JP2.4 HIGH RESOLUTION WRF-ARW STUDIES AT THE U.S. ARMY RESEARCH LABORATORY FOR USE IN SHORT-RANGE FORECAST APPLICATIONS

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1. INTRODUCTION

The U.S. Army Research Laboratory (ARL) is currently performing research involving various aspects of the Advanced Research version of the Weather Research and Forecasting (WRF-ARW) model (Skamarock et al., 2008) versions 3.0 and 3.1 . This research focuses primarily on the utility of the WRF-ARW for limited area short-range forecast/nowcast purposes at grid spacing ranging between 0.3 km -3 km, and is being partially supported through the Air Force Weather Agency (AFWA). In particular, ARL is testing various perturbations involving model vertical resolution, time stepping, microphysics, planetary boundary layer (PBL) and turbulence parameterization, observation nudging data assimilation, and sub-nesting to hundreds of meters grid spacing. To provide proper metrics using traditional statistical and newer object- based verification approaches, the National Center for Atmospheric Research (NCAR) Model Evaluation Tool (MET) is being implemented and is now under evaluation as a part of this research (http://www.dtcenter.org/met/users/support/). This paper focuses mainly upon the research strategies and model test perturbations/configurations being employed, but also will show some examples of a few modeling results.

2. WRF-ARW Modeling Overview

The Advanced Research WRF (WRF-ARW) versions 3.0 and 3.1 are currently used at ARL to evaluate the capabilities of the model for producing short-range predictions (or nowcasts) on limited domains and for fine resolutions spanning 0.3 km – 3 km grid spacing. These are critical scales for the U.S. Army, since most its operations are executed near the earth's surface or in the lower planetary boundary layer, where cloud-to-storm (and even soldier/building) spatial and temporal scales of meteorology become important to execution-level decision making. With support from the Air Force Weather Agency (AFWA), a series of experiments have been ongoing at the ARL, with the aim of better understanding the potential of running the WRF-ARW at km or even sub-km grid spacing resolutions. In particular, issues such as choice of PBL physics, explicit moist microphysics, vertical resolution, domain size, four dimensional data assimilation (FDDA), and time step are being explored.

One series of tests of the model involve the use of a 3 km/1km double nest configuration, and the National Center of Environmental Prediction's WRF-based North American Model (NAM) (http://www.dtcenter.org/wrf-nmm/users/OnLineTutorial/NMM/index.php) 218 grids as initial conditions and lateral boundary conditions for the outer nest. The NAM 218 datasets (~ 12 km grid spacing) are obtained from the National Oceanic and Atmospheric Administration's National Operational Model Archive and Distribution System (http://nomads.ncdc.noaa.gov/). The specifications of the ARL WRF-ARW nests, along with a control set of namelist options, are given in Table 1. In Table 2, the set of perturbations from the control configuration which are also being simulated are given. Both the control and the subset of perturbations are being run for a small 3-5 member set of predetermined case studies, with the grid domain centered over Dugway Proving Ground (DPG), Utah. For all cases, a full 24 h simulation period is being examined between 06 UTC and 06 UTC. The location of our model domain was selected based on several things: excellent complex terrain area with a nearby large inland lake, seasonal changes in meteorology which run a wide spectrum of synoptic phenomena, proximity to the Utah mesowest and special observations from DPG, and the potential for additional ground truth boundary layer meteorology measurements via the West Desert Test Center at DPG. The size of the modeling domains is similar to what is being explored for use in ARL meteorological modeling applications for the Army, and the use of the NAM 218 is similar to the operational resolutions run currently at AFWA at a four times daily frequency (15 km, 5km). In addition to the various model physics and dynamics simulations being produced over the DPG domain, a couple of other interesting research efforts using WRF-ARW are also ongoing.

A second research area is focused upon the development of the WRF-ARW FDDA for the same limited area domains and grid space resolutions being studied over the DPG region. The FDDA option in WRF-ARW is based on observation nudging (Liu et al., 2007), is much less computationally expensive to 4D variational (Huang et al, 2009) or ensemble Kalman filtering (Zupanski et al., 2008) approaches, and is thought to be a viable method for asynoptic meteorological observation assimilation and

