ARMY RESEARCH LABORATORY

Evaluation and Applications of the Weather Research and Forecasting Model

by Jeffrey E. Passner

ARL-TR-4335 **December 2007**

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White Sands Missile Range, NM 88002-5501

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14. ABSTRACT
The Advanced Research version of the Weather Research and Forecasting model (WRF-ARM) was studied by the U.S. Army Research Laboratory (ARL) to determine how accurate and robust the model is under a variety of meteorological conditions, with an emphasis on fine resolution, short-range forecasts in complex terrain. This model study was done in support of the short-range Army tactical analysis/nowcasting system called the Weather Running Estimate-Nowcast (WRE-N) as well as for longer-range forecasting support. While much of the study centered on basic model output such as temperature, moisture, wind direction, and wind speed, the WRF parameterizations and output were also examined.

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Summary

The Advanced Research version of the Weather Research and Forecasting (WRF-ARW) model was studied by the U.S. Army Research Laboratory (ARL) to determine how accurate and robust the model is under a variety of meteorological conditions. This model study was done in support of the short-range Army tactical analysis/nowcasting system called the Weather Running Estimate-Nowcast (WRE-N) as well as for longer-range forecasting support. Typically, weather forecast data provided by the Air Force Weather Agency to Army Combat Weather teams and lower echelon battlefield users falls short of meeting the time and space requirements for the current and future weather needs of the Soldier. Thus, in this study there was an emphasis on fine-resolution, short-range forecasts in complex terrain in an effort to support real-world combat weather and enhance battlefield planning.

The model was run and evaluated for 24 h at locations centered in and on Iraq; Salt Lake City, UT; Owens Valley, CA; Oklahoma City, OK; White Sands Missile Range, NM; and urban northeastern New Jersey. Much of this study centered on basic model output such as temperature, moisture, wind direction, and wind speed at Salt Lake City with an effort to study the model wind performance in the very complex areas of the Salt Lake Valley.

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1. Introduction

To study how accurate and dynamic weather models are in complex terrain, the Advanced Research version of the Weather Research and Forecasting (WRF-ARW) model was studied by the U.S. Army Research Laboratory (ARL) under a variety of meteorological environments. This model study was done in support of the short-range Army tactical analysis/nowcasting system called the Weather Running Estimate-Nowcast (WRE-N) as well as for longer-range forecasting support. The Weather Research and Forecasting (WRF) model was run and evaluated for 24 h at locations centered in Iraq; Salt Lake City (SLC), UT; Oklahoma City, OK; White Sands Missile Range (WSMR), NM; Owens Valley, CA; and urban northeastern New Jersey. Much of the study centered on the Salt Lake Valley with an emphasis on the wind flows and basic model output, such as temperature, moisture, wind direction, and wind speed. This report shows the results of the model performance, an evaluation of these results, as well as applications for Army and military operations.

2. The WRF

The WRF model is a next-generation mesoscale weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a three-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. The WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. (*1*)

The effort to develop WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the National Centers for Environmental Prediction (NCEP), the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration. WRF is currently in operational use at NCEP.

2.1 WRF used at ARL

The WRF model at ARL in this research was initialized using Eta 40-km input data. The initialization with these data is done on a machine known as TCWest0, which is a dual processor Advanced Micro Devices (AMD) based system running RedHat 8.0. The system consists of two

1.9 GHz AMD central processing unit with 2 gigabytes (GB) of random access memory and 500 GB of disk space. The postprocessing and graphics program, Grid Application Development Software Project (GRADS), are also run on TCWest0. (*2*)

The WRF model in this study was run on the Army's High Performance Computing Research Center Linux Network Evolocity II, which is a commodity cluster system consisting of dual processor blades that can be configured as compute, storage, management, login, or analysis nodes. The machine, JVN, has 1024 dual-processor compute nodes, each with 4 GB of memory; and seven dual-processor login nodes, each with 8 GB of memory. The system utilizes a high speed Myrinet interconnect and global shared file system. The processors on JVN operate at a frequency of 3.6 gigahertz, resulting in a peak floating-point rate of 7.2 Gigaflops per processor. In total, JVN consists of 2,048 compute processors, delivering 14.7 Teraflops.

