U.S. Army Research Laboratory WRF-ARW modeling for T-REX

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1. Introduction

The Advanced Research version of the Weather Research and Forecasting modeling system (WRF-ARW) is being studied by researchers at the U.S. Army Research Laboratory (ARL) and the Army High Performance Computing Research Center (AHPCRC) as a short-range predictive component of an Army tactical analysis/nowcasting system, called the Weather Running Estimate-Nowcast (WRE-N). The WRE-N is being developed as a rapid cycling, high spatial and temporal resolution, data assimilation and short-range prediction system tailored for tactical applications (Dumais, 2005).

The WRF-ARW (Skamarock et al., 2005) is currently being studied to see how it numerically simulates complex mountain and boundary layer meteorology at horizontal grid spacings of 1-2 km. The spring 2006 Terrain-induced Rotor Experiment (T-REX) across the Owens Valley of California has provided an opportunity for ARL and AHPCRC modelers to run the WRF-ARW in near real-time mode, and at the horizontal grid spacings of most interest to the U.S. Army. At ARL and AHPCRC, the WRF-ARW was executed and tested under extreme topographical conditions in both perturbed and quiescent meteorological states.

A large number of multi-agency and international research groups collected surface, remotely sensed, and aircraft observations during the field study, which are being used for extensive model evaluation.There has also been (and continues to be) collaborative interactions with other research groups running the same and other mesoscale numerical weather prediction models (at similar fine scales) during the field study.

It is expected that this research will provide ARL (and others with WRF-ARW interest) with an improved understanding of the model performance, including both strengths and weaknesses, in complex terrain at meso-γ or "storm" scales. This paper briefly discusses both the recently completed and further planned ARL and AHPCRC modeling activities associated with the field study, providing some preliminary assessments of the WRF-ARW performance to date.

2. Brief Overview of T-REX

The T-REX was a large multiagency and international field program that was executed during the months of March and April, 2006 (Grubišić et al., 2004). Following upon a smaller-scope study in 2004 (across the same region) called the Sierra Rotors Project (http://www.mdml.dri.edu/), the primary goal of the T-REX was to study details of the complex mountain wave/rotor/boundary layer system under strongly perturbed atmospheric conditions conducive to such phenomena. The T-REX was conducted in and around the Owens Valley, California.

This geographical region, mostly between the towns of Independence and Bishop, is well known for its strong downslope wind storms, lee wave activity, low-level rotors, dust storms off the dry lake beds, and complex topographically-forced flows (Billings and Grubišić, 2005; Sheridan and Vosper, 2006; Cahill et al., 1996; Doyle and Durran, 2002). The valley floor is located between the high Sierra Nevada to the west and the Inyo to the east.

Although not a continuous increase in slope from the valley floor to the highest peaks of the Sierra Nevada, there does exist an impressive elevation change of roughly 3000 m over a relatively short spatial distance. During the spring season in this part of California, strong mid latitude and upper level weather systems often migrate from the north and west through the local area, producing conditions highly supportive of mountain lee wave activity and associated rotors.

To improve upon the scientific knowledge base of such perturbed meteorological events, the T-REX established a high density, state-of-the-art measurement program consisting of ground based, aircraft, upper air, and remotely sensed observations to characterize the four-dimensional atmosphere across the valley. Observations were taken from sensors on both in-situ and mobile platforms, and included automated weather station (AWS) surface mesonets, radiosonde, radar profiler, Doppler lidar, multiple research aircraft, tethersonde, towers, and many others (http://www.joss.ucar.edu/trex/documents/T-REX-Ops-Plan-Draft-2-2.doc).

When local meteorological conditions were anticipated to be perturbed and favorable for lee wave activity, an intensive observing period (IOP) was set up to measure aspects of the evolving event. In addition, if large-scale conditions were anticipated to become quiescent immediately following the IOP, an extended observing period (EOP) was sometimes included to focus upon features of the diurnal complex terrain boundary layer, including the stable nocturnal boundary layer, when primary forcing was by the local topography and morphology. A total of 15 IOPs and 5 EOPs were collected during T-REX.

