MODELING AND FORECASTING LEE SIDE SPILLOVER PRECIPITATION RESULTING IN MAJOR FLOODING IN AN URBAN VALLEY LOCATION

Michael L. Kaplan*, Phillip J. Marzette, Christopher S. Adaniya and K.C. King
Division of Atmospheric Sciences, Desert Research Institute, Reno, Nevada

S. Jeffrey Underwood
Department of Geography, University of Nevada Reno, Reno, Nevada

* Corresponding Author Address: Michael L. Kaplan, Division of Atmospheric Sciences, Desert Research Institute, Reno, Nevada, 39512; e-mail:mike.kaplan@dri.edu

1. INTRODUCTION

Forecasting weather on the urban scale is extraordinarily challenging. This is particularly true when the urban location is surrounded by complex terrain such as a coast or mountain range. The scale of local geographic forcing is so much smaller than the larger scale synoptic environment that simultaneous circulations at the synoptic and multiple mesoscales can occur with complex nonlinear interactions among them. Most important is the simple fact that even large urban areas are essentially point locations when compared to the multiple atmospheric circulations that control their local weather. Thus the problem of simulating the interaction among terrain-induced circulations and the larger scale environment represents an extraordinary challenge for the future of both numerical modeling and weather forecasting at the urban regional scale.

2. MOTIVATION AND HYPOTHESIS

With some frequency devastating cold season flooding occurs in the lee side mountain valleys of the intermountain western U.S. The flood of late December 2005 in the Truckee River Basin of northwestern Nevada including the cities of Reno and Sparks, Nevada, was such an event. During this event, major urban flood damage and economic dislocation occurred as the Truckee River overflowed its banks when river stream flow rates exceeding 15,000 cubic feet/second were recorded in downtown Reno (e.g., Underwood et al. 2009). Rainfalls in excess of 250 mm were widespread on the upslope of the Sierra Nevada and Carson Mountain Ranges that drain into the Truckee as it crosses from California to Nevada (Fig. 1). Additional spillover precipitation on the immediate lee of the Carson Range exceeded 100 mm while the local urban observations at Reno within the Washoe Valley approached 50 mm all in less than 36 hours. Such 36 hour rainfall in the Reno area is extreme for a lee side semi-arid valley location where ***annual*** precipitation is 175 mm. Very warm temperatures insured that the liquid precipitation occurred on the mountain ranges to elevations in excess of 3 km MSL.

In this study we will examine the state-of-the-science of numerical weather prediction in an effort to diagnose the capabilities and limitations of numerical models in simulating such a complex weather event spanning the synoptic, meso-α, β and γ (urban) scales of atmospheric motion. In particular, we will test the following hypothesis: *the inability of a numerical model to accurately simulate the location and evolution of counter rotating meso-γ scale vortices on the lee side of a mountain within an urban valley from contemporary large scale analyses datasets contributed to a displacement of precipitation location amount that represented a major urban scale error in precipitation amount at the point location of the Reno, Nevada airport. A fundamental error in this simulation reflected the imperfect representation of the Froude number in the precursor environment thus biasing the location of the meso-γ scale vortices southwestward relative to their inferred observed location.*

3. METHODOLOGY

For this 30-31 December 2005 event, we will describe the observational processes employing asynoptic observations in and surrounding the Reno-Sparks, Nevada urban region. These observations include: Automated Surface Observing System (ASOS), Doppler radar, rawinsonde, as well as the North American Regional Reanalysis (NARR; Mesinger et al. 2006) 32-km horizontal resolution dataset in 3-hour intervals.

To provide meso-α, β and γ (urban) scale spatial detail, enhanced time continuity, and to determine more about the state-of-the-science numerical modeling/simulation of such an event, a numerical weather prediction modeling system was employed for in depth comparative analyses. The numerical model employed was the Operational Multiscale Environment model with Grid Adaptivity (OMEGA) developed by Science Applications International Corporation (SAIC; e.g., Bacon et al. 2000). OMEGA is a nonhydrostatic numerical weather prediction model that uses an unstructured, adaptive triangular prism grid for its mesh instead of a conventional structured lattice. The reasoning for the triangular grid being that triangular prisms are better suited for adapting to complex terrain and plumes, efficiently placing the highest resolution where it is needed. Since terrain-induced processes are critical to this study, the static grid adaptivity option in OMEGA is desirable in which very high resolution is focused on the region of strongest terrain gradients. A detailed explanation of the model physics that OMEGA employs is available in Bacon et al. 2000. The model simulations employed in this research were full-physics (control) for two different initial conditions (e.g., Marzette et al. 2009). A comparison of initialized datasets was performed. The initialized dataset comparison included: 1) the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR; Kalnay et al. 1996) reanalysis with a 2.5 x 2.5 degree horizontal resolution dataset and 2) the Aviation Quasi-Rectangular Octant grid (AVN) with approximately 1.25 x 1.25 degree horizontal resolution.