2.2 Model Configuration for ARL Study

While it makes evaluation of different model studies more problematic, several model configurations were utilized in this study; however, once a model configuration was set, it remained constant through the study. As an example, the WRF runs at SLC were completed using WRF version 2.1.1, while the WRF models in New Jersey were run with version 2.1.2. Otherwise, the models were very similar in initial conditions, boundary conditions, and parameterizations. All the models used the advanced research WRF-ARW dynamical core and were initialized with 0000 universal time coordinates (UTC) 40-km Eta model data, although on the New Jersey runs, the model was initialized with 40-km WRF data. The models were run for a period of 24 h with model output available every hour. For most of the model runs, a two-nest configuration was used, with the outer domain having 8-km grid resolution and the inner domain having a 2-km grid resolution. Both nests contained 31 vertical levels. The New Jersey model runs used a three nest configuration of 18-km, 6-km, and 2-km grid resolutions with 43 vertical levels.

The physics packages used for all model runs were the following:

- Lin Microphysics
- Rapid Radiative Transfer Model (RRTM) long-wave radiation
- Dudhia short-wave radiation
- Mesoscale Model Version 5 (MM5) similarity for surface-layer physics
- Noah Land Surface Model
- Yonsei University scheme for planetary boundary layer
- Kain-Fritsch cumulus parameterization for 8-km grids only
- Four soil layers

3. SLC WRF Model Runs and Evaluation

3.1 SLC Terrain

The Salt Lake Valley is one of the most unique places to study meteorological models and meteorological conditions. SLC is located at 40°45' N, 111°53'W, with an average elevation of 4,327 ft (1,320 m) above sea level. The lowest point within the city is 4,210 ft (1,284 m) near the Jordan River and Great Salt Lake, while the highest point within city limits is Grandview Peak at 9,410 ft (2,859 m). (*3*)

The city is surrounded by the Great Salt Lake to the northwest, the Wasatch mountains to the east, and the Oquirrh mountain range to the west. The Great Salt Lake actually varies in size depending on rainfall and runoff from the local mountains. The lake depth average is only 14 ft (4.3 m) and due to the shallow depth, the water temperature remains warm most of the year and contributes to lake-effect snows or rain. The Traverse Mountains to the south extend to 6,000 ft (1,830 m) and nearly connect the Wasatch and Oquirrh Mountains. All of these terrain features are visible in figure 1.

Figure 1. The complex, urban terrain of the Salt Lake Valley in Utah (source: http://www.visitsaltlake.com/getting_around/maps.html).

Additionally, the valley with a large population has become an intriguing region to study air pollution and aerosols, since the valley atmosphere is often characterized by a stable boundary layer with a strong morning inversion especially in the cold season. The complex terrain is also a challenge because of a variety of wind flows influenced by the mountains and the lake.

3.2 SLC Wind Tendencies

In recent years, there has been an increased interest in the localized wind flows in complex terrain with an extensive study conducted in the SLC area in October 2000. This study, the Vertical Transport and Mixing (VTMX) field campaign, placed an emphasis on complicated thermally driven flows and the valley boundary layer. (*4*, *5*)

Zumpfe and Horel (*6*), in their study of the lake breeze, discussed long-term observations of the thermally driven flows in the Salt Lake Valley (hereafter valley) of northern Utah. The up-and down-slope flows within the valley develop in response to the horizontal temperature contrasts between the slopes that surround the valley. The up-valley winds are from the north and originate over the lake (also known as lake breeze), while the down-valley winds (also known as valley winds) are directed from south to north. The up-and down-canyon flows are winds that develop in response to the local slope flows and are often referred to as upslope and downslope winds.

Zumpfe and Horel (*6*) have noted in their work that on days from April to October without precipitation, the wind direction tends to be either down valley 53% of the time or up valley 29% of the time at the SLC airport. They also mention that on occasion, the up-valley wind is accompanied by significant increases in dew point and decreases in temperature. Typically, these lake-breeze fronts are not accompanied by precipitation but they are vital since they provide rapid vertical mixing of aerosols in the boundary layer.

Whiteman (*7*) indicates that the strongest nocturnal downslope winds typically occur around sunset when the mountain slopes first go into shadows, while Banta (*8*) observed during VTMX that the reversal from up-valley to down-valley nighttime winds seem to occur from 2000–2200 local standard time (LST). As expected, larger-scale pressure differences had a strong influence on the development of the down-valley winds.