3. WRF-ARW configuration during T-REX

The ARL/AHPCRC configuration of WRF-ARW as executed daily for T-REX is shown in Table 1. This configuration was decided upon after numerous discussions between many modelers at ARL, AHPCRC, National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA), U.S. Naval Research Laboratory (NRL), and the WRF Developmental Test Center (DTC).

The model was initialized at 12 UTC each day to produce a 48 h forecast, with the inner nest (2 km) products being transferred via file transfer protocol (ftp) onto the NCAR Joint Office for Science Support (JOSS) Earth Observing Laboratory (EOL) data catalog website (http://catalog.eol.ucar.edu/trex/). The message passing interface (MPI) parallelized version of WRF-ARW was executed on the AHPCRC Cray X1E maintained by Network Computing Services, Inc., using 32 processors.

Typically, the model runs and the subsequent postprocessing and graphical product generation were not available on the EOL webpage until late evening or the next morning. The Grid Analysis and Display System (GrADS) (http://www.iges.org/grads/) software package was used for the graphical product generation.

Table 1 : ARL/AHPCRC WRF-ARW configuration for T-REX

- Runge-Kutte 3rd order numerics
- 5th order horizontal advection
- 3rd order vertical advection
- Kain-Fritsch cumulus (18 & 6 km)
- Lin microphysics
- w-damping on
- 3:1 grid space/time step ratio
- Dudhia short wave (called every 10 min)
- RRTM long wave
- NOAH land surface model
- YSU PBL with surface MO similarity
- conventional terrain averaging
- diffusion damping for top boundary
- dampcoef set to 0.01
- zdamp set to 5000 m
- divergence damping set to 0.1
- external mode damping set to 0.01

Due to the latency involved in getting products onto the EOL website, although useful for research purposes, the ARL/AHPCRC WRF-ARW results were not used in daily forecast discussions for operations planning. Still, the products were very useful in a research role, since they could be compared to mesoscale model output produced by other groups during the field study.

For example, NRL provided twice-daily forecasts out to 48 h with the Coupled Ocean and Atmosphere Modeling Prediction System (COAMPS) (http://www.nrlmry.navy.mil/coamps-web/base/docs/COAMPS_2003.pdf) , while the NOAA Global Systems Division (GSD) ran both WRF-ARW and WRF-NMM (http://www.dtcenter.org/wrf-nmm/users/docs/overview.php) out to 24 h twice-daily. Both NOAA and NRL ran their models with a similar finest mesh of 2 km grid spacing. In addition, the Las Vegas National Weather Service Office (NWSO) ran a version of WRF-ARW to 4 km grid spacing.

4. Preliminary Observations

Although detailed analysis of the ARL/AHPCRC WRF-ARW model runs has yet to be accomplished, due to the short timeframe since the exercise completed and to the fact that many of the special IOP and EOP datasets have yet to be made available, there has been a number of preliminary observations made based on subjective evaluation, intermodel comparisons, and limited sets of statistical evaluations. For example, ARL has generated statistical comparisons of surface parameters from throughout the two month study period, using Desert Research Institute (DRI) AWS hourly-averaged mesonet observations. A statistical comparison of surface winds compiled over all DRI sites for each model forecast hour is shown in Fig. 1.

One of the initial observations concerns the perturbed lee wave phenomena. The ARL/AHPCRC version of WRF-ARW seems to capture significant trapped lee wave events fairly well, including reasonable evolution of stronger events into downslope wind storms (Figs. 2 and 3) during several IOPs. Intermodel comparisons also seem to indicate that the ARL/AHPCRC WRF-ARW predicts a somewhat similar magnitude of wave signature to the NOAA GSD WRF-ARW, usually a bit stronger signature than the NOAA GSD WRF-NMM, and a weaker and less amplified signature (particularly in upper levels) than the COAMPS.

