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PERFORMANCE OF THE WRF-ARW IN THE COMPLEX TERRAIN OF SALT LAKE CITY

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1. INTRODUCTION

The Army Research Laboratory has an interest in high spatial and temporal resolution weather products with an emphasis on the boundary layer in complex terrain. In order to study and investigate small-scale weather processes, the advanced research Weather Research and Forecasting model (WRF-ARW) was run over a variety of locations. One of the more intriguing model areas of study was over the Salt Lake City (SLC) area where a nested version of the model was run for a 24-h period mainly during the cold season. Approximately 40 model runs were completed and results of the temperature, dew point, wind speed, and wind direction were examined over the forecast period. One of the main objectives of the 2-km model runs was to study the interaction of the Lake breeze, valley breeze, and downslope winds off the local terrain. Results show that the WRF-ARW had a bias to overforecast the downslope winds from the east, underforecast the downslope winds from the west, and performed well in forecasting the Lake breeze. The most accurate wind speeds were noted at 1200 UTC, but the model underforecasted wind speeds during the afternoon hours. This paper will investigate some of these trends and evaluate the performance of the model in this difficult and complicated forecast region.

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2. THE WRF MODEL CONFIGURATION

The WRF runs at Salt Lake City were completed using version 2.1.1; however, the recent WRF models were run with version 2.1.2 and demonstrated in section 4 of this paper. All the models run were utilized with the advanced research WRF-ARW dynamical core and were initialized with 0000 universal time coordinate (UTC) 40-km ETA model data. The models were run for a period of 24 hours 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, although the model output shown in section 4 used a three nest configuration of 18-km, 6-km, and 2-km grid resolutions.

The physics packages used for all model runs were:

- Lin microphysics
- RRTM long-wave radiation
- Dudhia short-wave radiation
- 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. CHARCTERISTICS OF SALT LAKE CITY WINDS

The SLC area is one of the most unique places to study meteorological models and meteorological conditions. 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 feet (4.3m) and due to the shallow depth, the water temperature remains warm most of the year and contributes to lake-effect snows or rain. Additionally, the valley with a large population has become an intriguing region to study air pollution and aerosols, since the valley is often characterized by a stable boundary layer with a strong morning inversion. The complex terrain is also a challenge because of a variety of wind flows influenced by the mountains and the lake.

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 during October 2000. This study, the Vertical Transport and Mixing (VTMX) field campaign, (Doran et al, 2002) placed an emphasis on complicated thermally driven flows, and the valley boundary layer.

Zumpfe and Horel (2007), in their study of the lake breeze noted some long-term observations of the thermally driven flows in the Salt Lake Valley of northern Utah. The up-and downslope 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) blow from south to north. The up-and down-canyon flows are winds that develop in response to the local slope flows and may sometimes be referred to as upslope and downslope winds.

Zumpfe and Horel also note that on days from April to October without precipitation, the wind direction tends to be either down valley 53 percent of the time or up valley 29 percent of the time at the SLC airport. They also remark that on occasions, the up-valley wind is accompanied by significant increases in temperature and 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 (2000) indicates that the strongest nocturnal downslope winds typically occur around sunset when the mountain slopes first go into shadows, while Banta et. al. (2002) observed during VTMX that the reversal from up-valley to down-valley nighttime winds seem to occur from 2000-2200 (LST). As expected, larger-scale pressure differences had a strong influence on the development of the down-valley winds.

In this current study, data were collected and used for verification 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 (www.airmonitoring.utah.gov).

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. The winds were evaluated in the same general time periods as the model output evaluation.