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deterministic fine scale modeling applications such as those which the Army is interested. The ARL is focused on using observation nudging as a tool for assimilating forward battlefield observations which may not routinely get ingested as part of the AFWA operational WRF-ARW modeling and 3D variational data assimilation system (Surmeier and Wegiel, 2004), such as local surface mesonet/sensors, local radiosonde/dropsonde (such as artillery), on-board aircraft or unmanned aerial vehicle sensors such as Tropospheric Airborne Meteorological Data Reporting (TAMDAR) , and even radar/lidar generated profiles. One current ARL effort with FDDA is focused upon the ingestion of a special dataset of surface and radiosonde observations collected over Yuma Proving Ground (YPG), AZ, during the period 1200 UTC 30 Nov – 0000 UTC 01 Dec 1 2007. Sufficient observations exist to perform a 12 h experiment of data assimilation cycling, where each cycle is updated hourly through a 3 h pre-assimilation FDDA window and a subsequent new 3 h prediction. Additional experiments, through collaboration with AIRDAT (http://www.airdat.com/), are also ongoing to investigate using FDDA for a few well-selected case studies over the Great Lakes area. In the Great Lakes cases, the same general grid configurations/resolutions and FDDA will be applied as in YPG, except that aircraft TAMDAR will be the primary observation focused upon (Jacobs et al., 2009).

A final research effort is investigating the potential for sub-kilometer grid space nesting in the WRF-ARW, and is aimed at exploring issues such as whether or not to use PBL parameterization, terrain treatment, lateral boundary condition effects, two-way nesting potential, domain size and computational feasibility, and time step influence. This effort is in its infancy, although an initial domain and simulation has just been completed for a model region near the White Sands Missile Range's Main Post, with a fine nest of 300 m grid spacing using the Mellor-Yamada-Janjic (MYJ) PBL option (Janjic, 2002) for all nests (2.7 km, 900 m, 300m). Again, the NAM 218 is the source of initial conditions and lateral boundary conditions for the outer nest. Anticipation is that one or two good case studies can be selected with several perturbations per each case as mentioned above, with enough ground truth verification to make some general subjective assessment of model performance. The remainder of this paper, however, will focus on the DPG tests being run at 1 km grid spacing.

3. WRF-ARW Experiments over Dugway Proving Ground, Utah

The two cases already simulated over the Dugway Proving Ground have involved (i) precipitation and potential impact of model explicit microphysics (26 Mar 2009) and (ii) weak synoptic flow and thermodynamic-driven local basin circulations under a ridge (21 Apr 2009). This section of the paper will very briefly discuss a few general aspects of surface forecast fields from the model at forecast times 17 h and 20 h of the 0600 UTC 21 Apr 2009 simulations (on the 1 km inner nest). The case of 21 Apr 2009 was characterized synoptically by warm surface temperatures, fairly light winds, and generally clear skies, under the effect of an upper level ridge. However, as will be discussed below, there were still some interesting microphysical and radiation effects of note uncovered. In addition, a potential minor bug in the WRF code was uncovered when nest feedback is applied, but it seems not to have an impact on the subsequent simulations.

The 17 h forecast (valid at 2300 UTC /1700 Local 21 Apr) of surface wind and temperature is discussed first for just the control run. The plots shown in all figures in this manuscript were generated using the NCAR ARWpost program (http://www.mmm.ucar.edu/wrf/users/graphics/ARWpost/ARWpost.htm) and the Grid Analysis and Display System software package (http://grads.iges.org/grads/). At 10 m above ground level (agl), a general northerly wind (up-valley) with upslope flow on most sides of the mountains is simulated (Figure 1) . This is to be expected during the late afternoon hours under clear skies and ridging conditions. The model's vertical motion field at this same time shows generally uniform light upward vertical motions near the surface at the first model etap level, although a peculiar small zone of stronger upward vertical motion is noted right at the lateral boundary near the southwest grid corner. This area of strong vertical motion on the nest boundary only exists on model level 1, and appears to also be seen only when using the two-way nest feedback option. It has been seen before in this exact same fashion for other modeling experiments run at ARL with past WRF-ARW versions, and is believed to be a fictitious artifact of the feedback option's interpolation/smoothing of heights/geopotential fields right at the lateral boundary between parent and child nests. It appears to have no consequence on other model fields throughout simulations. Also noteworthy is the strength of the upslope flow condition around the topographical barrier in the southwestern grid quadrant, with a clear forecast of easterly upslope winds on east-facing slopes and westerly upslope flow on west-facing slopes.

The surface 2 m agl temperature field at 2300 UTC shows a range between 280 deg K-300 deg K. The basin is mostly around 299 deg K, with 281 deg K predicted over the highest terrain. The surface fields appear to compare quite well with the mesonet observations shown in Figure 2. The majority of the simulation perturbations agree pretty closely at 2300 UTC (at least in a subjective sense) with the control forecast at the surface. Surface winds and vertical velocities for a perturbation using the MYJ PBL scheme is shown in Figure 3, and it is evident that the solution is pretty close to the control other than some small differences. The MYJ run does appear to produce slightly higher surface temperatures around the small hill/peak in the center of the model grid domain (not shown), along with some flow differences to the west of the large mountain range on the western grid domain. Although not shown in this paper, the 18 h surface temperature field seems to also be in general agreement across all the various simulation members.

