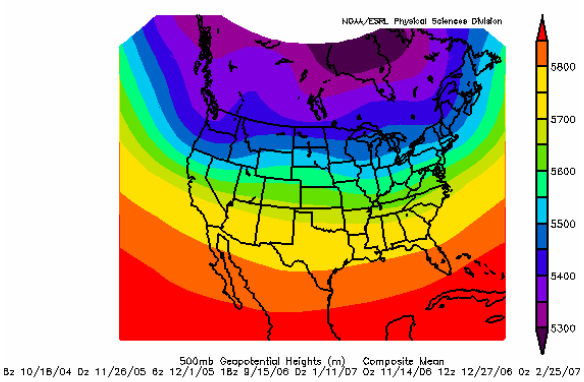

Figure 3. NCEP/NCAR reanalysis composite of the 10 Type 1 events. The color image depicts the mean 500 hPa height field.

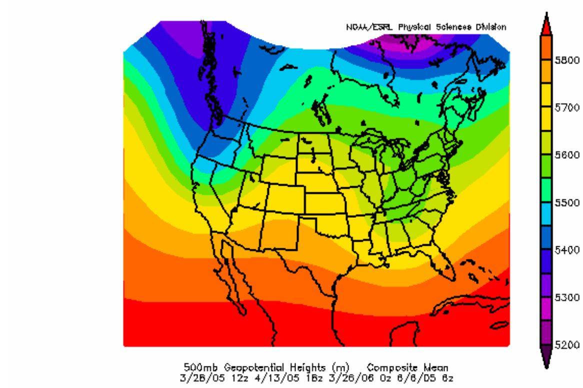

Figure 6. NCEP/NCAR reanalysis composite of 4 Type 2 events. The color image depicts the mean 500 hPa height field.

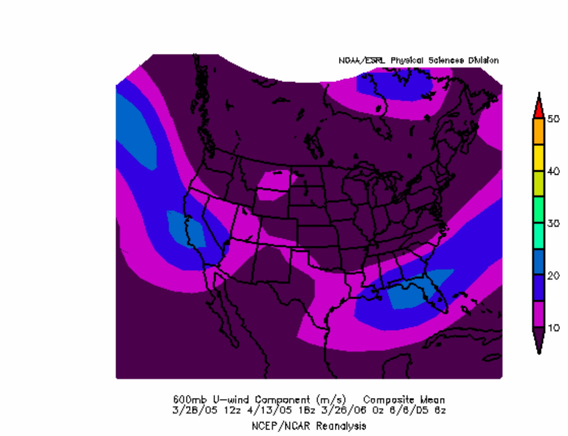

Figure 7. NCEP/NCAR reanalysis composite of 4 Type 2. The color image depicts the mean wind speed in m s $^{-1}$ at 600 hPa.

Fig. 8a. Station 1 (DRI-Mesonet) – 2005 March 28. 24-hour plot of wind direction. Time is in LST (PST).

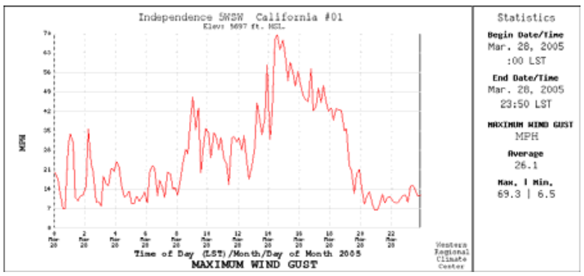

Fig. 8b. Station 1 (DRI-Mesonet) – 2005 March 28. 24-hour plot of wind gust. Time is in LST (PST).

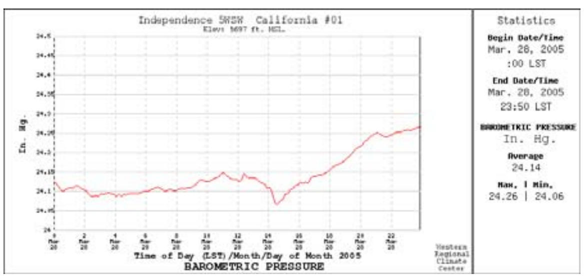

Fig. 8c. Station 1(DRI-Mesonet) – 2005 March 28. 24-hour plot of surface pressure. Time is in LST (PST).