A maximum resolution statically adaptive grid (adapted to the terrain gradients) was employed for the simulations, which contained a 1-km horizontal resolution mesh, within a 5-km horizontal resolution mesh, within a 20-km horizontal resolution mesh along with 34 unevenly-spaced vertical levels. There was no interactivity among grids so that each simulation was a subexperiment and the lateral boundary conditions as well as initial conditions were adapted from the same synoptic scale observed dataset. The physics in OMEGA included a PBL scheme that treats the surface, viscous and transition layers separately with the turbulence kinetic energy (TKE) closure scheme derived from Mellor and Yamada (1974). The full-physics simulations used a non-mixed phase microphysics package (Lin et al. 1983) and the Kuo-Anthes convective parameterization scheme (Kuo 1965; Anthes 1977). The results, to be discussed, were all from the 1 km statically adaptive grid simulation.

All dry Froude number calculations in this study were performed employing the following equation:

$$F=U/NH \tag{1}$$

where U represents the average wind velocity in the layer from ~1500m MSL to 2500m MSL, N the dry Vaisalla Frequency over that same layer and H the average height of the upstream terrain above the Reno airport location in the direction between 180 and 270 degrees from Reno, i.e., ~1000 m. This layer and wind quadrant was selected based on the height and location of the Carson Mountains upstream from Reno.

4. RESULTS

4.1 Theory of Counter-Rotating Vortices

There have been many studies in the literature concerning mesoscale lee-side vortices that form during low Froude number regimes, i.e., high static stability regimes accompanying upstream blocking, (e.g., Smolarkiewicz and Rotunno 1989; Smith 1989; Rotunno and Ferretti 2001; Epifanio 2003). The formation mechanism involves the tilting of baroclinically-generated vorticity on the lee side of the mountain as well as the nonconservation of potential vorticity by turbulence dissipation. By specifying dry Froude numbers ~0.22 in an idealized atmosphere, Smolarkiewicz and Rotunno simulated flow around a bell-shaped mountain in which a pair of counter-rotating vortices formed on the lee side. These circulations disappeared as the Froude number was increased to 0.66 in additional simulations, indicating flow over as opposed to around the terrain. Likewise Ferretti and Rotunno simulated the sensitivity of flow around idealized Alpine terrain to the moisture in the column and its effects on static stability with similar results. They found that a saturated air plume with higher moist Froude number tended to flow over complex terrain while a dry air plume with lower moist Froude number rotated around the barrier thus producing a convergence zone that favored heavy precipitation. Additionally, Smith (1989) and Epifanio (2003) created a regime diagram relating inverse dry Froude number to mountain spatial aspect ratio which indicated that for oblong terrain geometries, the transition from wave breaking above a mountain to flow splitting into accompanying lee side vortices tended to occur with Froude number transitions from ~0.7 - 0.5 thus substantiating dry Fr values between 0.5 and 0.6 as the transition from flow over to flow around complex terrain. In this 31 December 2005 case study, Froude number calculations indicate a regime favoring relatively low static stability (Fr~0.4-0.5) and therefore flow around as opposed to over the complex terrain to the southwest of Reno, Nevada during the period of significant spillover precipitation. Both 1) the geometry of the south-north elongated Carson Range just southwest of Reno and the Washoe Valley as well as 2) the wind flow at an angle to the range make for complexities to vortex structure quite different from the aforementioned idealized simulation studies which are based on linear theory and don't take into account the true complexity of natural terrain as well as variations of Coriolis force. Nevertheless, counter-rotating vortices develop in the simulated fields at the meso-β/γ scales, which control the local circulations including complex low-level convergence zones during the period of heavy lee side spillover rainfall. It will be shown that their structure varies as a function of the model initial conditions.

4.2 Observations

Figure 1 describes the subsynoptic precipitation pattern over the Sierra Nevada, northeastern California and northwestern Nevada during the period of the 31 December 2005 event. One can see that the extremely heavy upslope precipitation exceeding 250 mm diminishes gradually over the Carson Range to the east of Lake Tahoe including the Truckee River drainage basin. While this precipitation is still substantial along the immediate lee side of the Carson Range, the western fringe of the precipitation exceeding 25 mm diminishes as one approaches Reno, Nevada (RNO) with further rapidly diminishing values to the northeast. This region including the Carson Range and Reno lies at the meso-α scale in the left exit region of a strong polar jet streak that exhibits gentle curvature and substantial upper-tropospheric velocity divergence. This can be diagnosed from the 250 hPa isotachs and wind barbs depicted in Figure 2 and valid at 1500 UTC during the heavy precipitation at Reno. The strongly diverging ageostrophic vectors support a highly divergent wind flow aloft where the left exit region over the Sierra Nevada lies in proximity to the right entrance region of the downstream jet streak over northern Nevada. Such a left jet exit region and its transverse ageostrophic circulation configuration supports both a low-level return branch circulation as well as diabatically-generated mid-level jetlet with both cross-mountain (~235 degree/west-southwestward) flow and relatively low moist-neutral 700-800 hPa static stability over Reno as can be seen the 1200 UTC sounding in Figure 3. The mass flux divergence in the upper-level flow over the heavy rainfall region can be further confirmed by the northwest-southeast meso-α and meso-β scale low pressure centers/troughs evident in the NARR analyses at 1500 UTC in Figure 4, which subsequently propagate to just west-southwest of RNO by 1800 UTC (not shown). The mesolow near Blue Canyon, California (BLU) at 1500 UTC just west-northwest of RNO is proof of the deep diverging flow with surface southwesterly winds to the west and south of RNO and surface southeasterly winds to the east and north of RNO.

