12TH ANNUAL CONFERENCE ON MOUNTAIN METEOROLOGY

P2.5 OPERATIONAL FORECAST SUPPORT BY NATIONAL WEATHER SERVICE FORECAST OFFICE IN LAS VEGAS, NEVADA DURING THE TERRAIN-INDUCED ROTOR EXPERIMENT

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1. INTRODUCTION

The National Weather Service Forecast Office (NWSFO) in Las Vegas, NV provided operational forecast support to the Terrain-induced Rotor Experiment (T-REX) during March and April of 2006. The primary geographic area of interest for T-REX was Owens Valley in California located along the eastern side of the southern Sierra Nevada. Owens Valley is ideally located for the development of mountain waves, downslope windstorms and rotors 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. These mountain waves and particularly the rotor circulations pose a severe hazard to the aviation community. Additionally, the development of downslope windstorms can produce damaging surface-based wind speeds in excess of 50 m s^{-1} (locally). 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 conference call.

2. BACKGROUND

There have been very few research programs which investigated rotor circulations. The Sierra Wave Project, which was also based in Owens Valley, took place during the 1950s (Holmboe and Klieforth 1957) and was the first major field program to study mountain waves and rotors. This was followed by the Colorado Lee Wave Program which took place in the lee of the Rocky Mountains in Colorado during the 1960s and into the early 1970s (Lilly and Toutenhoofd 1969). Recent advances in remote sensing technology, atmospheric modeling and the understanding of boundary-layer processes have provided an opportunity to further study rotors with T-REX (Grubisic and Kuettner 2005).

There were two main weather regimes that were of importance to the T-REX scientific investigators. The first was the probability, timing and intensity of mountain waves, downslope winds and rotors. When some or all of these conditions were expected, the T-REX science director would schedule an Intensive Observing Period (IOP).

During IOPs, all T-REX assets were utilized including the deployment of three airborne platforms: The NCAR Gulfstream-V (G-V) HIAPER (High-Performance Instrumented Airborne Platform for Environmental Research) aircraft was stationed in Broomfield, CO; the University of Wyoming's King Air aircraft was based in Bishop, CA; and the University of Leeds BAe-146 aircraft operated from Fresno, CA. Additionally, during IOPs more frequent soundings from wind profilers and radiosondes were scheduled and full activation of all other remote sensing instrumentation was enacted.

The second weather regime of importance was referred to by scientific investigators as quiescent conditions. During quiescent conditions, light flow aloft and thermally driven circulations at the surface were the dominant meteorological conditions. When these conditions were expected the science director would call for an EOP (Enhanced Observing Period), where all assets were utilized except the airborne platforms.

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3. PREDICTION OF TERRAIN-INDUCED PHENOMENON

Operationally, it is the development of conditions that are conducive to produce a significant downslope wind event that was the main interest of the NWSFO Las Vegas. 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

A small set of recent cases which occurred in Owens Valley that produced vertically propagating waves, strong downslope winds and the development of a rotor indicated the presence of:

1) stronger cross barrier flow (15+ m s^{-1})
2) stable environment at ridge top level
3) reverse shear aloft

In addition to predicting the occurrence of downslope wind events, the daily weather discussion also contained other terrain induced phenomenon including mountain waves, vertically propagating waves, breaking waves and rotor circulations.

The conditions necessary for the development of mountain waves include:

1) sufficient cross barrier flow (minimum threshold of 10 m s^{-1} near ridge top level)
2) neutral or preferably stable environment near ridge top level.

To aid in determining whether conditions would favor trapped waves or vertically propagating waves, the 1.6 rule was utilized. Trapped lee waves are likely to occur when significantly increasing forward wind shear exists. 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.

Much of the theoretical understanding of mountain waves, downslope winds and rotors have been concisely organized into a web training module from UCAR's Meteorology Education and Training (METED) website (www.meted.ucar.edu). This module, along with forecast experience from the SRP, was applied by NWSFO Las Vegas during their forecast support of T-REX.

4. SUPPORT

The primary Forecast Operations Center (FOC) for T-REX was located at the NWSFO in Las Vegas, Nevada. Additional forecast support was provided by meteorologists at the T-REX Operations Center in Bishop, CA which entailed nowcasting, pre-flight briefings and other specialized forecasts that were issued as needed.