Stalker (*9*), in his work during the VTMX, noted that there were four distinct periods of wind regimes in the SLC valley:

1. Early evening transition period from 1800–2100 LST: This period was dominated by drainage winds flowing into the basin.

2. Nighttime, 2300–0300 LST: This period is marked by drainage flow. The boundary layer is well mixed and surface temperatures increase as a southerly flow persists. The well-mixed conditions may be pronounced in the downtown area due to the urban canopy.

3. 0300–0700 LST: During this period the long-wave radiational cooling of the shallow stable layer seems to dominate.

4. 0700 LST: Early morning transition as shortwave radiation begins and boundary layer grows.

In the ARL study (*10*), data were collected at the Hawthorne site of the Utah Air Monitoring Center (AMC). The Utah AMC is responsible for operating and maintaining an ambient air monitoring network that provides air pollution information for the daily air quality index. These data are available at a number of locations in and around the SLC area. In addition to air pollutants, many of the AMC sites provide information in wind direction, wind speed, relative humidity, temperature, and short-wave radiation.

This decision to use these data rather than the SLC airport was based on a focus to study a location closer to the downtown, urban center of the city and a location closer to the Wasatch Mountains in order to study how the WRF model performed in this environment.

Approximately 36 days of wind data were examined from January to May 2006 for all hours of the day. In an effort to follow the observations of Stalker's work, the nighttime winds were evaluated in the same general time periods, with some minor modifications (see table 1).

Table 1. Percentage of times the wind direction was observed from the listed wind directions at Hawthorne, UT, from January to May 2006 based on time of day.

Time (UTC)	**Downslope East (%)**	**Downslope West (%)**	**Up-Valley (%)**	**Down-Valley (%)**
0000	5	56	14	25
0300	42	22	14	22
0600	67	8	3	22
1200	47	14	8	31
1800	26	38	7	29

The results in table 1 are not totally surprising and show results somewhat similar to those observed in the VTMX experiment. At 0000 UTC (1700 LST), the dominating winds are from the west, a downslope winds off the Oquirrh Mountains into the valley. This occurs 56% of the time in these data. It should be noted that January to May is the time of year when stronger, dynamical weather systems tend to dominate the region, so the thermal circulations often are less influential than stronger flow from synoptic-scale weather systems.

After the sun sets, there is a distinct change in the wind pattern and the local terrain becomes more vital than the synoptic flow in the ensuing wind direction. During the 3-h interval from 0000 to 0300 UTC, commonly the surface wind shifts from a downslope wind from the west to a downslope from the east originating on the Wasatch Mountains. There still are a fair number of cases with the wind from the west and even a number of cases from a down-valley direction or from the south to the north. By 0600 UTC (2300 LST) 67% of the cases were a downslope wind from the east with a less frequent down-valley wind from the south. At 1200 UTC (0500 LST) there was a slight increase in the number of cases with a south wind but the most common wind was still a downslope wind from the east. Finally, as the sun rose and the solar input increased, the winds again responded to vertical mixing, and the downslope wind from the west became more frequently observed. By late morning, 38% of the wind cases were recorded as downslope from the west, however there were still a significant number (29%) of data samples where the main wind was down-valley or from the south as well as downslope from the east (26%).

It becomes an interesting experiment to see how well the WRF model handles this complex interaction of the larger-scale pattern and the thermally induced wind flows due to terrain in the region.

3.3 SLC WRF Performance and Evaluation

The evaluation period was from January to May 2006 at the Hawthorne, UT, site, coinciding with the observation results in section 3.2. The model variables examined were temperature, dew point, wind direction, wind speed, and short-wave radiation. Table 2 shows the average forecast, average observation, average absolute temperature error, mean error, and correlation coefficient for the 2-km model output at all forecast hours.