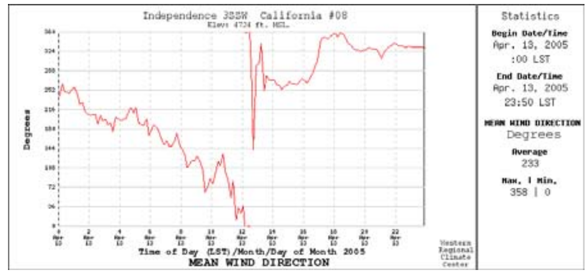

Fig. 8d. Station 8 (DRI-Mesonet) – 2005 April 13. 24-hour plot of wind direction. Time is in LST (PST).

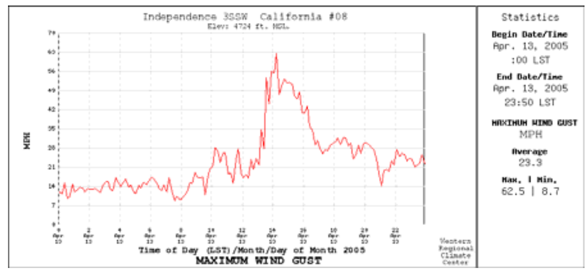

Fig. 8e. Station 8 (DRI-Mesonet) – 2005 April 13. 24-hour plot of wind gust. Time is in LST (PST).

Fig. 8f. Station 8 – (DRI-Mesonet) – 2005 April 13. 24-hour plot of surface pressure. Time is in LST (PST).

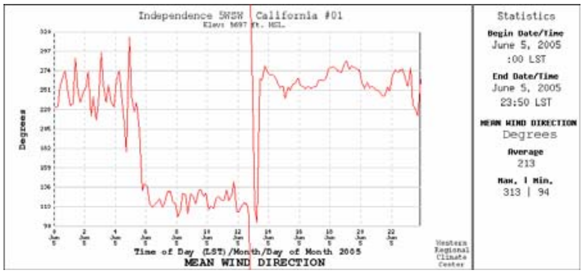

Fig. 8g. Station 1 (DRI-Mesonet) – 2005 June 05. 24-hour plot of wind direction. Time is in LST (PST).

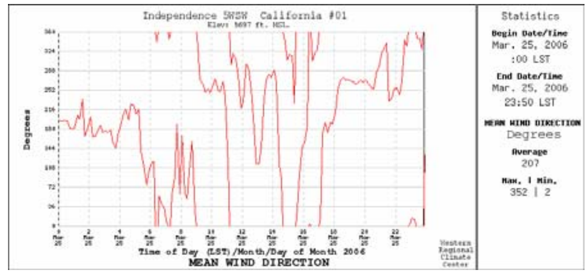

Fig. 8j. Station 1 (DRI – Mesonet) – 2005 March 25. 24-hour plot of wind direction. Time is in LST (PST).

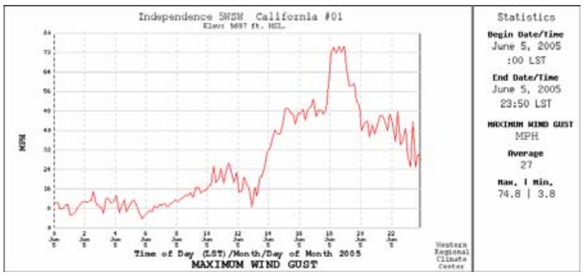

Fig. 8h. Station 1 (DRI-Mesonet) - 2005 June 05. 24-hour plot of wind gust. Time is in LST (PST).

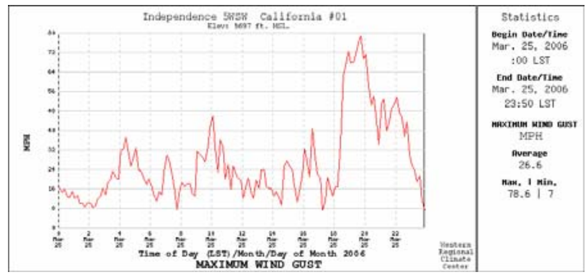

Fig. 8k. Station 1 (DRI – Mesonet) – 2005 March 25. 24-hour plot of wind gust. Time is in LST (PST).

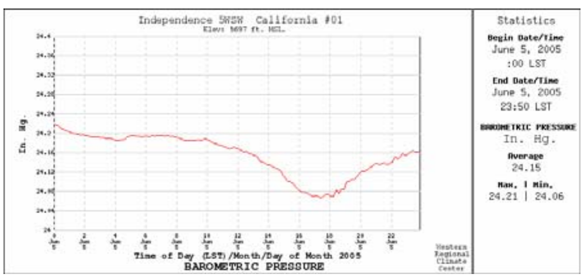

Fig. 8i. Station 1 (DRI-Mesonet) – 2005 June 05. 24-hour plot of surface pressure. Time is in LST (PST).