It is interesting and potentially critical to understanding the pattern of spillover precipitation, that the RNO meteogram in Figure 5 does ***not*** simply mimic the elongated northwest-southeast cyclonic circulation evident in the Figure 4 pressure and wind flow in this region. While the mean sea level pressure field and its variation several hours before and after 1500 UTC depicted in Figure 5 shows a steady uninterrupted fall as would be expected from Figure 4, at 1200 UTC and at 1800 UTC the south-

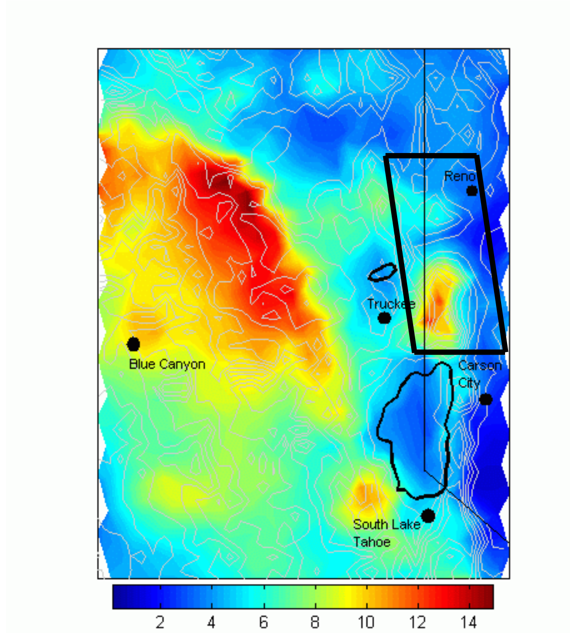

FIG. 1. Multi-sensor analyses precipitation field (inches) for 30-31 December 2005 (25 mm ≈ 1 inch). Black box indicates spillover zone.

southeasterly surface flow abruptly shifts to north-northeasterly flow flanking periods of heavier precipitation at RNO. Importantly, these substantial oscillations in predominantly meridional flow also are confirmed in the local region at surface wind observing locations a few kilometers west and a few kilometers north of the airport, i.e., the University of Nevada Reno and Desert Research Institute observing locations indicating the urban scale signal of these fluctuations. Furthermore, large scale RAWS network observations extending 10's of kilometers in all directions from these urban scale locations do not support these meridional wind observations at the urban scale as they look much more like the NARR analyses in Figure 4. Thus, these various observations at a multitude of scales of motion are indicating a possible meso-γ scale circulation or circulations that are not resolved by the NARR or any other larger scale analyses.

