

**Statistical Analysis of Atmospheric Forecast Model
Accuracy – A Focus on Multiple Atmospheric Variables and
Location-Based Analysis**

by Jeffrey O. Johnson, John W. Raby, and David I. Knapp

ARL-TR-6915

April 2014

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Statistical Analysis of Atmospheric Forecast Model Accuracy – A Focus on Multiple Atmospheric Variables and Location-Based Analysis

Jeffrey O. Johnson, John W. Raby, and David I. Knapp
Computational and Information Sciences Directorate, ARL

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14. ABSTRACT: Atmospheric effects on commercial and military air platforms are of concern and must be considered for flight planning or military mission execution. Atmospheric models exist that can forecast adverse weather, thus mitigating the impacts on operations. The Weather Research and Forecasting (WRF) model is a numerical weather prediction system designed for operational forecasting and atmospheric research. This report examined WRF model output and investigated any potential value-added for higher-resolution model grids using statistical methods. As a supplement to a Phase 1 of analyses conducted by the lead author of this report, Phase 2 examines additional atmospheric variables beyond surface temperature and then performs a location-based analysis to assess model performance. The model performs best for surface temperature and upper-level winds. Surface temperature was selected as the primary variable for this study. The analysis separated the observation station data into three categories: Valleys, Plains, and Mountains. Results showed significant improvement of correlation coefficients when compared to the Phase 1 effort, but the higher-resolution 1-km results showed little improvement compared to the lower-resolution 3-km model results, suggesting that examination of more data is in order.					
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Contents

List of Figures	iv
List of Tables	iv
Acknowledgments	v
1. Introduction	1
2. Description of the Data	1
3. Models and Approaches	5
4. Results	6
4.1 Part 1-Variables: Correlation Analysis.....	6
4.2 Part 2-Location-Based Analysis	6
4.2.1 Correlation Analysis and T-Tests	7
5. Conclusions	15
6. References	16
Appendix A. Snippet of the MET Output Data	17
Appendix B. Detail Plotted Correlation Coefficient Results	19
Appendix C. Individual Stations	25
List of Symbols, Abbreviations, and Acronyms	32
Distribution List	33

List of Figures

Figure 1. Screenshot of Google Earth showing approximate bounding box for sample area at DPG, UT, and all 25 observation stations (blue icons).....	2
Figure 2. Screenshot of data set showing 1- and 3-km model forecast and surface observation data grouped by geographic location type used in analysis effort (only the first two region-types are visible).....	4
Figure 3. Screenshot of surface temperature (K) data set showing surface observation data versus 1-km model forecast data for all data points (all geographic regions and all times) used in analyses.....	7
Figure 4. Screenshot of surface temperature (K) data set showing surface observation data versus 3-km model forecast data for all data points (all geographic regions and all times) used in analyses.....	7
Figure 5. Probability plots for each of 1 km, 3 km, and observation data (Valley). Surface temperature (K) is indicated along the x-axis.	9
Figure 6. Probability plots for each of 1 km, 3 km, and observation data (Plain). Surface temperature (K) is indicated along the x-axis.	10
Figure 7. Probability plots for each of 1 km, 3 km, and observation data (Mountain). Surface temperature (K) is indicated along the x-axis.	11
Figure 8. Histogram plots for each of 1 km, 3 km, and observation data (Valley). Surface temperature (K) is indicated along the x-axis.	12
Figure 9. Histogram plots for each of 1 km, 3 km, and observation data (Plain). Surface temperature (K) is indicated along the x-axis.	13
Figure 10. Histogram plots for each of 1 km, 3 km, and observation data (Mountain). Surface temperature (K) is indicated along the x-axis.	14

List of Tables

Table 1. Summary of available forecast model and observation data at DPG, UT, 4 July 2010.....	3
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1. Introduction

Atmospheric effects on commercial as well as military air platforms and any associated subsystems is of critical concern, whether for commercial flight planning or for military mission execution.

Knowing when and where adverse weather conditions will exist to a high level of accuracy is an ongoing effort for atmospheric forecast modelers. However, atmospheric models are known to involve some of the most complex equations in any software system, and for this reason have even been used to benchmark some of the most powerful super computers in the world (2).

The Weather Research and Forecasting (WRF) model is a mesoscale (one to several hundred kilometers in horizontal spatial dimension) numerical weather prediction system designed for operational forecasting as well as atmospheric research (3). With the complexity of the atmospheric equations in WRF, identifying trade-offs between increased model resolution and the time and resources required to complete WRF model runs remains an ongoing source of research, while some work by others focuses on modifying physics models or number of model runs (4, 5, 6).

The research conducted in this report examined the WRF atmospheric forecast model output from a 2010 test (7), and investigated whether there is any potential value-added for higher-resolution model runs. WRF-generated output of 1- and 3-km horizontal grid point resolution for surface temperature (in kelvins [K]) were compared to surface temperature observation data for a 100×100 km area at Dugway Proving Ground (DPG), UT. Analysis of these data was then performed using statistical methods including correlation analysis, t-test, and normal distribution fit. Extending the research conducted by Johnson (2011) (1) of 1- versus 3-km WRF using forecast time bins, this research implemented a two-fold plan for analysis:

Part 1 – Variables: Determine what other atmospheric variables are modeled well using the WRF model.

Part 2 – Location-Based Analysis: Use location-based analysis to determine if the WRF model performs better when areas of analysis are separated by geographic location-type.

2. Description of the Data

The data for this research were collected during a test conducted at DPG in July 2010. Data for a single day (4 July 2010) were used, with observation data collected from 25 different surface stations within a 100×100 km domain. For the research conducted, variations in horizontal

resolution of coinciding WRF model nest outputs for the same domain were the focus for the analyses. WRF model data were generated for both 1- and 3-km horizontal resolution within this domain. The data examined are continuous data (temperature), with discrete samples at specified time intervals.