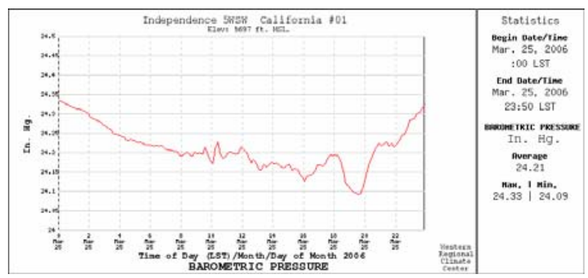

Fig. 8l. Station 1 (DRI – Mesonet) – 2005 March 25. 24-hour plot of surface pressure. Time is in LST (PST).

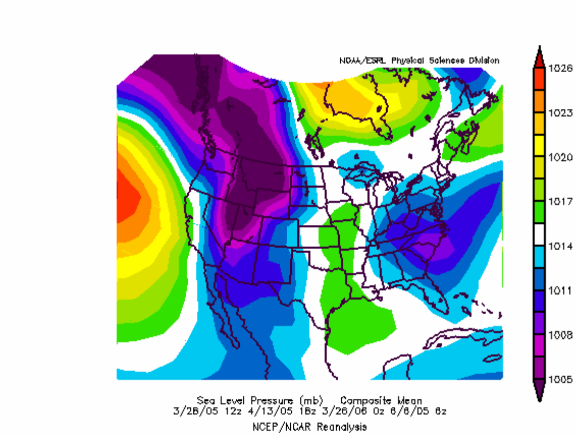

Figure 9. NCEP/NCAR reanalysis composite of 4 Type 2 events. The color image depicts the mean Sea Level Pressure field.

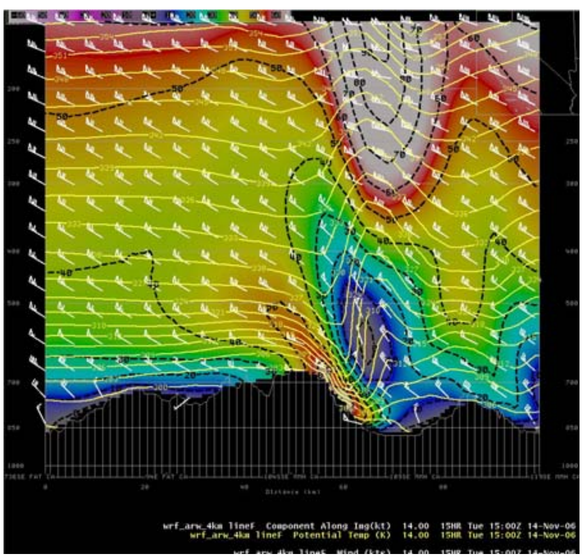

Figure 10. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF-ARW centered over Independence, CA at 1500 UTC 14 November 2006. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

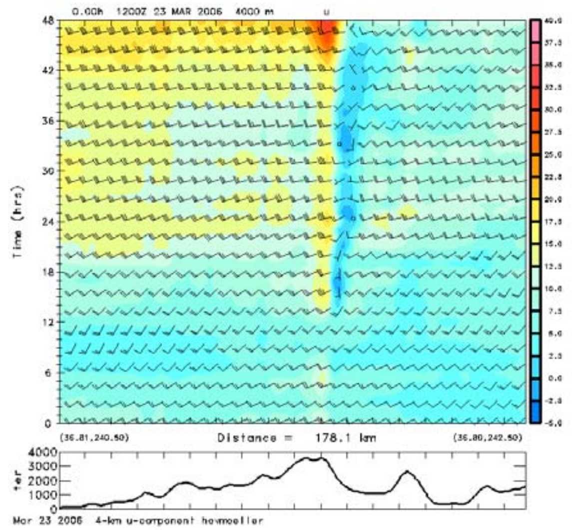

Figure 11. 48-hour hovmoeller diagram from 2-km NRL COAMPS run at 1200 UTC 23 Mar 2006. The horizontal wind speed (m s^{-1}) and direction are shown. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