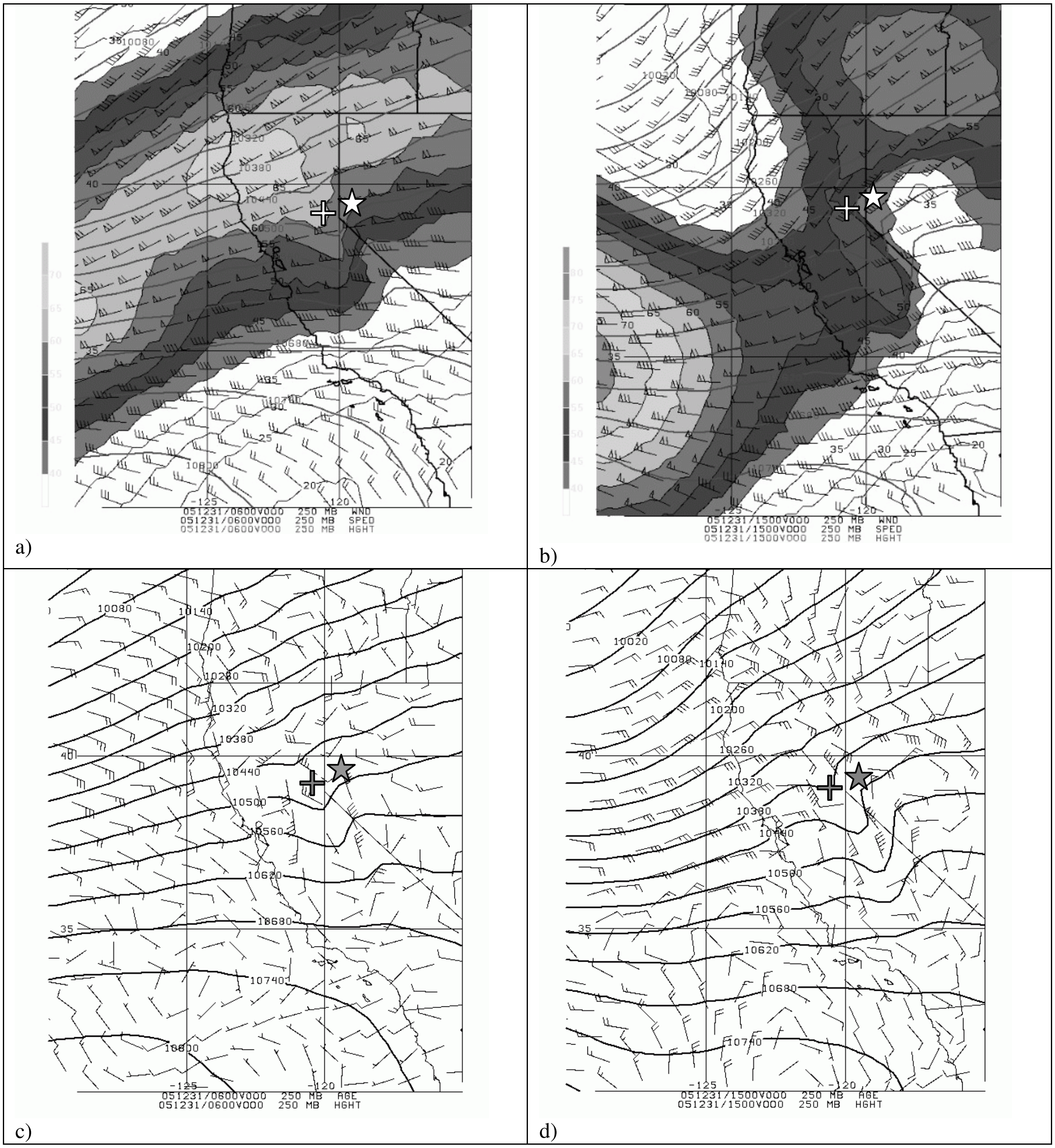

FIG. 2. North American Regional Reanalysis (NARR; a, b) 250 hPa geopotential height (thick contour), isotach (thin contour-color fill) and wind barb (ms^{-1}) plan views and (c,d) 250 hPa geopotential height and ageostrophic wind barb (ms^{-1}) plan view for (a,c) 0600 UTC and (b,d) 1500 UTC 31 December 2005. Star symbols represent Reno, NV and crosses represent Blue Canyon, CA.