There still appears to be the area of etap level 1 excessive rising motion on the southwestern border of the grid in all perturbations.

The net surface shortwave downward radiation flux at 2300 UTC shows a nice apparent shading effect at the base of the mountain range in the western model domain of the control run (not shown). The range of values in the control run are from 670 w/m2 on the mountain peaks to about 615 w/m2 at the eastern base of the mountain range. However, it was quickly discovered that the apparent terrain shading influence on the 1 km nest was due mostly to some other cause, since the 2300 UTC net surface shortwave downward radiation flux varied quit alot across the microphysical perturbations in particular. Further investigation uncovered that the net surface shortwave downward radiation flux patterns on the 1 km nest had a lot to do with the generation of cloud ice by the different microphysics packages at a level of about 12 km above sea level aloft. This cloud ice did not seem to initiate until about 2200 UTC, and varied in amount and coverage between microphysics packages. The cloud ice also seemed to relate with a level where relative humidity values with respect to water were around 50-55%, temperatures were in the low-to-mid -60's, and some areas of weak upward motion apparently due to orographic lift or wave behavior existed in the model. This will obviously be a great area to study in more depth over time. It was also apparent that the pure terrain slope/shadow effect could be seen quite clearly on the 3 km nest, but not as well (if at all) on the 1 km nest. We will be investigating whether the slope/shadow effect is being turned on properly for nest 2.

The control run valid at 21 h (0200 UTC Apr 22/ 2000 Local 21 Apr) shows a continued slight trend for northerly winds (up-valley) although it is greatly reduced on the north half of the grid (transition to a downvalley nocturnal southerly flow may be occurring). Upslope flow is still appearing on many of the east-facing slopes, although there do appear to be drainage flows initiating on some of the west-facing slopes (Figure 4). This transition to drainage flow in the early evening hours has been examined both observationally and numerically by many researchers (e.g; Whiteman and Zhong 2008, Zhong and Whiteman 2008) under such synoptic conditions across complex terrain regions of the western United States. Most of the model members show this same basic pattern at 0200 UTC. Note that the excessive vertical motion problem at etap level 1 on the nest's southwestern lateral boundary still exists. The surface temperature and moisture fields at 0200 UTC also do not vary much across the various model members (not shown). Much like at 2300 UTC, there is pretty good agreement with observations at this time (Figure 5). By this time some of the model runs no longer indicate extensive cloud ice material higher aloft, giving some support to the idea that orographically – induced convection or wave generation may have had some role. It is difficult to verify cloud ice material at the high levels on this afternoon based solely on the archived satellite imagery examined.

4. Summary

The ARL has initiated a full set of research experiments to investigate the WRF-ARW model at scales ranging from cloud-to-storm, especially over complex terrain regions of the western US. The real focus is on modeling scales to about 1 km (or even finer) grid spacing, minimal nesting (ie; double nesting), lateral boundary conditions supplied from operational mesoscale models such as NAM or AFWA WRF, and limited model domain sizes. In addition, the ARL has also been developing FDDA experiments using the WRF-ARW v 3.1 observation nudging package, focusing on the assimilation of potential future types of forward battlefield meteorological observations as might be collected from sensors on fixed or mobile surface platforms, onboard unmanned aerial vehicles (like TAMDAR), radiosondes /dropsondes, and ground-based or airborne radar/lidar. Successful development of such a capability, called a Weather Running Estimate-Nowcast (WRE-N) by the ARL, would provide the Army with a relatively fast ability to rapidly update (up to hourly cycling) and "nowcast" the local battlefield meteorological conditions out to 3 h forward. Satellite-based observations could potentially be used as well, especially for improving ground state initial conditions, but the heavy emphasis and large dedicated processing of radiance data will be left to the operational mesoscale models and data assimilation systems running at AFWA, NCEP, etc. Although this research is in a relatively early stage, it is anticipated that the ARL will be able to learn and better utilize important physical and dynamical features of the WRF-ARW as applied to scales around 1 km grid spacing. Verification efforts associated with the DPG control configuration of WRF-ARW are also ongoing, using the MET software's PointStat module to generate surface statistics from DPG mesonet sites and upper level statistics from available radiosonde and aircraft observations. Eventually, the ARL hopes to use some of the object-oriented evaluation tools of MET as well. Through collaborations with modelers at AFWA and NCAR, a productive mechanism appears in place to test, improve, and apply the model in new and innovative ways that could benefit the Army and others in the DoD and civilian communities.

5. References

Huang, X.Y., Q. Xiao, D.M. Barker, X. Zhang, J. Michalakes, W. Huang, T. Henderson, J. Bray, Y. Chen, Z. Ma, J. Dudhia, Y. Guo, X. Zhang, D.J. Won, H.C. Lin, and Y.H. Kuo, 2009: Four-dimensional variational dtaa assimilation for WRF: formulation and preliminary results. Mon. Wea. Rev., 137, 299-314.