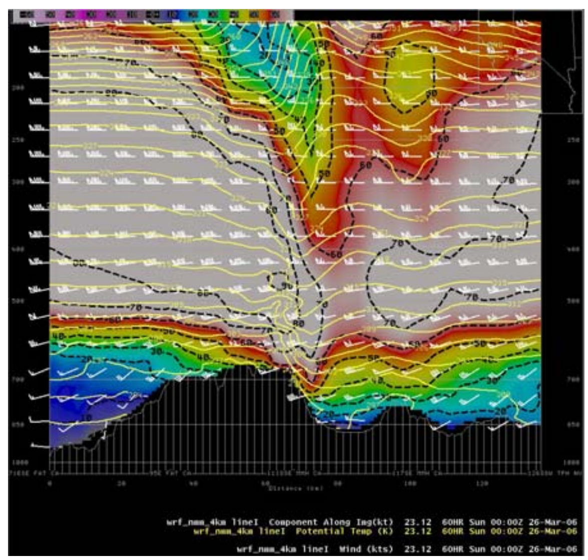

Figure 12. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF centered over Independence, CA at 0000 UTC 26 March 2006. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

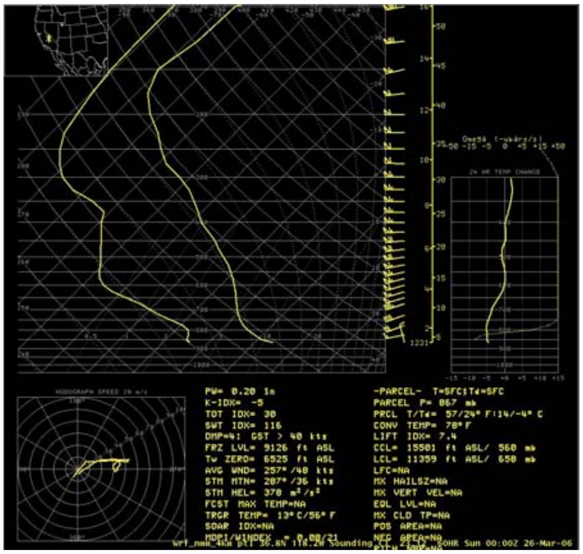

Figure 13. Skew-T Log P thermodynamic sounding for Independence, CA at 0000 UTC 26 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

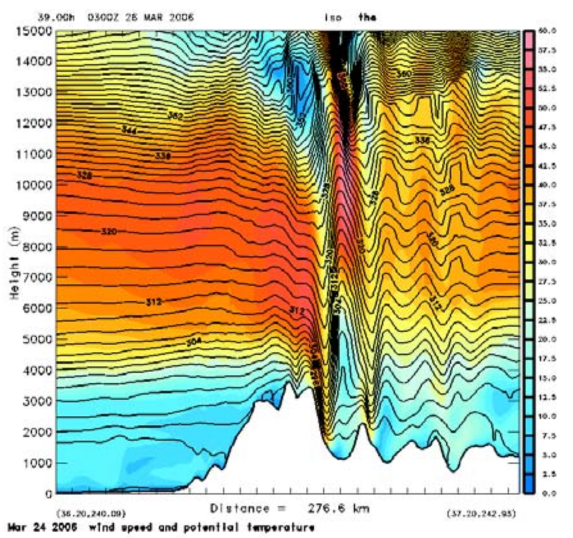

Figure 14. East-west vertical cross section from the 2-km NRL COAMPS centered over Independence, CA at 0300 UTC 26 March 2006. The color image depicts the wind speed (m s^{-1}). The black lines depict lines of potential temperature.

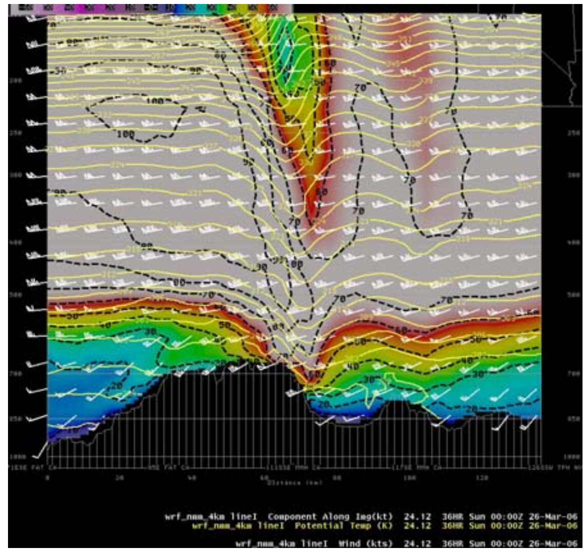

Figure 15. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF centered over Independence, CA at 0000 UTC 26 March 2006. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