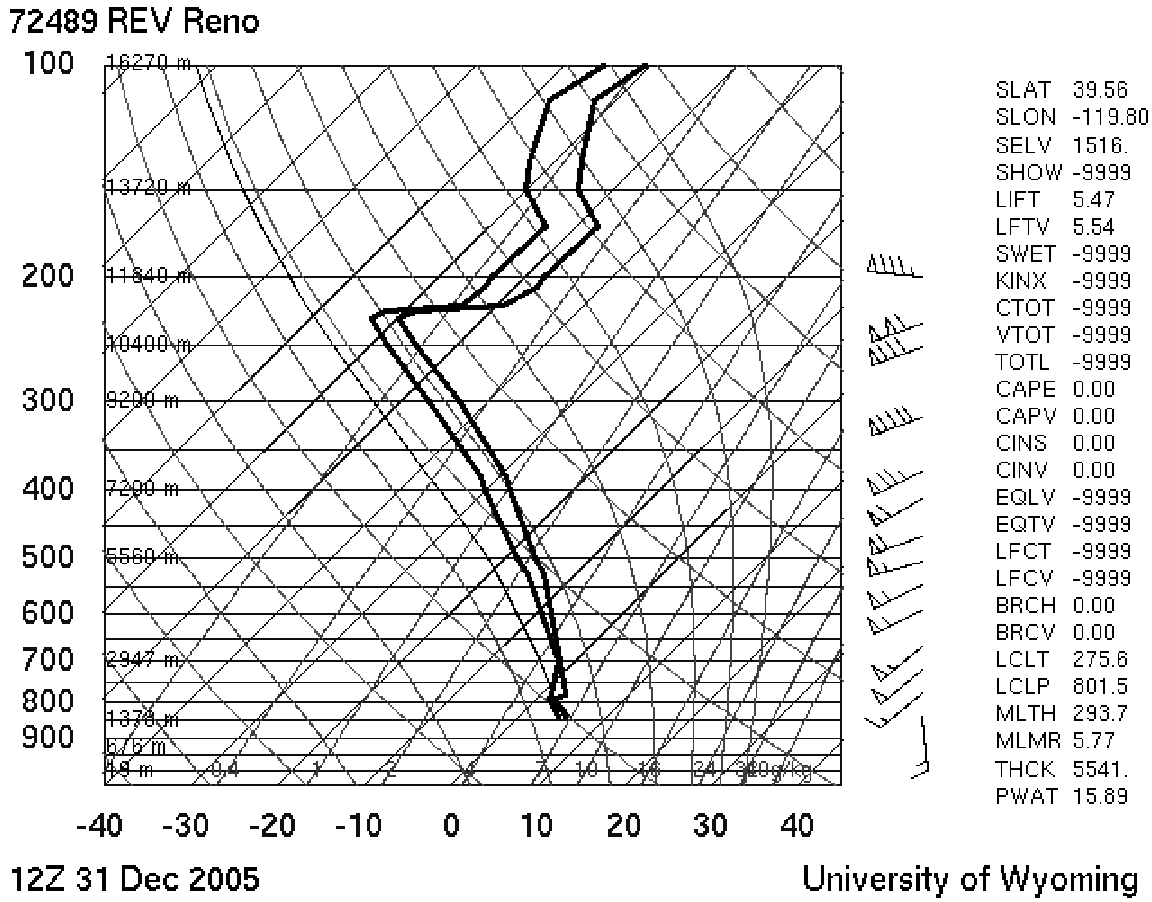

FIG. 3. Observed rawinsonde sounding for Reno, NV (REV) for 1200 UTC 31 December 2005.

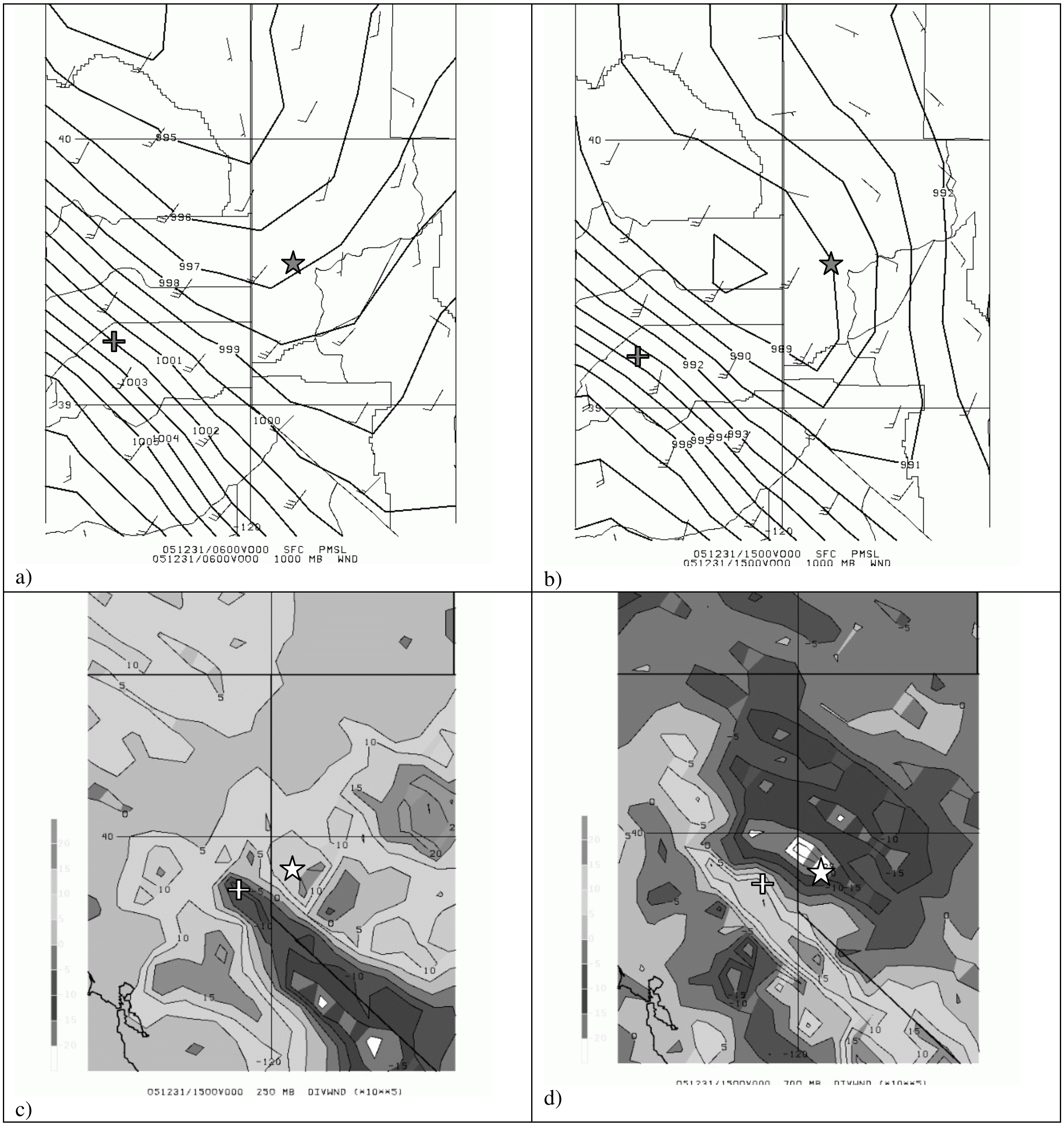

FIG. 4. MSLP (hPa) and surface wind barb (ms^{-1}) plan views for a) 0600 UTC and b) 1500 UTC 31 December 2005. 1500 UTC 31 December 2005 divergence (10^{-5} s^{-1}) at c) 250 hPa and d) 700 hPa.