Jacobs, N., P. Childs, M. Croke, Y. Liu, and X-Y Huang, 2009: The optimization between TAMDAR data assimilation methods and model configuration in MM5 and WRF-ARW. 13th Conference on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and land Surface (IOAS-AOLS), 89th AMS Meeting, Jan 10-16, 2009. Phoenix, AZ.

Janjic, Z.I., 2002: Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP meso model. NCEP Office Note No. 437, National Center of Environmentral Prediction., 61 pp.

Liu, Y., A. Bourgeois, T. warner, and S. Swerdlin, 2007: An observation-nudging based FDDA for ARW-WRF for mesoscale data assimilation and forecasting. 4th Symp. Space Weather, 87th AMS meeting, Jan 13-18, 2007. San Antonio, TX.

Skamarock, W.C., J.B. Klemp, J. Dudhia, D.O. Gill, D.M. Barker, M.G. Duda, X-Y. Huang, W. Wang, J.G. Powers,, 2008: A description of the Advanced Research WRF Version 3. NCAR/TN-475=STR,; NCAR Technical Note, Mesoscale and Microscale Meteorology Division, National Center of Atmospheric Research, June 2008, 113 pp.

Surmeier, M.T., and J.W. Wegiel, 2004: On the optimization of the Air Force Weather weapon System's next generation mesoscale numerical weather prediction model: The Weather Research and Forecast Model (WRF). HQ Air Force Weather Agency (AFWA), 20th Confrence on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction, 84th AMS Meeting, Jan 10-16, 2004. Seattle, WA.

Whiteman, C.D., and S. Zhong, 2008: Downslope flows on a low-angle slope and their interactions with valley inversions. Part I. Observations. J. Appli. Meteor. Climat., 47, 2023-2038.

Zhong, S., and C.D. Whiteman, 2008: Downslope flows on a low-angle slope and their interactions with valley inversions. Part II. Numerical modeling. J. Appli. Meteor. Climat., 47, 2039-2057.

Zupanski, M., I.M. Navon, and D. Zupanski, 2008: The Maximum Likelihood Ensemble Filter as a non-differentiable minimization algorithm. Q.J. R. Meteor. Soc., 134, 1039-1050.

Namelist parameter	Option selected
Shortwave radiation scheme	Dudhia
Longwave radiation scheme	RRTM
Explicit moist microphysics	WSM-5 class
Cumulus parameterization	None on both nests
PBL scheme	Yonsei State University (YSU) non-local closure
Surface layer	Monin-Obukhov
Land surface scheme	NOAH
6th order numerical diffusion	Yes
Horizontal subgrid diffusion	2nd order on coordinate surfaces
Subgrid turbulence closure	Horizontal Smagorinsky 1st order closure
Upper boundary	w-Rayleigh damping
Vertical velocity damping	Yes
Feedback	Yes- with smooth-desmooth-smooth filter
Nesting	Two-way
Terrain slope/shadow radiation effect	Yes
Time step (s) to grid spacing (km) ratio	3:1
Number of vertical etap terrain-following levels	60

Table 1 Namelist options for WRF-ARW control

Thompson explicit moist microphysics
Lin et al explicit moist microphysics
Mellor-Yamada-Jancic (MYJ) PBL scheme with MYJ surface layer
Time step (s) to grid spacing (km) ratio of 1:1
Number of vertical etap terrain-following levels = 40
Number of vertical etap terrain-following levels = 80

Table 2 Individual simulation perturbations from WRF-ARW control that were executed