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

Time/Wind Direction	Downslope East (%)	Downslope West (%)	Lake Breeze (%)	Valley Breeze (%)
0000 UTC	5	56	14	25
0300 UTC	43	22	13	22
0600 UTC	67	8	3	22
1200 UTC	47	14	8	31
1800 UTC	27	38	6	29
0000 UTC	3	65	21	11

The results in table 1 are not totally surprising and show that 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 percent 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 dramatic change in the wind patterns and the local terrain becomes more significant than the synoptic flows in the resulting 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 number of cases with the wind from the west and even a number of cases from a valley direction. By 0600 UTC (2300 LST) 67 percent 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) the 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 solar input increased, the downslope from the west became more frequently observed than downslope from the east and the south wind. By late afternoon, 65 percent of the cases were recorded as downslope from the west with a slight number (22 percent) from the north or Lake breeze

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

4. WRF MODEL EVALUATION IN THE SALT LAKE CITY AREA

The evaluation period was from January to May 2006 at the Hawthorne site, coinciding with the observation results in section 3. 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

	Ave Forecast	Average Observations	Ave Abs Error	Mean Error	Correlation
Temp °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 Dir (deg)	191	208	59	-5.1	0.37
Wind Speed knots)	4.2	6.6	3.7	-2.0	0.61
Radiation (w/m^2)	507	653	206	-141	0.72

As can be seen in the table, the model does have larger errors than other WRF evaluation studies, however this is not unexpected given the terrain issues and complex wind flow. 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. 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.

Over the 24-h forecast period the temperature forecast is underforecasted for all hours. The dew point is underforecasted for the first 12 hours, 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 overforecasted at all hours except 12-h (1200 UTC) where the forecast and observation error 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 (up to down) 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 reasonably well in forecasting the general wind flow during the 24-h forecast period. As an example, 31 times the model forecasts a Lake Breeze and 31 times and this verified. An even higher percent 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 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 initiate the downslope winds from the east. The model did have a 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 1 the streamline plot in the Salt Lake City area shows the general downslope winds at 1200 UTC on 16 May 2007. The forecasted winds are generally variable in the valley as the model does respond to some of the smaller-scale features which act as obstacles to the overall flow. At 1200 UTC the wind reported at the SLC airport was from 140 degrees at 9 knots although the forecasted winds at the airport are backed more to a 090 direction.