Table 2. Model results at the Hawthorne, UT, site from January to May 2006

	Average Forecast	**Average Observation**	**Average Absolute Error**	**Mean Error**	**Correlation**
Temperature (°C)	3.8	6.7	3.5	-3.3	0.94
Dew point (°C)	-3.8	-2.9	3.1	-0.8	0.68
Wind direction (deg)	191	208	59	-5.1	0.37
Wind speed (m s^{-1})	2.2	3.4	1.9	-1.0	0.61
Radiation (w/m^2)	507	653	206	-141	0.72

As can be seen in table 2, the model does have large errors; however, this is not unexpected given the terrain issues and complex wind flow. As seen by the mean errors in table 2, the trend is for the model to underforecast the temperature and dew points over the 24-h forecast period with a bias to underforecast the wind speed. The minus sign in wind direction indicates that the wind error is negative or the winds are backed slightly on average. The radiation forecasts are also in error on the "negative" side, where the forecasted short-wave radiation is less than the actual observation at 1800 UTC, the time evaluated and shown in table 2.

While not shown in table 2, over the 24-h forecast period the temperature forecast is underforecasted for all hours. The dew point is underforecasted for the first 12 h, and then overforecasted at 18 and 24 h after the initial time period. Thus, the dew points are overforecasted during the afternoon hours in the model when surface winds tend to be from the west, but underforecasted at night when winds tend to be from the east. Wind speed is underforecasted at all hours except 12 h (1200 UTC), where the forecasted and observation difference is relatively small. Table 3 shows the forecast and observation of the prevailing wind direction during the entire 24-h period. Forecast values are left to right, observed values top to bottom.

Table 3. Forecasted wind regime (left to right) and observed wind regime (top to bottom) for the 24-h forecast period.

	Lake	Valley	Downslope (East)	Downslope (West)
Lake	31	12	8	6
Valley	6	29	12	0
Downslope (east)	2	13	47	3
Downslope (west)	5	6	8	7

The results in table 3 indicate the model does well in forecasting the wind-flow direction during the 24-h forecast period. As an example, 31 times the model forecasts a lake breeze and 31 times this verified. An even higher percentage of success is noted for the downslope winds from the east. If there are inconsistencies in the model performance it appears to be with the downslope flows from the westerly direction where the forecast errors are spread out evenly in all directions.

At the 0-h forecast period (0000 UTC, 1700 LST), the dominating wind observation was a westerly wind, not a surprise for the spring months. The model had a slight bias to under forecast this trend and perhaps a slight bias to overforecast the winds off the lake. Once the sun set, the dominating wind observation was from the east or the drainage winds off the Wasatch Range. If any trend was noted it was that the model went too quickly to the drainage flow rather than taking into the consideration the winds from the more dominating synoptic spring winds from the west or valley wind. However, by 0600 UTC (2300 LST), both the model and observations were nearly matched with a dominating downslope flow from the east and less frequent secondary flow from south to north in the valley. The model continued excellent statistical agreement with the observations at 1200 UTC with an even distribution of downslope and valley winds. As the daylight hours advanced, the skill of the model did decrease slightly with a trend to underforecast the downslope from the east and overforecast the valley wind from the south. By 24 h (0000 UTC, 1700 LST), the model skill was vastly reduced with a strong trend to underforecast the downslope winds from the west and again too quickly initiating the downslope winds from the east. The model did have good agreement on the lake breeze during the afternoon hours. An example of this occurred on 16 May 2007 using the 2-km WRF runs (version 2.1.2) on a day that the lake breeze was observed at the SLC airport.

In figure 2 the streamline plot in the SLC area shows the forecasted downslope winds at 1200 UTC 16 May 2007. The winds are predicted to be variable in the valley as the model does respond to some of the smaller-scale terrain features. At 1200 UTC, the wind reported at the SLC airport was from 140° at 4.6 m s^{-1} although the forecasted winds at the airport are backed more to a 090 direction.