Due to the level of support that was required for T-REX, a dedicated T-REX forecast shift was instituted at NWSFO Las Vegas for the duration of field experiment. A 4-hour shift was required for the preparation, production and presentation of the daily weather discussion. In addition to the normal suite of observations, NCEP guidance and products that are available through the Advanced Weather Interactive Processing System (AWIPS), several project specific models were run and utilized in support of T-REX forecast operations.

The project specific models included a nested 2/6/18-km Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS) model run by the Naval Research Laboratory (NRL) and a 4-km Nonhydrostatic Mesoscale Model (NMM) core of the Weather and Research Forecasting (WRF) system which was run locally at the NWSFO Las Vegas. These models were run twice daily at 0000 UTC and 1200 UTC. The COAMPS was run for a duration of 48 hours and the WRF NMM was run through 60 hours.

There were two main methods that NWSFO Las Vegas utilized in providing operational forecast support during T-REX. The first was by using the T-REX field data catalog set up by the National Center for Atmospheric Research's (NCAR) Earth Observing Laboratory (http://catalog.eol.ucar.edu/trex/). A written forecast discussion and its associated images and forecast products were posted to the data catalog on a daily basis. This written discussion consisted of an analysis of current conditions, a detailed one to three day forecast and an extended outlook (which ranged from 5 to 10 days). Observations (surface, radar, satellite, etc.), model prognostics and data from research instrumentation were all utilized in the production and delivery of the daily weather discussion.

The AWIPS imagery that was included in the written discussion was captured and uploaded to the T-REX data catalog prior to the delivery of the 1200 Pacific Time conference call.

The second method of forecast support was through a conference call that was conducted daily at 1200 PST/PDT. The written forecast discussion and the associated images were utilized in a conference call during the daily operations meeting. Images from the data catalog were pre-loaded at the T-REX operations center and used to provide context for the forecast issues throughout the forecast period. The daily conference call generally lasted thirty minutes which included time for the discussion and a period of question and answers.

Additionally, during IOPs a morning update was posted to the T-REX data catalog to provide the latest thinking for the potential or the status of an ongoing mountain wave or downslope wind/rotor event.

During the project Stan Czyzyk (NWSFO Las Vegas Science and Operations Officer) and John Adair (NWSFO Las Vegas Senior Meteorologist) conducted a site visit to the T-REX operations center in Bishop, CA and to various instrumentation sites in and around Independence, CA. The site visit was invaluable and provided a better sense of how the information was being utilized in decision making and provided an enhanced level of understanding on the scope of the project. Based on the visit, a conference call was added to the beginning of the forecast shift in order to discuss the pertinent operational issues of the day with the science director. This phone call provided an opportunity to affirm or redirect the focus of the noon briefing.

5. CASE STUDY – 25 MARCH 2006

a) 23 March 2006

A Hovmoeller diagram (Fig. 1) from the 1200 UTC run of the COAMPS was indicating strong cross barrier flow beginning at 0600 UTC 25 March. The local WRF run from 1200 UTC 23 March was depicting a strong mountain wave signature (Fig. 2), critical level aloft (between 150 and 200 mb) and 30-35 m s^{-1} of cross barrier flow at ridge top, increasing to 45 m s^{-1} of cross barrier component at 450 mb at 0000 UTC 26 March. A sounding also at Independence at 0000 UTC 26 March depicted a stable layer between 600 and 700 mb (Fig. 3). A similar depiction (although slightly weaker) was indicated for Bishop (not provided).