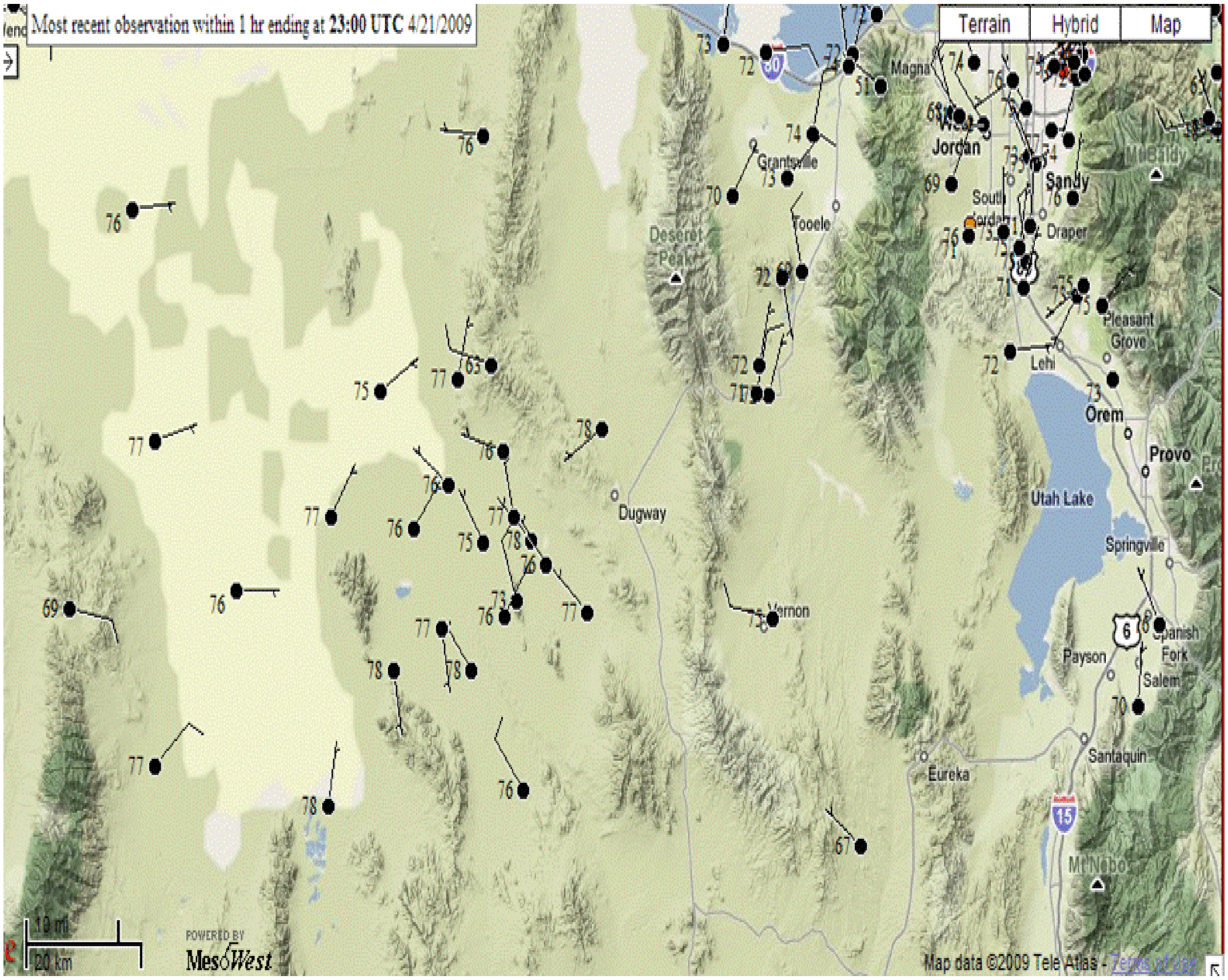

Figure 1 Utah Mesowest surface observations at 2300 UTC 21 Apr 2009

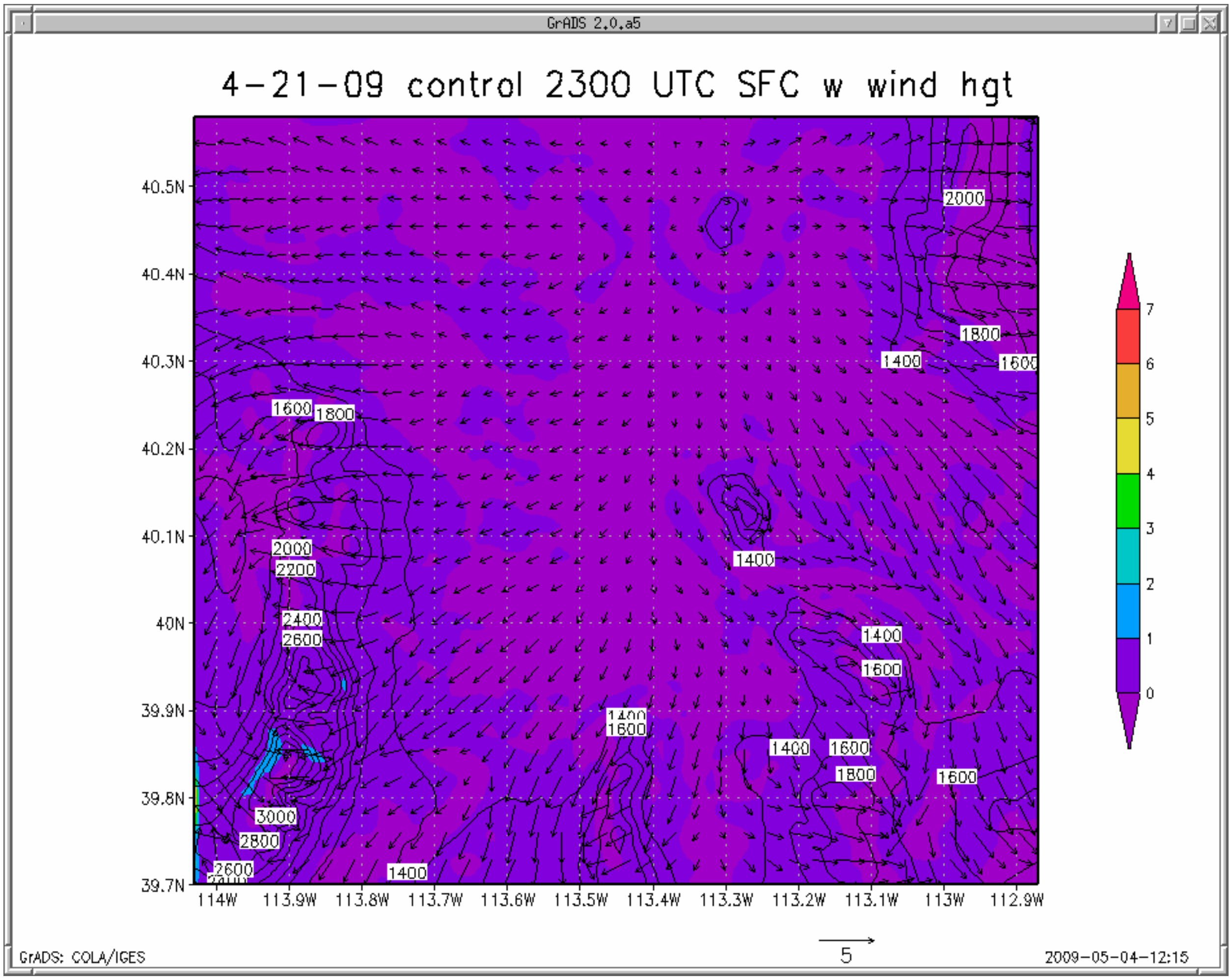

Figure 2 surface winds and vertical velocities (m/s) over terrain (m) from control run at 2300 UTC 21 Apr 2009 (1 km nest)