These observations may differ from case to case, and are just general subjective observations noted throughout the field study. Both The NOAA and ARL/AHPCRC simulations initialized from cold start, while the NRL COAMPS used data assimilation, which should be noted.

Another interesting finding of both the ARL/AHPCRC and NOAA GSD groups (Steve Koch, Personal Communication) running WRF-ARW: the Runge-Kutte 3rd order numerics (http://www.mathcs.emory.edu/ccs/ccs315/ccs315/node32.html) appeared to require much smaller time step (s) -to-grid spacing (km) ratios to remain computationally stable during the stronger IOPs. For example, ARL/AHPCRC began using a ratio of 5:1, but ended up going with a 3:1 ratio to avoid violating Courant-Fredrich-Lewy (http://www.mathcs.sjsu.edu/faculty/rucker/capow/paper/node3.html)criteria for stability.

It has been discussed that although remaining numerically stable, perhaps even 3:1 is not an optional ratio for the T-REX model runs. However, ARL/AHPCRC did run the model with the “w-damp” vertical motion damping option turned on. Scientists at NOAA GSD experienced similar time step issues with their model runs, and anticipate that post- study research will focus much attention on this issue (Steve Koch, Personal Communication).

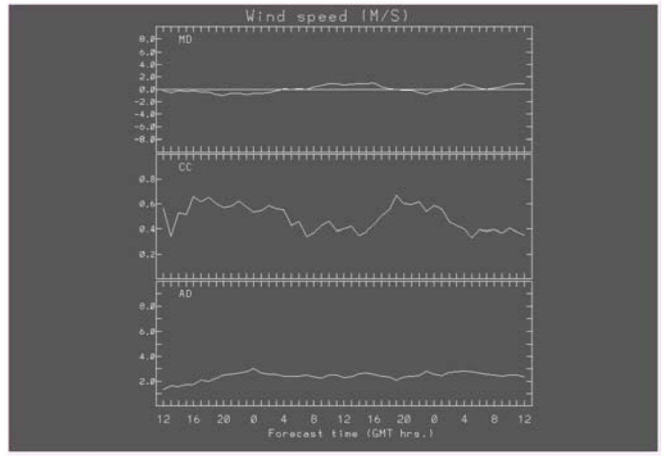

Figure 1. Wind speed mean differences (bias), correlation coefficients, and mean absolute differences compiled for all DRI mesonet sites by each forecast hour, during the Mar-Apr 2006 T-REX period.

Based on the DRI comparisons, a few very early comments can be made about the ARL/AHPCRC WRF-ARW 2 km nest and its ability to simulate surface meteorology in the Owens Valley. In terms of the longer term statistics, the model did quite well in predicting the evolution of diurnal winds and temperature in the valley. In particular, mean absolute and root mean square errors, along with correlation coefficients, were quite

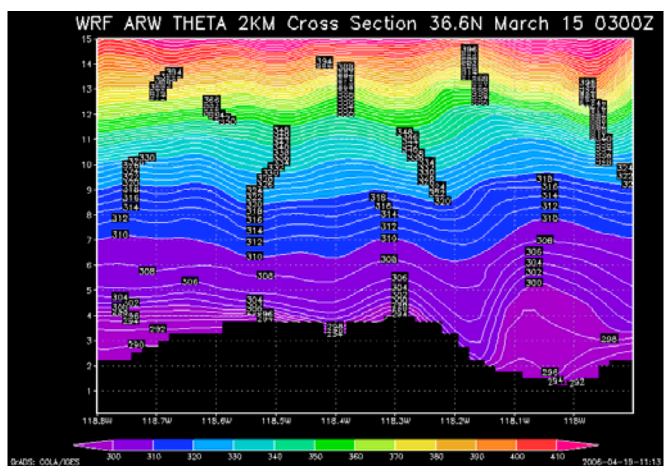

Figure 2. WRF-ARW (2 km resolution) 15-h forecast of W-E vertical cross-section including southern Owens Valley in IOP4, 03 UTC Mar 15 2006, showing potential temperature isentropes kinking to lee of Sierra Nevada and hinting at a transition from trapped lee wave to lee downslope wind event.

reasonable for wind speed magnitude, u-component, and v-component.