The following was an excerpt from the T-REX forecast on 23 March, *"Saturday afternoon appears to be the best opportunity for the strongest waves, breakings waves and the potential for downslope winds into the Owens Valley."*

Following the discussion the decision was made to put the T-REX community on alert for a possible IOP from 2000 UTC 24 March through 0500 UTC 26 March.

b) 24 March 2006

The COAMPS run at 1200 UTC depicted significant mountain wave activity in cross section centered on Independence and strong downslope wind along the eastern Sierra and into Owens Valley peaking at 0300 UTC 26 March (Fig. 4). The local WRF run at 1200 UTC continued to depict strong mountain waves and a significant downslope wind event peaking at 0000 UTC 26 March (Fig. 5). The WRF also continued to hint at the potential of a self induced critical level aloft (150-200 mb). A sounding from the WRF near the Sierra crest west of Independence at 0300 UTC 26 March indicated a stable layer between 650 and 550 mb and 25 m s^{-1} of cross barrier flow at ridge top (Fig. 6). The surface wind forecast from the WRF showed 30 m s^{-1} along the Sierra crest at 0000 UTC 26 March 26 (Fig. 7) and easterly flow along the east side of the valley, hinting at the presence of a rotor circulation.

The following was an excerpt from the T-REX forecast on 24 March, *"Between 15 and 00Z the COAMPS depicts more of a trapped wave scenario due to the strong forward shear. This shear is decreased around the time of the trough passage. This is consistent with the ECMWF and 4km WRF. Both of these models depict the strongest vertically propagative waves during Saturday afternoon/evening from 21Z through 03Z." "Two soundings taken from the WRF near the crest of the Sierra west of Bishop depict a more conducive stability profile at 00Z and even moreso by 03Z when strong westerly flow persists. The COAMPS also shows a similar stability profile at 00Z Sunday at*

Independence. Beyond 03Z the flow becomes more northwesterly behind the trough. You can see strong 60 knots of surface wind over the higher terrain west of Independence and easterly flow along the east side of the valley, hinting at the presence of a potential rotor."

Prior to the discussion, the decision was made to start the IOP at 2000 UTC 24 March and continue it through 0500 UTC 26 March 26.

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. 8). A GPS dropwindsonde from the G-V aircraft, at 2220 UTC 25 March, (3-4 hours prior to the onset of the downslope wind event) indicated an inversion near 600 mb and 12 m $s-^{1}$ of ridge top cross barrier flow with strong forward shear (Fig. 9). A sounding from the National Center for Atmospheric Research's (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 mb (Fig. 10), a backing of the wind and a reduction in the forward shear with the approach of the trough.

The following was an excerpt from the T-REX forecast on 25 March, *"Mesoscale models continue to suggest maximum activity this afternoon and early evening between 21Z and 03Z (1 pm - 7 pm PST). A plan view from this morning's 2km COAMPS run for 00Z and a cross section over the Owens Valley for 03Z illustrate the event when it is forecast to be at its peak."*

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 Independence 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 Independence 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 1145 meters). In addition to impacting the local population, these downslope wind events impact a highly traveled corridor of US 395 through Owens Valley. The severe winds are a fairly common occurrence and during T-REX two tractor trailers were blown over along US 395.

6. LESSONS LEARNED

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 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 4-km WRF model was less sensitive to mountain waves in particular, but many instances provided a more realistic depiction and timing for the moderate to strong downslope wind events. The availability and use of high resolution non-hydrostatic mesoscale models provided a significant enhancement to both the understanding of mountain waves and downslope wind events and in the ability to better forecast these 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 during that time of day. 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.

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 as previously discussed.

Many of the events occurred as strong southerly flow rather than a classic westerly downslope wind flow. Although we correctly forecasted the high winds in many of these events, we did not anticipate the southerly component.

Significant mountain wave activity and breaking waves can reach the tropopause and into the lower stratosphere as was observed by the NCAR G-V.

6. ACKNOWLEDGEMENTS

The entire forecast staff at NWSFO Las Vegas played a key role in support of T-REX. In particular, John Adair and Barry Pierce provided valuable input in preparing for T-REX and continued to play a significant part throughout the project. Charles Bell also prepared many of the daily discussions and played a pivotal role in support of T-REX.

7. REFERENCES

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Colle, B. A., and C. F. Mass, 1998: Windstorms along the western side of the Washington Cascades. Part II: Characteristics of past events and three-dimensional idealized simulations. *Mon. Wea. Rev.*, 126, 53-71.