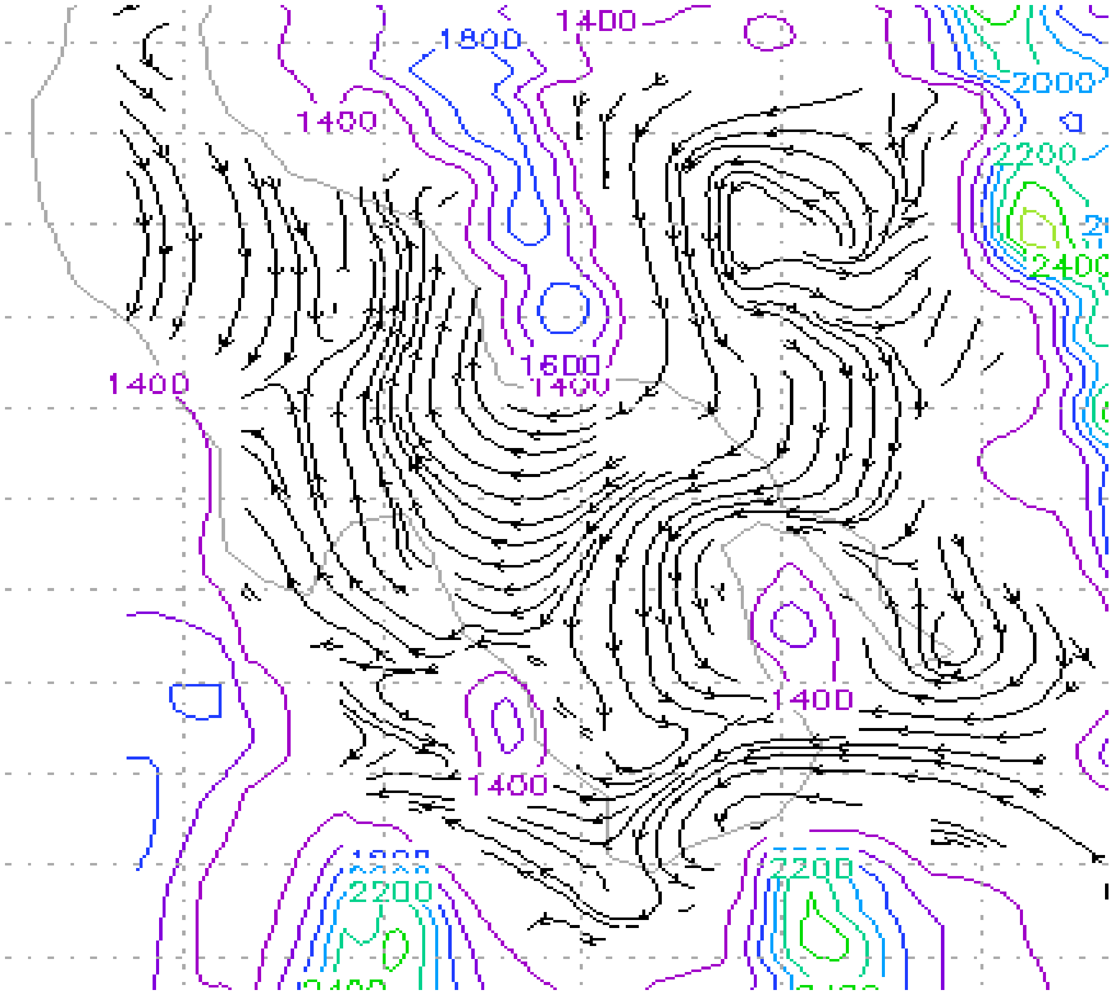

Fig 1. 1200 UTC May 16, 2007 wind flow centered in the SLC valley/

By 1600 UTC, as seen in figure 2, 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 smaller eddies forecasted near the southeast corner of the grid which is close to the airport. At 1600 UTC the SLC airport was reporting variable winds at 3 knots. 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. By 1900 UTC, the general forecasted winds are from the lake into the city as seen in figure 3. The forecasted winds near the airport are from 340 degrees. At 1900 UTC, the observation at SLC was 340 degrees at 8 knots.