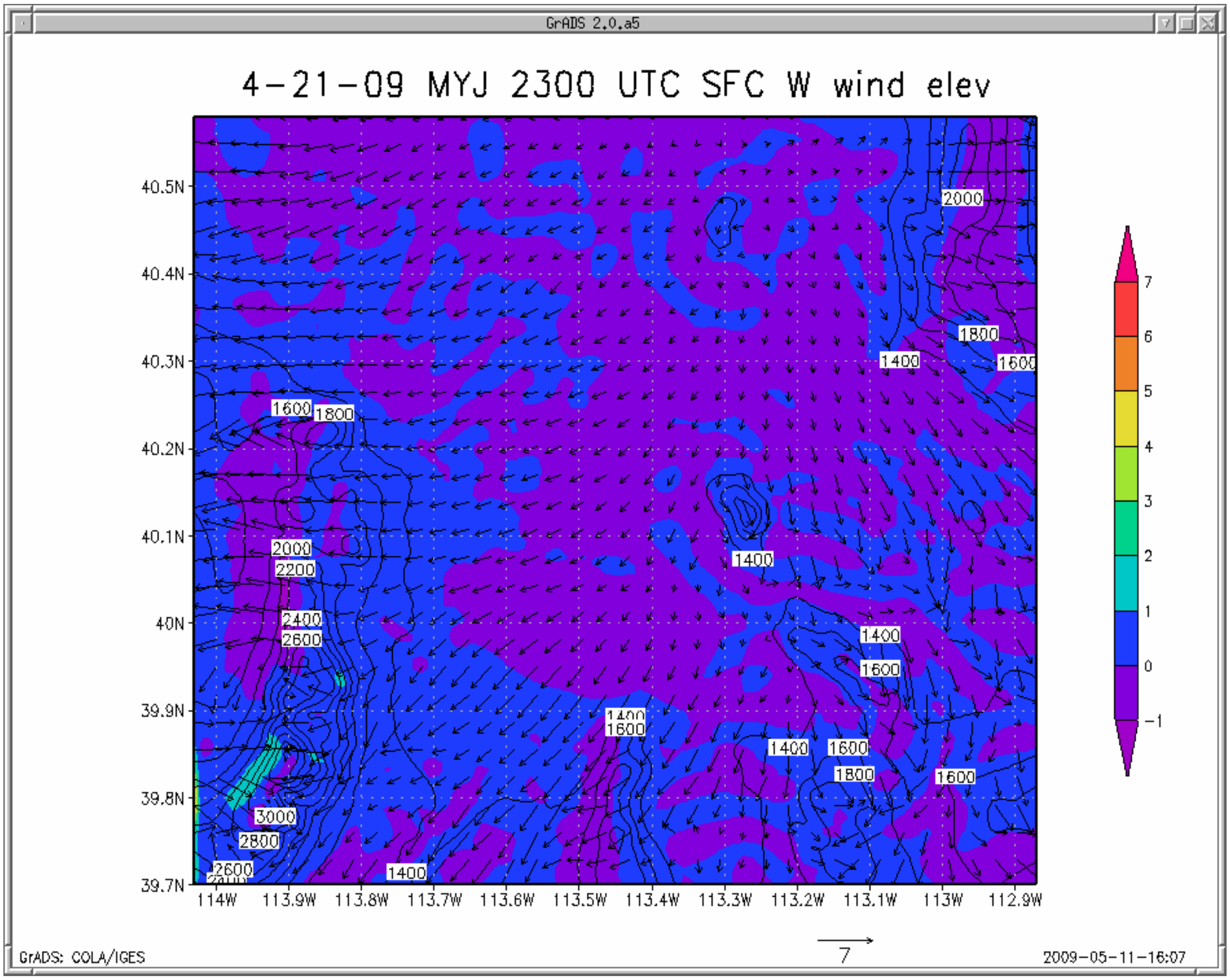

Figure 3 surface winds and vertical velocities (m/s) over terrain (m) from MYJ run at 2300 UTC 21 Apr 2009 (1 km nest)