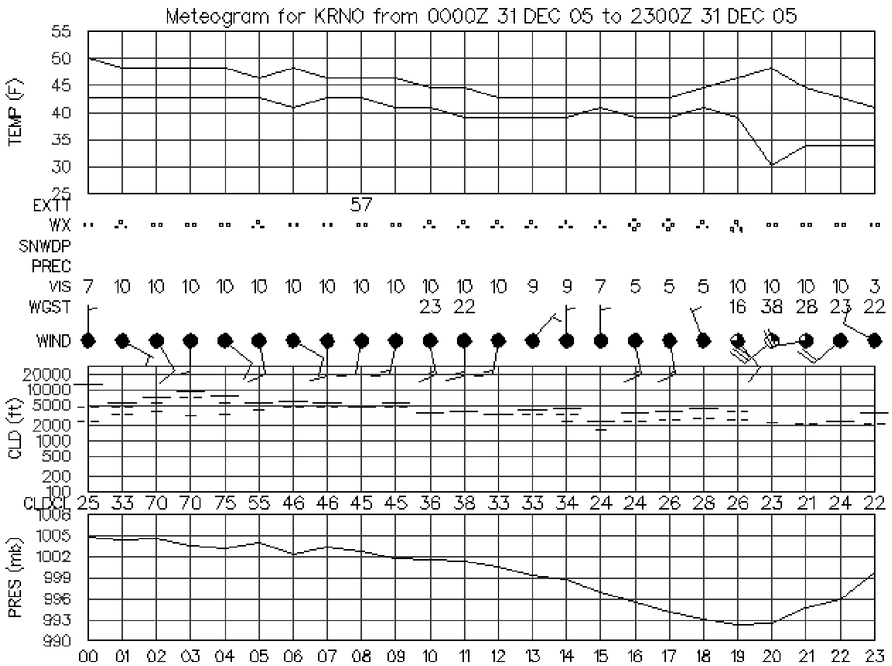

FIG. 5. Observed surface meteogram at Reno, NV (airport location) for 31 December 2005.

4.3 Simulations

The implications of the "urban" scale wind perturbations can be better diagnosed by comparing the two (1 km resolution) statically adaptive OMEGA numerical simulations whose initial conditions were discussed in section 3. Figure 6 depicts 4 key fields from the NCEP/NCAR data initialized simulation and Figure 7 does the same for the AVN data initialized simulation. These fields include: Reno's simulated 1200 UTC sounding for comparison with Figure 3's observed sounding (Figs. 6a, 7a), simulated 1500 UTC mean sea level pressure, surface winds and observed terrain elevation (Figs. 6b, 7b), simulated 1500 UTC 800 hPa vertical velocity (Figs. 6c, 7c) and the 30 minute precipitation from 1500 UTC – 1530 UTC (Figs. 6d, 7d). These fields reflect differing dry Froude number values calculated for Reno from the simulated soundings. The observational value of the Froude number is ~0.482, the NCEP/NCAR simulated value is ~0.406 and the AVN simulated value is ~0.521. Specific simulated features include lee side low and high pressure systems and their surface ageostrophic wind flows/circulations oriented southwest to northeast downstream from the highest terrain. This highest terrain represents the Carson Mountain Range ~10-20 km west and southwest of Reno. One can see several key differences between the NCEP/NCAR and AVN simulations. First, while both simulations exhibit a meso-γ scale (~10-20 km width) lee side low pressure system southwest of Reno and a meso-γ scale high pressure system northeast of Reno consistent with the concept discussed above of counter rotating vortices, in the NCEP/NCAR simulation the lee side low is deeper and displaced to the southwest of the low in the AVN simulation. Furthermore, the features in the NCEP/NCAR simulation have a more circular geometry and near Reno, there is less zonal kinetic energy in the NCEP/NCAR simulation than in the AVN simulation just southwest of Reno. The vertical motion fields indicate that the northwest-southeast band of strong ascent/descent near Reno is just southwest of the city in the AVN simulation while in the NCEP/NCAR simulation it is located farther southwest, is weaker and is not accompanied by a strong descending node, only an ascending node. The rainfall rate is larger in the NCEP simulation and is also displaced somewhat southwest of the AVN simulation.