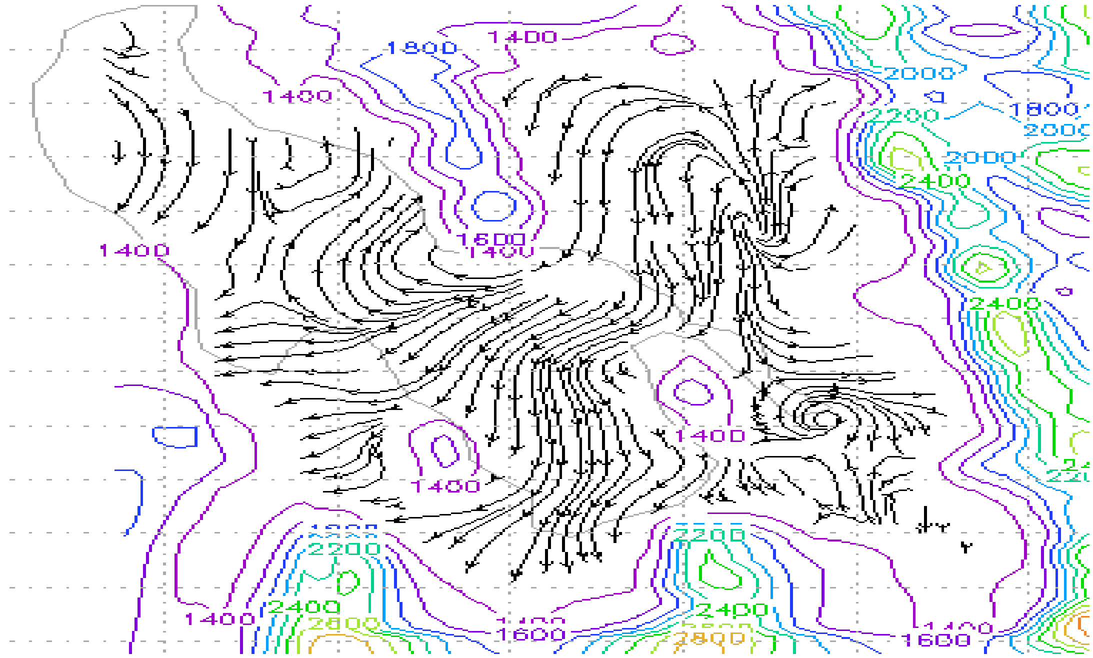

Figure 2 -- 1600 UTC 16 May 2007 wind flow in Salt Lake Basin

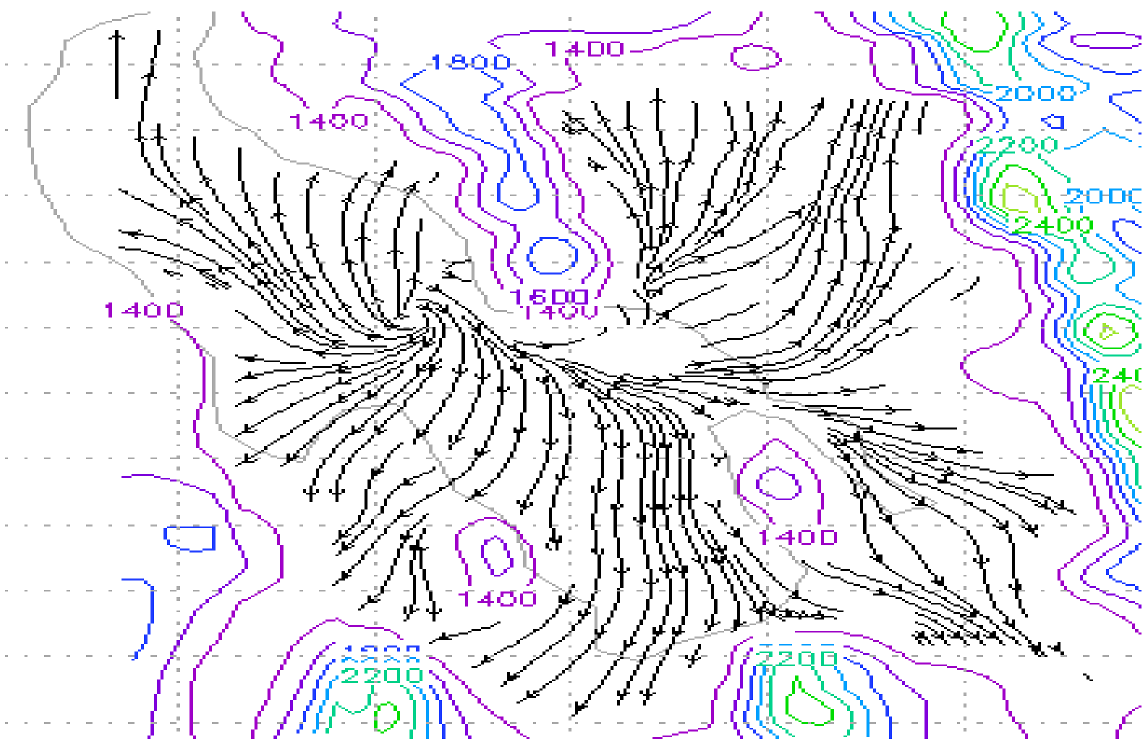

Figure 3: 1900 UTC, 16 May 2007 wind flow in the SLC region

5. SUMMARY AND CONCLUSIONS

The WRF-ARW was run at Salt Lake City initialized with 0000 (UTC) 40-km ETA model data for a period of 24 hours 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, although the recent runs used a three nest configuration of 18-km, 6-km, and 2-km grid resolutions as seen in figures 1-3. 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 percent 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, or a known WRF bias. It could be an issue of boundary-layer processes or parameterization. Future studies will include a more detailed study of local fluxes and to see how WRF interactions in the boundary layer respond to different parameters.

6. REFERENCES

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