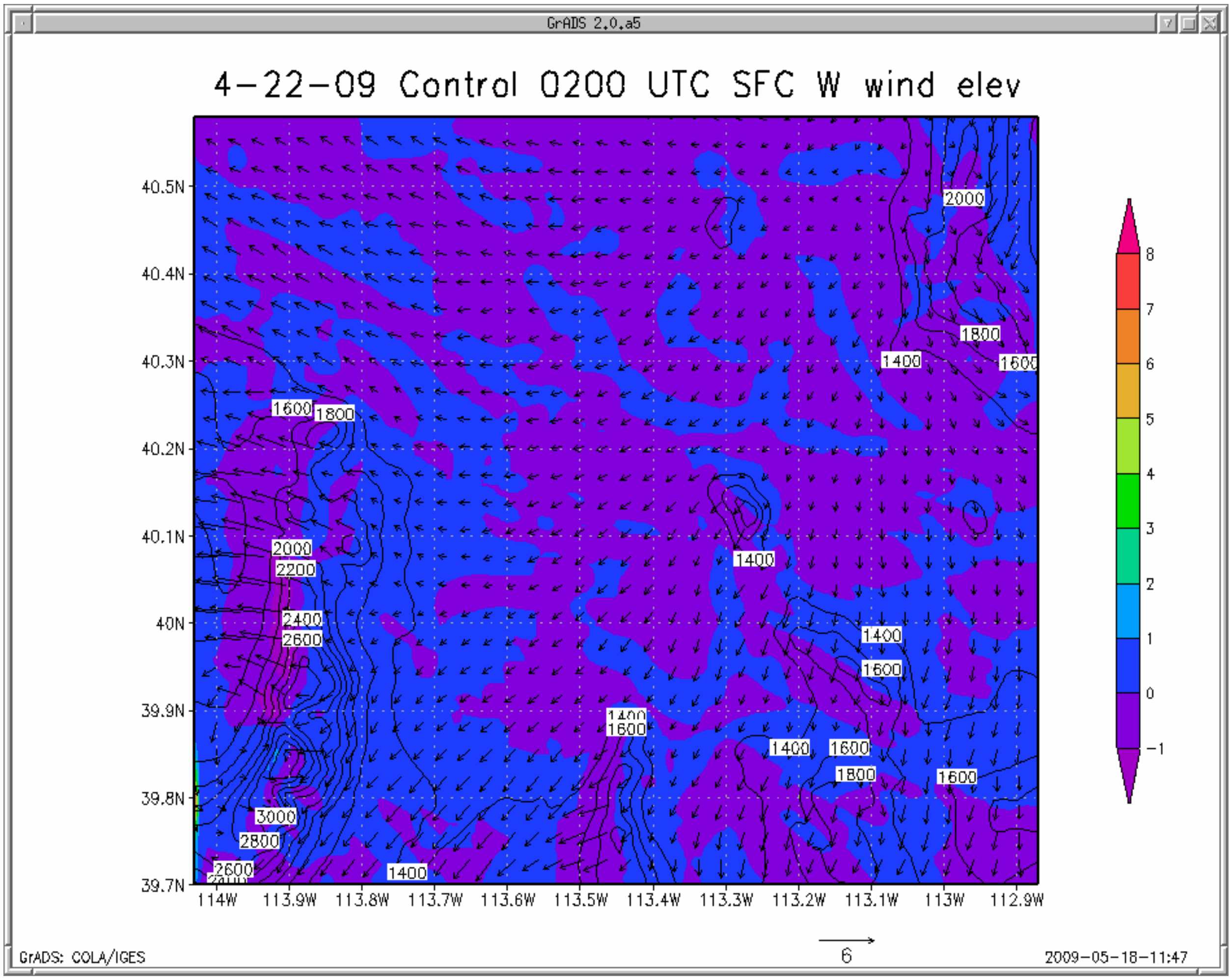

Figure 4 surface winds and vertical velocities (m/s) over terrain (m) for control run at 0200 UTC 