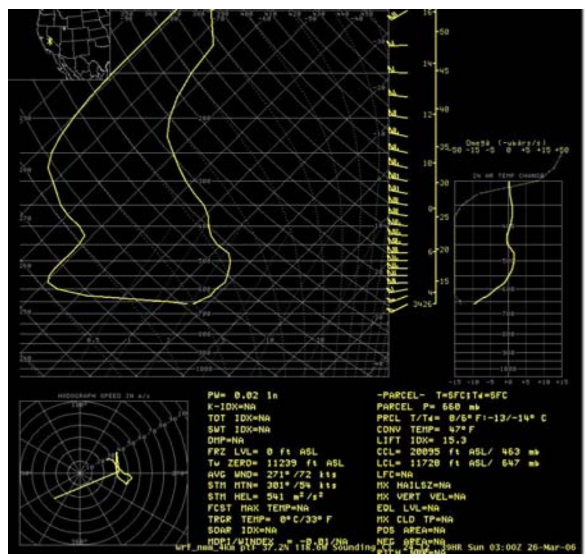

Figure 16. Skew-T Log P thermodynamic sounding for Sierra crest west of Independence, CA at 0300 UTC 26 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

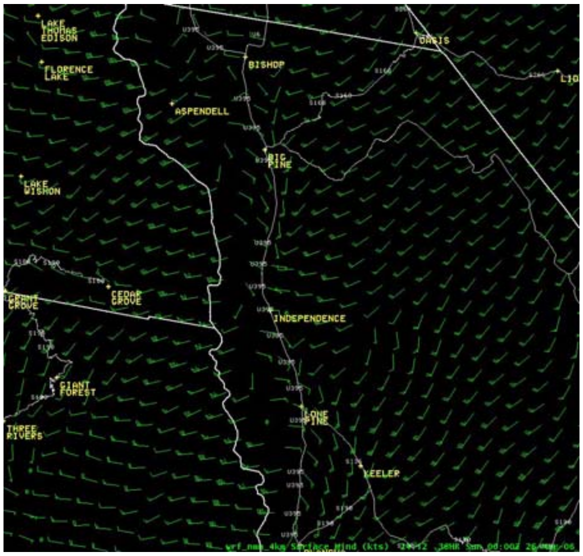

Figure 17. Surface wind speed (m/s) from NWSFO Las Vegas 4-km WRF for 0000 UTC 26 March 2006. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

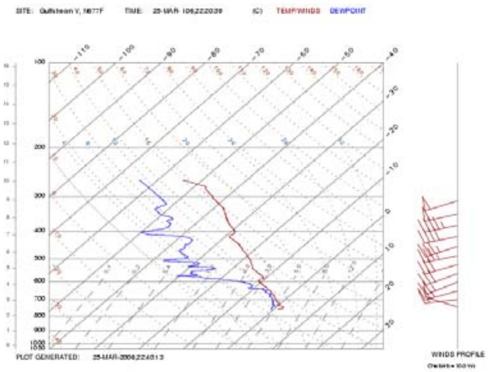

Figure 19. Skew-T Log P thermodynamic sounding from an NCAR Gulfstream-V dropwindsonde near the Sierra crest southwest of Independence, CA at 2220 UTC 25 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

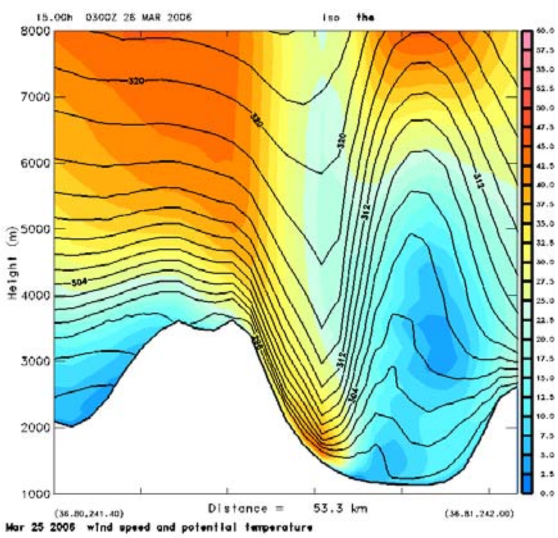

Figure 18. East-west vertical cross section from the 2-km NRL COAMPS centered over Independence, CA at 0300 UTC 26 March 2006. The color image depicts the wind speed (m s^{-1}). The black lines depict lines of potential temperature.