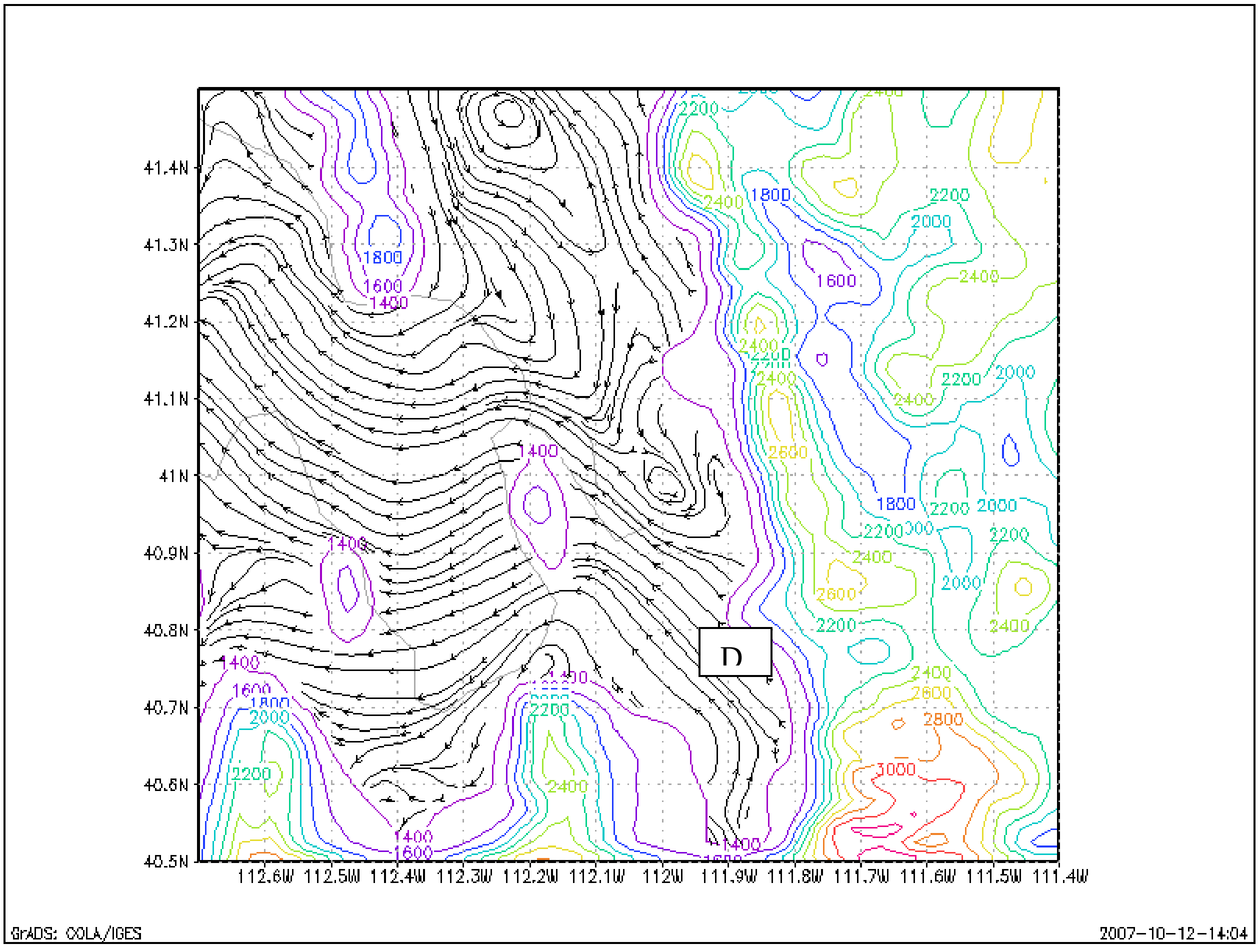

Figure 2. 1200 UTC 16 May 2007 surface winds centered in SLC valley; the “D” on the map shows the location of the urban downtown area of the city.

By 1600 UTC, as seen in figure 3, the overall surface wind flow near the mountain range are variable in direction with some hints of upslope flow starting in the southeast part of SLC with small surface-based circulations forecasted near the southeast corner of the grid. At 1600 UTC the SLC airport was reporting variable winds at 1.5 m s^{-1}. Meanwhile, as the surface became warmer, the wind on the lake had responded and the forecasted winds on the southern part of the lake had shifted to the north.