22 Apr 2009 (1 km nest).

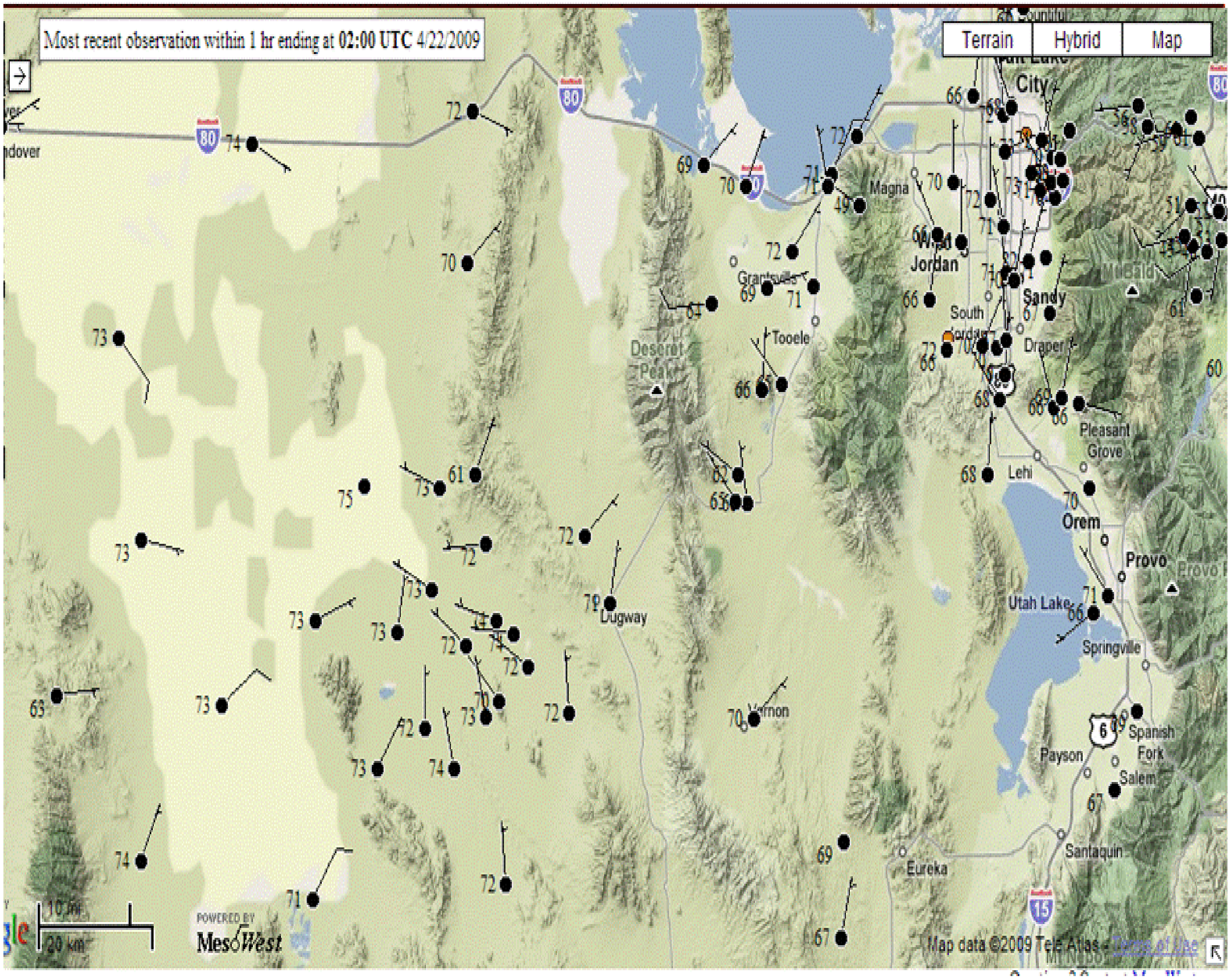

Figure 5 **Utah Mesowest surface observations at 0200 UTC 22 Apr 2009.**