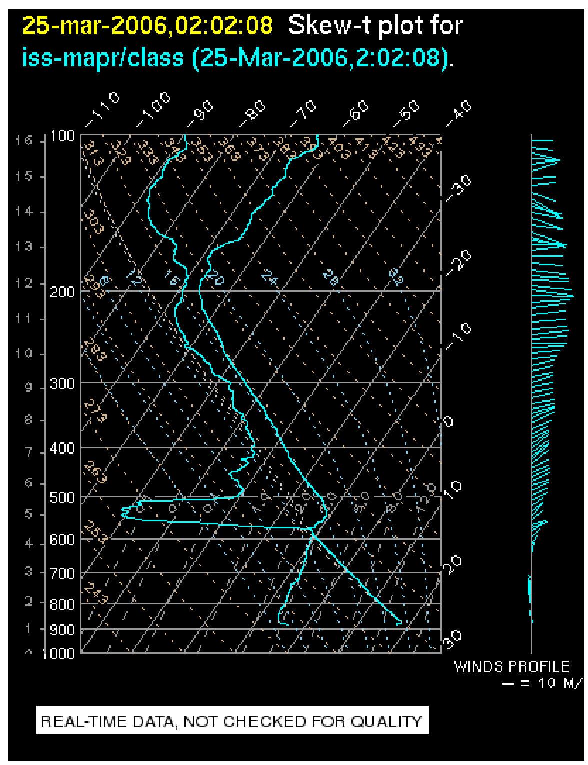

Figure 20. Skew-T Log P thermodynamic sounding from NCAR's MAPR in Independence at 0202 UTC 26 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right.

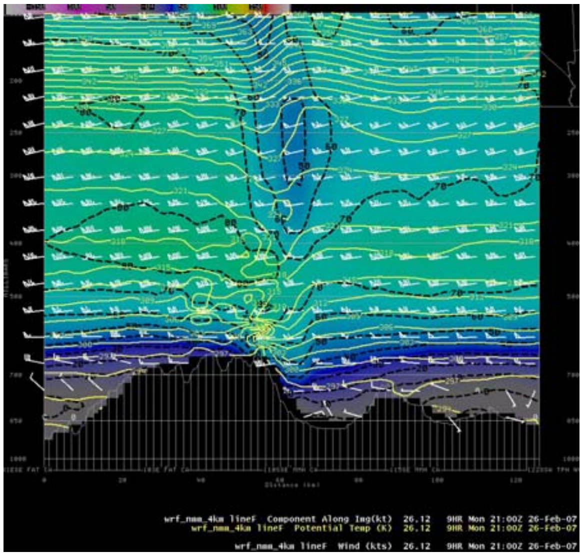

Figure 21. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF-NMM centered over Independence, CA at 2100 UTC 26 February 2007. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

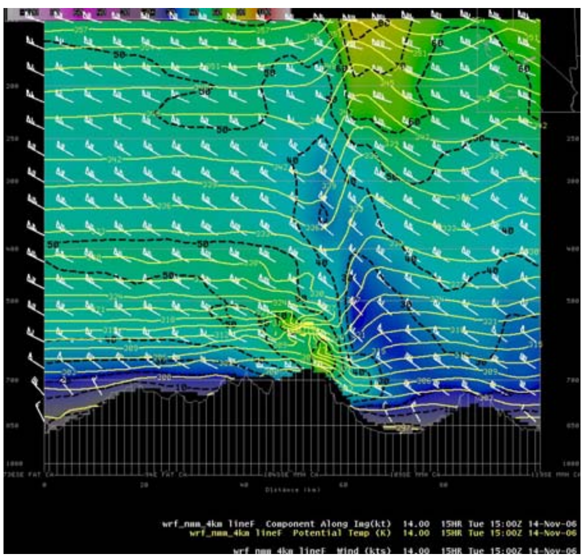

Figure 22. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF-NMM centered over Independence, CA at 1500 UTC 14 Novermber 2006. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