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8. ILLUSTRATIONS AND TABLES

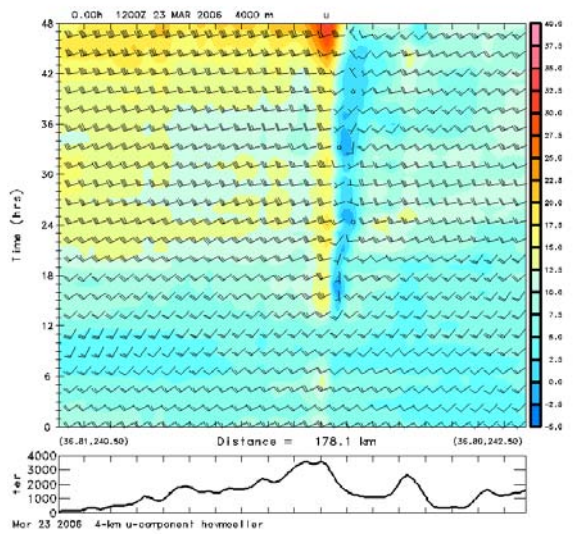

Figure 1. 48-hour hovmoeller diagram from 2-km NRL COAMPS run at 1200 UTC 23 Mar 2006. The horizontal wind speed (m s^{-1}) and direction are shown. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

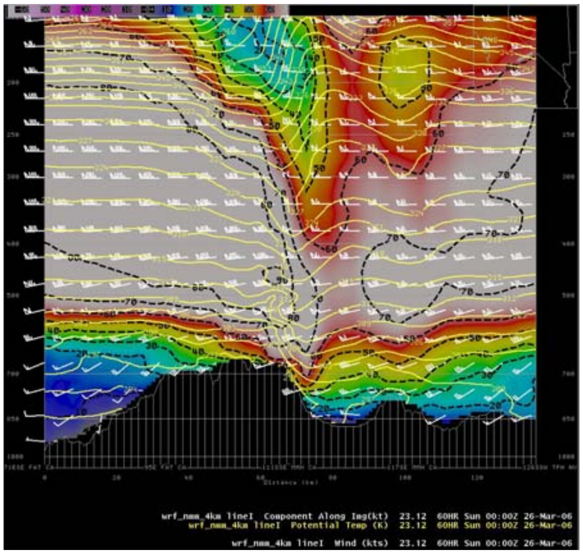

Figure 2. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF centered over Independence, CA at 0000 UTC 26 March 2006. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depicts the wind speed and direction.

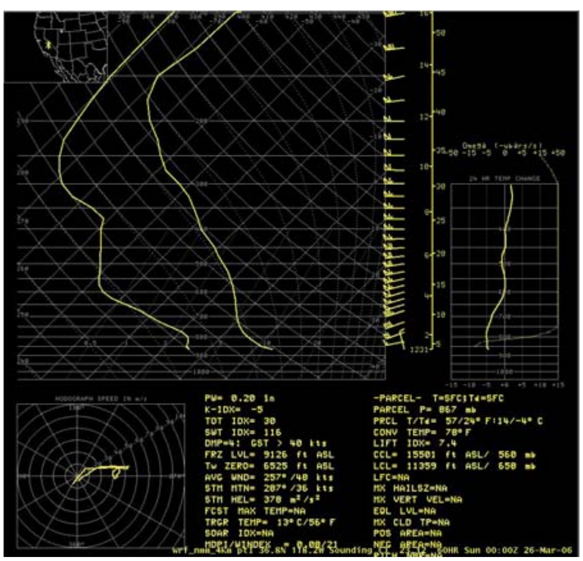

Figure 3. Skew-T Log P thermodynamic sounding for Independence, CA at 0000 UTC 26 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