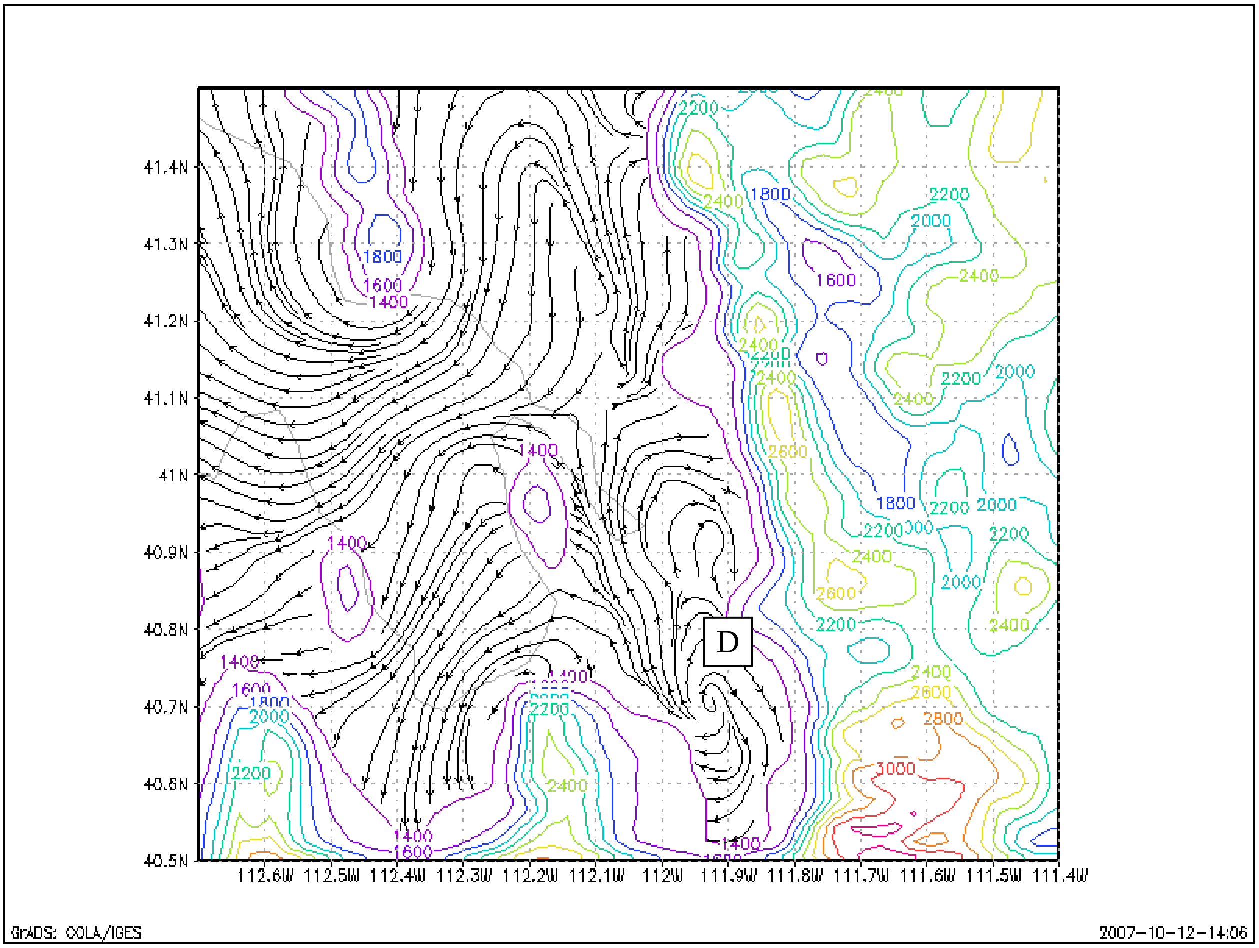

Figure 3. 1600 UTC 16 May 2007 surface wind flow in the SLC area; the “D” on the map shows the location of the urban downtown area.

By 1900 UTC, the forecasted winds are from the lake into the city as seen in figure 3. The forecasted winds near the airport are from 340°. At 1900 UTC, the observation at SLC was 340° at 4.1 m s^{-1}.