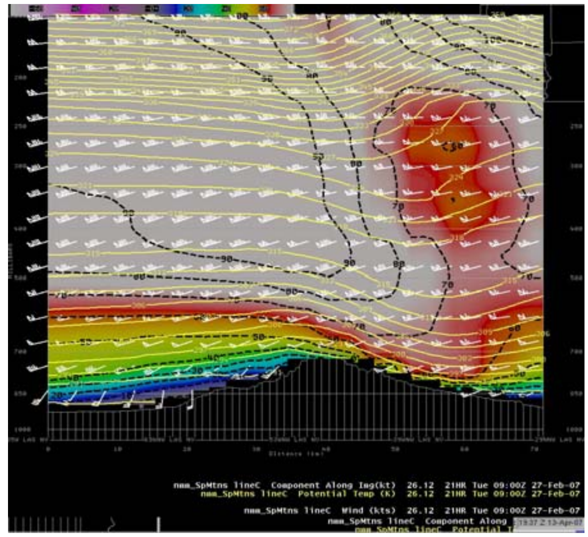

Figure 23. Northwest-southeast vertical cross section from the NWSFO Las Vegas 4-km WRF-NMM centered over the Spring Mountains and Red Rock Canyon, NV. The figure is a 21 hour forecast for 0900 UTC 27 February 2007 from 26 February 2007 12 UTC. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

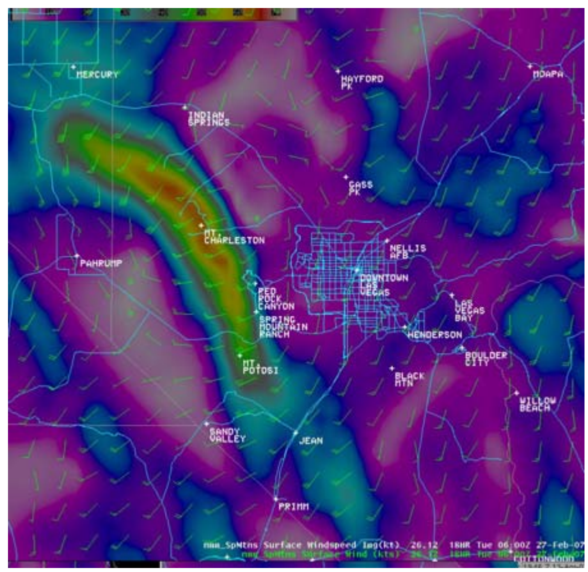

Figure 24. NWSFO Las Vegas 4-km WRF-NMM centered over the Spring Mountains and Red Rock Canyon, NV. 21-hour forecast for 0900 UTC 27 February 2007 from 26 February 2007 12 UTC. The color image depicts the wind speed (knots). The wind barbs depict the wind speed (knots) and direction.

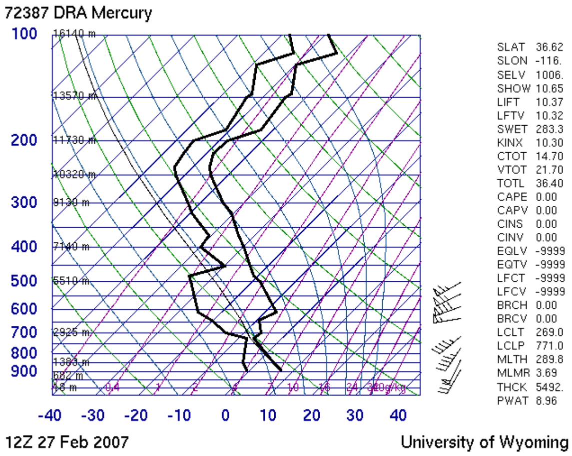

Figure 25. Skew-T Log P thermodynamic sounding from Desert Rock, NV at 1200 UTC 27 February 2007. The horizontal wind speed (knots) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

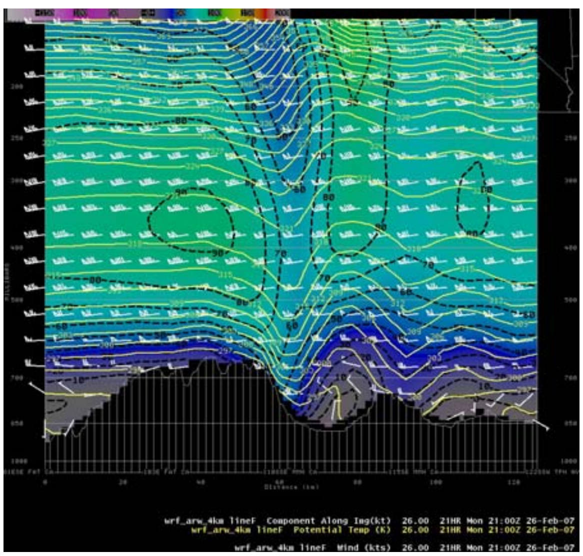

Figure 26. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF-NMM centered over Independence, CA at 2100 UTC 26 February 2007. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depict the wind speed and direction.