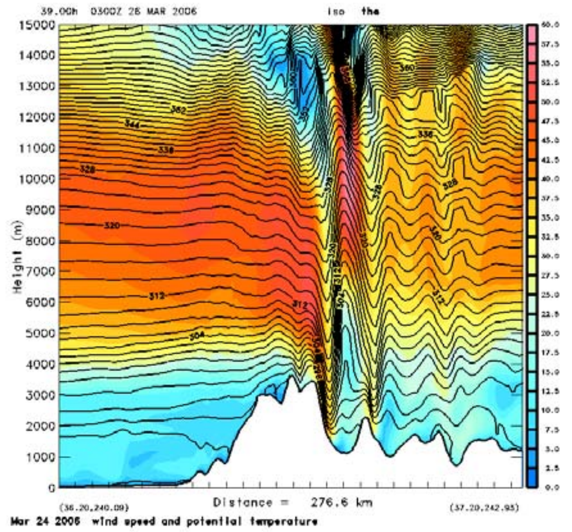

Figure 4. East-west vertical cross section from the 2-km NRL COAMPS centered over Independence, CA at 0300 UTC 26 March 2006. The color image depicts the wind speed (m s^{-1}). The black lines depict lines of potential temperature.

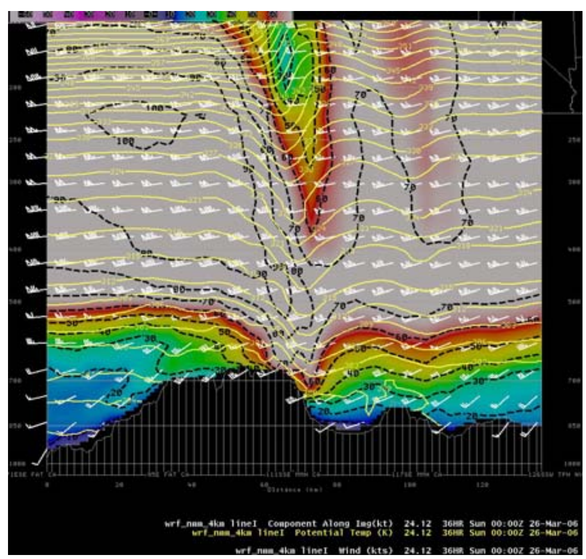

Figure 5. East-west vertical cross section from the NWSFO Las Vegas 4-km WRF centered over Independence, CA at 0000 UTC 26 March 2006. The color image depicts the wind speed (knots) component along the cross section. The green lines depict lines of potential temperature. The wind barbs depicts the wind speed and direction.

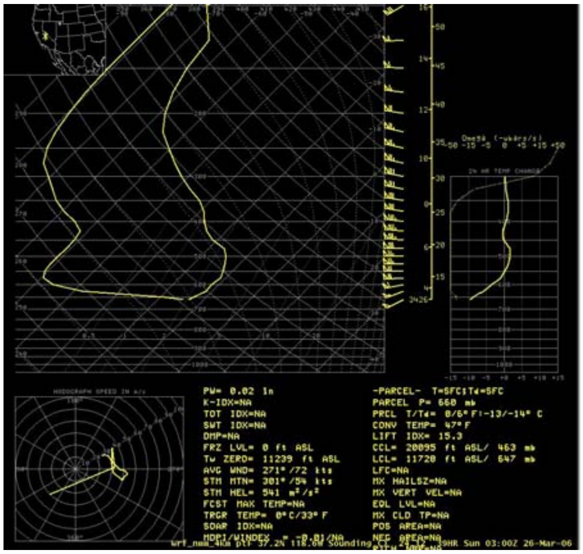

Figure 6. Skew-T Log P thermodynamic sounding for Sierra crest west of Independence, CA at 0300 UTC 26 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

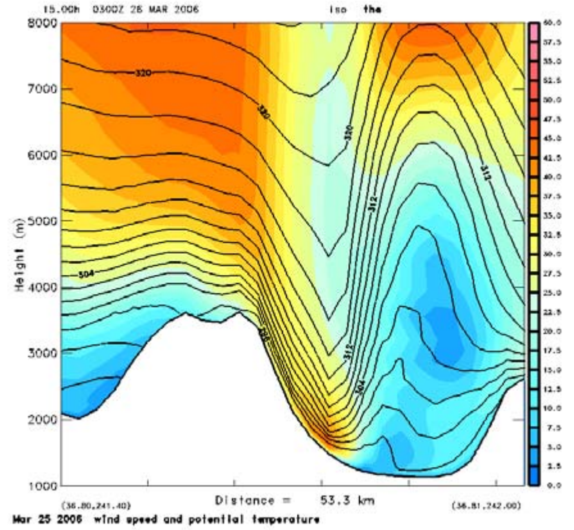

Figure 8. East-west vertical cross section from the 2-km NRL COAMPS centered over Independence, CA at 0300 UTC 26 March 2006. The color image depicts the wind speed (m s^{-1}). The black lines depict lines of potential temperature.