For winds, the most difficult periods to capture seem to be around /shortly after the morning and evening transition hours. On the other hand, errors even at 48 h were often quite acceptable. In terms of downslope wind events, although phase and spatial errors were noted (particularly in locations of apparent hydraulic jump regions), and mean lee wind magnitudes appeared overdone and more indicative of gusts, the model captured the gross features and evolution of these complex events quite well. The model also had a handle on elevated trapped lee wave situations, where flow decoupling in the valley was common.

In terms of surface temperature, there was a distinct bias noted, underforecasting the daytime maximum temperatures in the valley by 3-4 deg C, and underforecasting the nighttime minimum temperature by about 2 deg C. Correlation coefficients were quite high, however. The surface relative humidity also had a routine bias, being about 15-25% too moist at almost all hours (which may be related to the surface temperature bias).

5. Conclusion

The ARL and AHPCRC participation in the modeling activities during T-REX, through daily execution of a high resolution version of the WRF-ARW, gave its scientists tremendous experience with and insight into the modeling system.

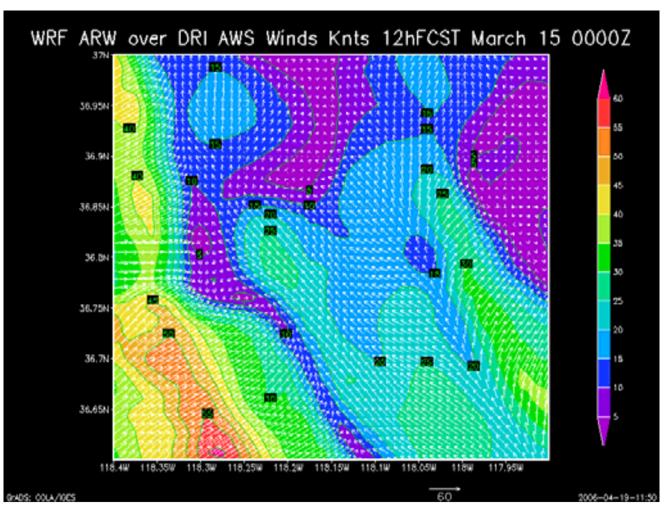

Figure 3. The 12-h WRF-ARW (2 km resolution) forecast for mean surface winds (kts) across the Owens Valley in IOP4, 00 UTC Mar 15 2006, hinting at a strong downslope wind event.

This was especially true given the complex nature of the meteorology in the vicinity of the Owens Valley, and the amount of joint agency participation and interaction.

Some very initial results and findings have been generated, and the groundwork has been established for much more detailed investigations in coming months and years. In addition, ARL and AHPCRC scientists intend to work closely with modelers from other participant groups at NOAA GSD, NRL, and NWSO Las Vegas in follow-on research involving WRF-ARW and other mesoscale numerical models.

A few of the stronger IOPs will be studied more closely by various groups, with aircraft, profiler, lidar, mesonets and radiosondes (among others) as useful observational tools. Issues such as time step, upper and lower atmospheric lee/gravity wave amplitude, wave breaking, upper level model damping, downslope winds/hydraulic jumps, and rotors are of particular interest.

The ARL/AHPCRC group, although interested in more detailed examination of at least one of the strong IOPs, will focus more heavily on the WRF-ARW performance throughout the Owens Valley lower boundary layer during quiescent EOPs, including aspects of model behavior during stable nocturnal periods. Such periods should provide a good opportunity to examine the overall model performance in regimes where local topographical and land use forcing dominates local flow patterns in the valley, in addition to determining weaknesses of the model anticipated around day/night stability transitions, associated with cold pooling, and involving intermittency during very stable nocturnal conditions.

It is hoped T-REX research with WRF-ARW will eventually lead to improved numerical and physical treatments in the model, which will have a positive effect on future use of the model by ARL in the WRE-N.

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