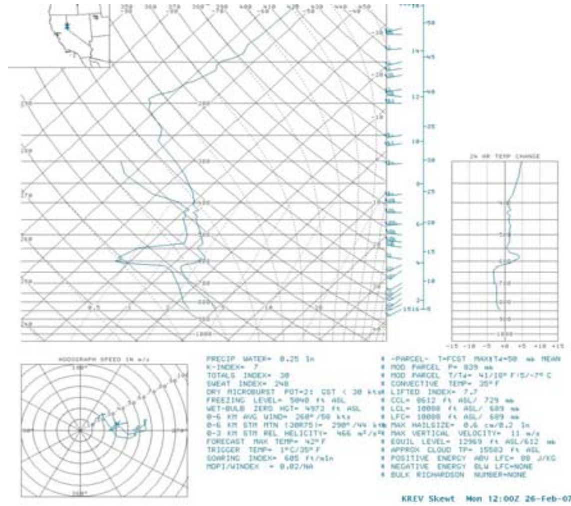

Figure 27. Skew-T Log P thermodynamic sounding from Reno, NV at 1200 UTC 26 February 2007. The horizontal wind speed (knots) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

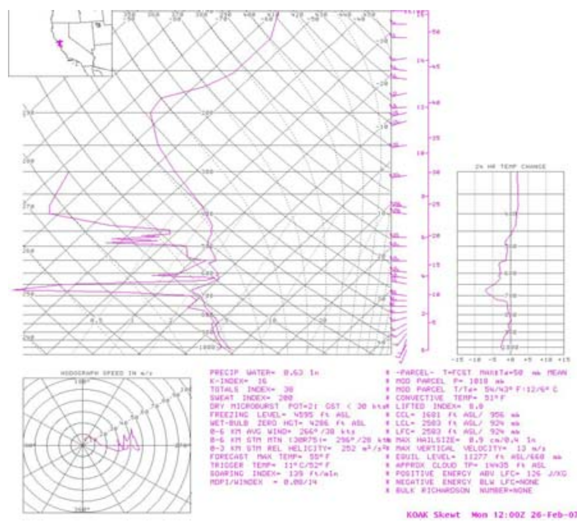

Figure 28. Skew-T Log P thermodynamic sounding from Oakland, CA at 1200 UTC 26 February 2007. The horizontal wind speed (knots) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

Hour of Day Ending at L.S.T.	Wind Ave. mph	Wind V. Dir. Deg	Wind Max. mph	Air Temperature Mean Deg. F.	Air Temperature Max Deg. F.	Air Temperature Min Deg. F.	Relative Humidity Mean Percent	Relative Humidity Max Percent	Relative Humidity Min Percent	Dew Point Deg. F.	Wet Bulb Deg. F.	Baro. Press. in. Hg.
1 am	9.8	25	26.2	44.3	46.6	41.5	29	33	27	14	33	25.96
2 am	9.1	344	17.4	42.8	46.5	38.3	31	38	27	15	32	25.97
3 am	5.3	100	10.8	40.3	42.9	37.5	34	38	31	14	31	25.97
4 am	4.7	80	9.8	38.2	40.9	35.2	39	47	35	16	30	25.97
5 am	4.9	21	10.0	34.0	35.4	32.1	49	52	46	17	28	25.98
6 am	5.3	133	10.8	31.8	33.8	29.8	57	62	49	19	27	26.00
7 am	3.5	49	7.5	30.1	32.5	28.9	64	68	57	21	26	26.00
8 am	4.0	126	9.3	33.9	41.3	28.4	61	71	51	22	29	26.02
9 am	6.5	125	12.5	45.0	48.5	41.0	47	51	39	26	36	26.01
10 am	12.1	150	27.3	50.3	52.5	47.9	36	41	31	25	39	26.00
11 am	16.9	117	31.0	58.2	63.2	52.2	23	32	15	20	41	25.98
12 pm	10.9	60	28.0	62.2	64.4	61.0	15	21	14	14	42	25.96
1 pm	16.4	343	38.9	62.4	63.6	61.4	13	15	11	11	41	25.94
2 pm	19.4	314	42.8	65.4	67.5	63.3	11	12	10	9	42	25.91
3 pm	17.4	322	39.9	66.5	67.8	65.1	10	11	9	9	43	25.89
4 pm	29.0	329	57.1	65.1	66.8	63.4	12	13	9	11	43	25.85

Figure 29. Station 12 of the DRI Mesonet located on the eastern side of the Owens Valley, 5 nm ESE of Independence, CA. An easterly component in the surface wind speed is shown during the morning hours, indicative of the footprint of a rotor circulation.