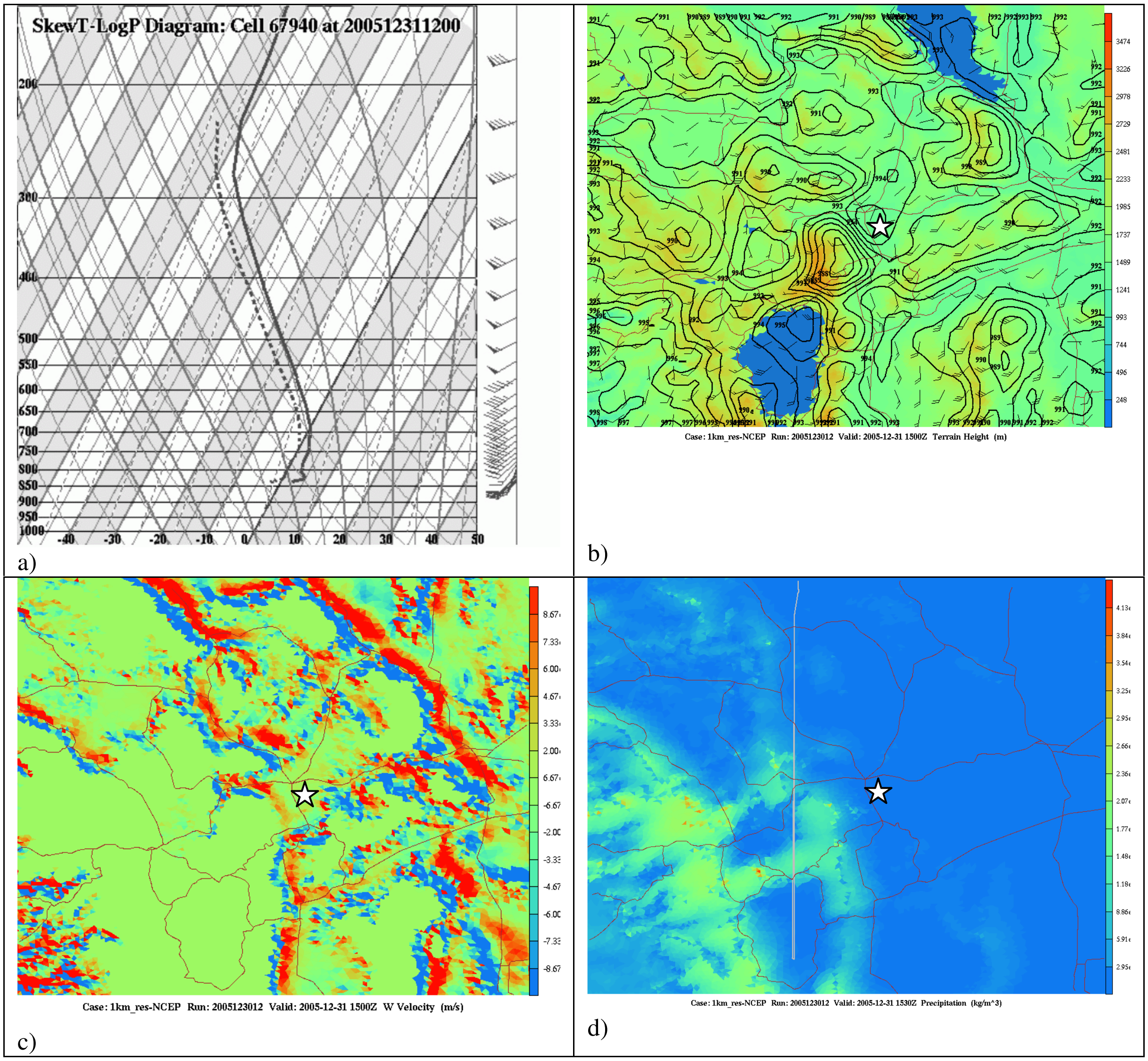

FIG. 6. NCEP-NCAR initialized simulated a) sounding at Reno, NV for 1200 UTC 31 December 2005, b) mslp (hPa), surface wind barbs (ms^{-1}) for 1500 UTC 31 December 2005 and observed terrain elevation (shaded in m), c) 800 hPa vertical velocity (shaded in cms^{-1}) for 1500 UTC 31 December 2005 and d) 30 minute precipitation (shaded in mm) for the period from 1500-1530 UTC 31 December 2005. Star symbols represent KRNO.