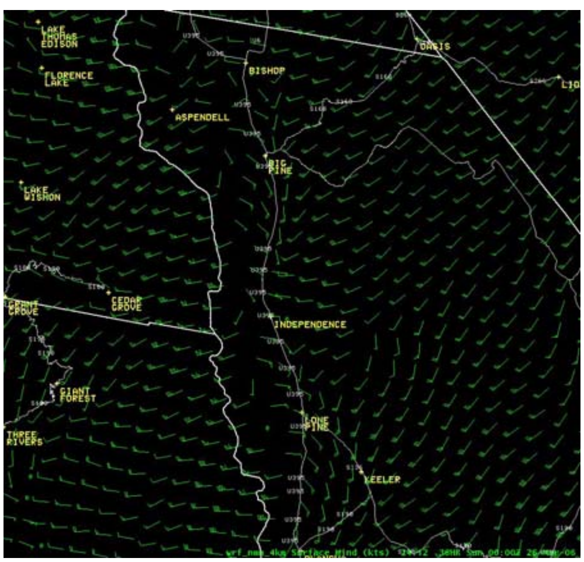

Figure 7. Surface wind speed (m/s) from NWSFO Las Vegas 4-km WRF for 0000 UTC 26 March 2006. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

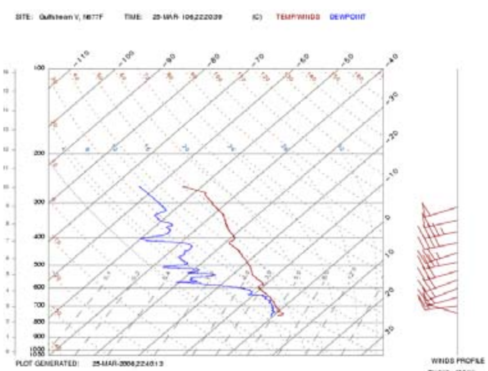

Figure 9. Skew-T Log P thermodynamic sounding from an NCAR Gulfstream-V dropwindsonde near the Sierra crest southwest of Independence, CA at 2220 UTC 25 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right. One full wind barb corresponds to 5 m s^{-1} and a flag denotes 25 m s^{-1}.

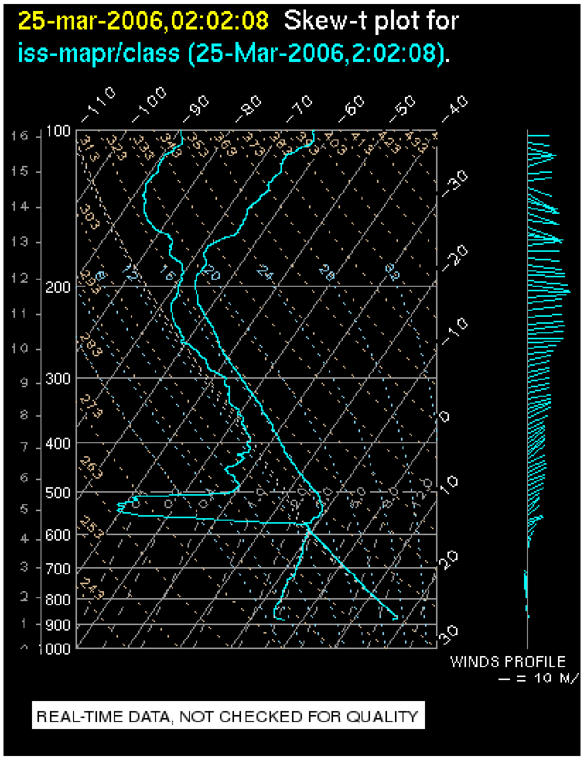

Figure 10. Skew-T Log P thermodynamic sounding from NCAR's MAPR in Independence at 0202 UTC 26 March 2006. The horizontal wind speed (m s^{-1}) and direction are shown to the right.