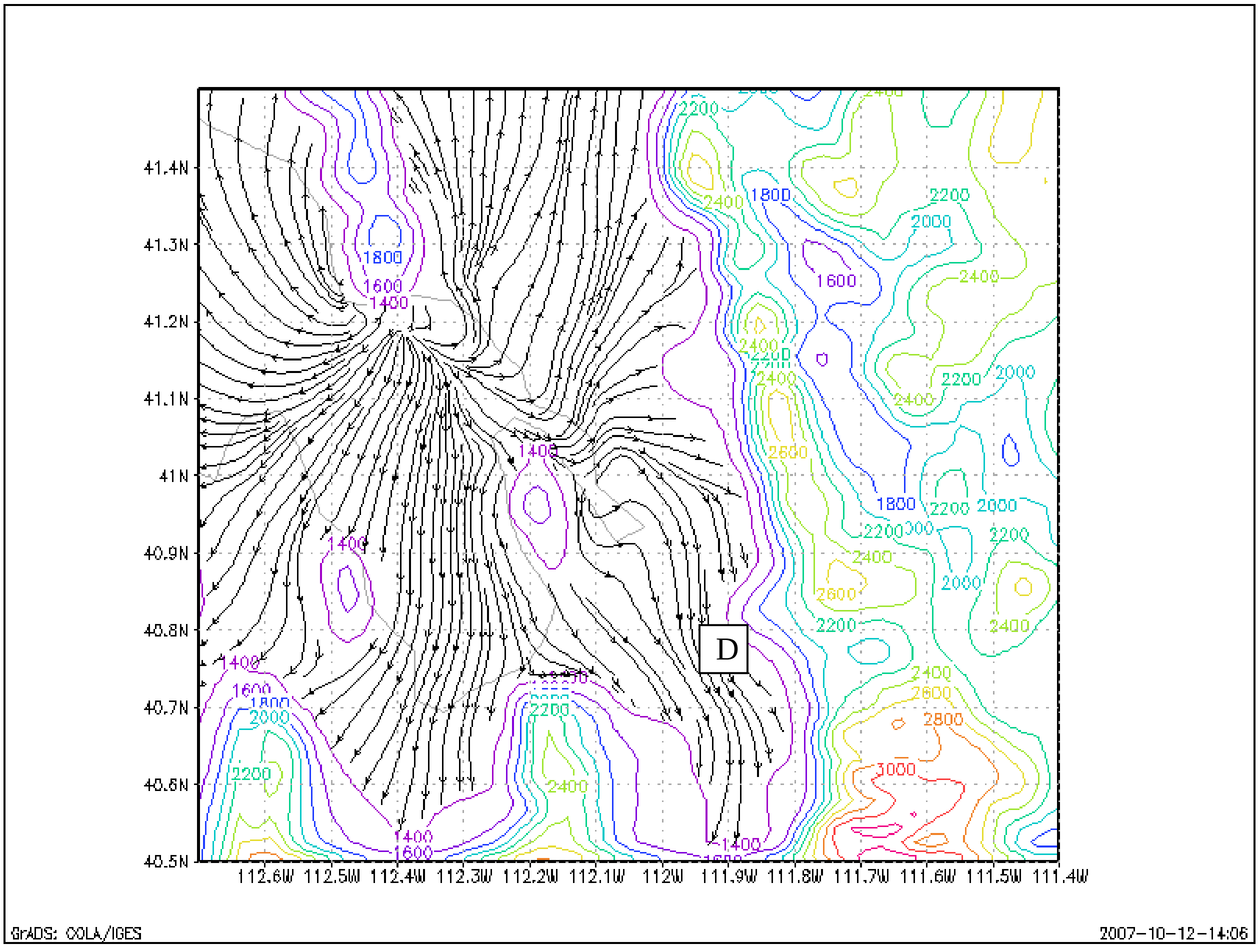

Figure 4. 1900 UTC 16 May 2007 surface wind flow in the SLC region; the "D" on the map shows the location of the urban downtown area.

4. WRF Results in Other Areas

A large number of studies have been completed by scientists interested in the WRF model performance and biases. Many of these have centered on case studies with much emphasis on precipitation. Additionally, researchers and operational meteorologists have investigated data assimilations techniques, parameterization schemes, and specific simulations such as tropical and hurricane model evaluation. As valuable as those research efforts are, they do not answer essential question relevant to Army scales or battlefield weather, typically on the order of 2-km or smaller. Much of the work in the current study has been unique in that it investigates model performance at the smaller scales. Other studies of the WRF have been conducted by ARL in many different locations to test the model performance in different terrain and meteorological regimes. While there may be some bias in the statistical comparisons since the model configuration may be slightly different, it is still useful to see how the model functions in dissimilar regions. The model configurations for each ARL study are described below:

- Iraq – The 15-km AFWA WRF, version 2.1.1, was used and observations were provided by AFWA in February and March 2006.
- Oklahoma City, OK – The 2-km WRF-ARW, version 2.1.1 was used. This study was done in April 2006, using observations provided by the NOAA at the Oklahoma City airport (OKC).
- WSMR, NM – The 2-km WRF-ARW, version 2.0, was used. Model runs were evaluated between 28 March–15 May, 2005 and verified with NOAA data and the Surface Atmospheric Measuring System data at WSMR, NM. (*11*)
- Owens Valley, CA – In conjunction with the Terrain-Induced Rotor Experiment (T-REX), this model used 2-km output for version 2.1.2 and verified with data provided by the T-REX project in the spring months of 2006. (*12*)

Table 4. The absolute errors for all model hours, initialized at 0000 UTC.

Location/Variable	**Iraq**	**SLC**	**OKC**	**WSMR**	**Owens Valley**
Temperature (°C)	1.1	3.5	1.4	3.9	2.6
Dew point (°C)	1.7	3.1	1.6	3.3	2.4
Wind direction (Deg)	33	59	23	55	50
Wind speed (m s^{-1})	1.5	1.9	4.1	1.2	2.4

As can be seen in table 4, the best model performance of the parameters examined occurs in Iraq and OKC, which should not be surprising given the flatter terrain of the stations tested, time of year, and perhaps smaller data sets. Results at SLC and WSMR are nearly identical. These results should not be interpreted as conclusive, since they are only point forecasts during a fraction of the year and were examined only to see how the model performed under strict conditions. Only the Owens Valley forecast verification had a large data, but the T-Rex experiment took place during a two-month time frame. Still, table 4 gives the model user some confidence that the model can and does perform well under certain conditions.

5. Conclusions

The WRF-ARW was run at SLC, initialized with 0000 (UTC) 40-km Eta model data for a period of 24 h with model output available every hour. A two-nest configuration was used, with the outer domain having 8-km grid resolution and the inner domain having a 2-km grid resolution. Model evaluation was conducted just southeast of downtown SLC and showed larger errors than other WRF evaluation studies. Given the terrain issues and the complex wind flow in this area, these results are not unexpected. The general trend is for the model to underforecast the temperature and dew points over the 24-h forecast period with a bias to underforecast the wind speeds.

Given the complex terrain, the wind flow was considered to be the WRF's most vital challenge. If any trend was noted it was that the model went too quickly to the drainage flow rather than taking into the consideration the winds from the more dominating synoptic seasonal winds from the west or from the south to north in the valley. During the entire 24-h evaluation forecast period the model overforecasted the drainage winds from the east and underforecasted the downslope winds from the west. The lake breeze only occurred in 11% of the cases and the model forecasted it with skill on most occasions as can be seen in the sequence of figures shown in section 4.

One of more interesting results, this apparent model error of having the WRF shifting the winds at the initial period and again too quickly reversing from a westerly flow to easterly flow at 24-h, should be an area of future study. It is uncertain if this is a localized problem, one likely to occur in complex terrain, a seasonal error, or a known WRF bias. Future studies will include a more detailed study of this region with an updated version of WRF with a triple nest and 1-km horizontal grid resolution. Additionally, there will be more of an emphasis on the thermal circulation and local fluxes in the boundary layer.

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List of Acronyms

3DVAR	three-dimensional variational
AFWA	Air Force Weather Agency
AMC	Air Monitoring Center
AMD	Advanced Micro Devices
ARL	U.S. Army Research Laboratory
FSL	Forecast Systems Laboratory
GB	gigabyte
GRADS	Grid Application Development Software Project
LST	local standard time
MM5	Mesoscale Model Version 5
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
OKC	Oklahoma City airport
RRTM	Rapid Radiative Transfer Model
SLC	Salt Lake City
T-REX	Terrain-Induced Rotor Experiment
UTC	universal time coordinates
VTMX	Vertical Transport and Mixing
WRE-N	Weather Running Estimate-Nowcast
WRF	Weather Research and Forecasting model
WRF-ARW	Advanced Research version of the Weather Research and Forecasting model
WSMR	White Sands Missile Range

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