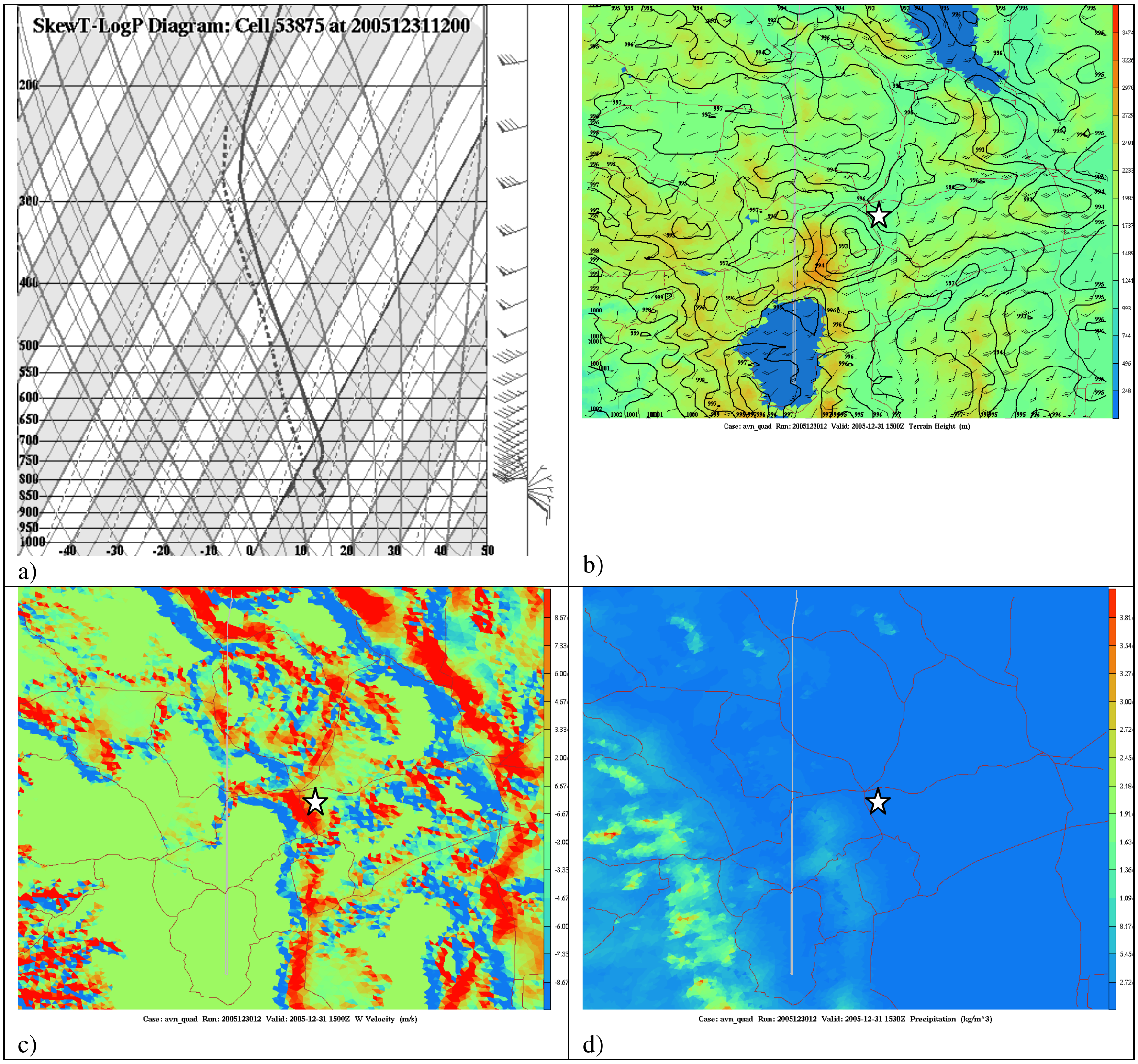

FIG. 7. Same as Fig. 6 for the AVN initialized fields.

5. SUMMARY, CONCLUSIONS AND DISCUSSION

The differences in the location, intensity and wind structure accompanying the simulated surface lee side vortices extending from just northeast of to just southwest of Reno generally reflect the aforementioned idealized studies based on linear theory. These studies unambiguously indicated that there is a regime transition zone from counter-rotating lee side vortices with flow around terrain to flow over terrain as a function of dry Froude number. The observations and two simulations have Froude number values within this transition zone between unambiguously 'flow around' to 'flow over' regimes. While the NCEP/NCAR simulation produces heavier rainfall and more realistic mean sea level pressure minima when compared to observations, its placement of the counter-rotating vortices is biased southwest, nearer the Carson Range relative to the AVN simulated vortices. Furthermore, the AVN wind field at the surface more realistically displays the meridional oscillations in wind direction at Reno and expands the precipitation downstream closer to Reno as observed. These differences do reflect and are consistent with the fact that the AVN reproduces a Froude number regime closer to the observations while the NCEP/NCAR's is less accurate and more stable. Both simulations reflect the fact that their Froude number regimes lie in the transitional range from counter-rotating vortices to flow over terrain. One could therefore infer that the northeastward shifted and more meridional flow vortices in the AVN simulation reflects weaker flow around the terrain and more downstream transport of momentum thus positioning the convergence zone, ascent and meriodional perturbations closer to Reno consistent with the surface observations and rawinsonde-derived Froude numbers. On the other hand the NCEP-NCAR simulated fields are biased closer to the terrain reflecting weaker flow over the mountain and flow more closely coupled/positioned to the oblong geometry of the terrain. Since the AVN produces a more intense and downstream-shifted convergence zone it is rational to deduce that it is more accurately replicating the feature key to extending spillover precipitation towards Reno unlike the NCEP-NCAR which is biased upstream. This dramatizes the difficulty of urban scale simulation in complex terrain in which subtle errors in lower tropospheric wind shear and static stability can shift convergence bands towards or away from features that surround urban regions. The wetter midtropospheric air simulated by OMEGA employing the NCEP/NCAR initial data produced more precipitation and better mesoscale pressure falls however, the increased latent heat associated with somewhat over predicted upstream mountain precipitation likely modified the lapse structure making the model simulation too stable. This in turn reduced the Froude number displacing the finest scale vortices too far to the southwest.

6. ACKNOWLEDGEMENTS

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