Figure 1 shows the data sample area (outlined in light purple box) and associated sample observation station (ground truth) locations.



Figure 1. Screenshot of Google Earth showing approximate bounding box for sample area at DPG, UT, and all 25 observation stations (blue icons).

To better represent the sample locations and their positions relative to the different geographic location-types, a Google Earth movie, which is fly-thru of the area of analysis, was also created and analyzed during this effort.

Standard mesoscale WRF atmospheric model forecasts were made available in 3-h increments: 0Z,3Z,6Z,9Z,12Z,15Z,18Z, and 21Z. These data samples are labeled according to the start of model run at the DPG location, starting at Hour 0 and ending at Hour 24. Thus, the data include the following:

Hr0(6Z), Hr3(9Z), Hr6(12Z), Hr9(15Z), Hr12(18Z), Hr15(21Z), Hr18(0Z), H21(3Z),
Hr24(6Z the following day) *(which is a total of nine time bins)*

For the dominant research in this report, which is [Part 2](#), and unlike the results in previous work (Johnson, 2011) ([1](#)), all 25 observation station locations were analyzed in this research effort. Because the data were analyzed based on station locations rather than time bins, all stations were included for each analysis sheet, even if some of the stations did not have data for all time periods.

The data were separated into the following three geographic location-types, and defined as follows:

1. **Valleys:** Observation stations flanked on the north/south or east/west sides by elevated areas (five stations).
2. **Plains:** Observation stations >6 miles (9.7 km) away from a 1,000-ft (304.8 m) increase in elevation, and were not already categorized as “valley” (nine stations).
3. **Mountains:** Being excluded from the “valley” and “plain” categories, mountain locations included all remaining observation stations (eleven stations).

A detail of the stations and reporting times is shown in table 1.

Table 1. Summary of available forecast model and observation data at DPG, UT, 4 July 2010.

Region	Station ID	Reporting Times
Valley	3	All Hours
	4	All Hours
	7	All Hours
	18	All Hours
	21	All Hours
Plain	6	Skip: HR03,24
	9	Skip: HR00
	10	All Hours
	13	All Hours
	15	All Hours
	17	All Hours
	23	All Hours
	24	All Hours
	25	All Hours
Mountain	1	All Hours
	2	All Hours
	5	All Hours
	8	Skip: HR24
	11	All Hours
	12	Skip: HR06
	14	All Hours
	16	All Hours
	19	All Hours
	20	All Hours
	22	All Hours

Interpolated values for model (both 1 km and 3 km) surface temperature matching the location for each of the observation data station locations were computed by the U.S. Army Research Laboratory (ARL) with the use of the Model Evaluation Tools (MET) verification package, developed by the National Center for Atmospheric Research (NCAR), Developmental Testbed

3. Models and Approaches

Correlation Analysis and T-Tests

Correlation coefficients for all data points as well as for each geographic location-type (Plains, Valleys, Mountains) were calculated using Microsoft Excel to determine whether or not there were any improved correlations of forecast data (1 and/or 3 km) versus observed data. Let there be p variables, and s is the sample covariance, then the sample correlation coefficient r for the i^{th} and k^{th} variables is given by:

$$r_{ik} = \frac{s_{ik}}{\sqrt{s_{ii}}\sqrt{s_{kk}}} = \frac{\sum_{j=1}^n (x_{ji} - \bar{x}_i)(x_{jk} - \bar{x}_k)}{\sqrt{\sum_{j=1}^n (x_{ji} - \bar{x}_i)^2} \sqrt{\sum_{j=1}^n (x_{jk} - \bar{x}_k)^2}}$$

For $i = 1, 2, \dots, p$, and $k = 1, 2, \dots, p$, and

r must be between -1 and +1

$r = 0$, no linear relationship

$r > 0$, positive linear relationship

$r < 0$, negative linear relationship

Note: Correlation coefficient analysis was the only analysis tool used for *analysis of different variables* ([Part 1](#)).

A t-test was performed to determine the significance of the correlation coefficients *for each geographic location-type* ([Part 2](#)) for each of the results (1 and 3 km). For this calculation, we have:

$$t = r \sqrt{\frac{n-2}{1-r^2}}$$

Where r is the correlation coefficient and n = number of samples, with hypotheses:

$$H_0: r_{1\text{km,obs}} = 0.0 \quad (\text{no relationship, 1-km case})$$

$$H_0: r_{3\text{km,obs}} = 0.0 \quad (\text{no relationship, 3-km case})$$

tested at a 95% confidence level.

This calculation was performed for each of the three geographic location-types (Plains, Mountains, and Valleys).

4. Results

4.1 [Part 1](#)-Variables: Correlation Analysis

Analysis of variables was performed using specific time bins. To determine which time bins, correlation coefficients and variance covariance matrices for “strong correlation” shown in surface temperature by Johnson (2011) ([1](#)) were used to select the specific time bins for each of the following atmospheric parameters:

- Dew point temperature
- U-component 10-m winds
- V-component 10-m winds
- U-component “upper-level” (875–775 mb) winds
- V-component “upper-level” (875–775 mb) winds
- Wind magnitude (10 m and upper-level)

The findings in the analysis of these different variables at specified times determined the following with respect to WRF model accuracy (detail plotted correlation coefficient results are listed in [appendix B, Part 1](#)):

- None of the variables were better modeled than surface temperature.
- Dew point temperature showed very poor, even negative correlation, and thus was *removed* as a possible variable for analysis of 1- versus 3-km model resolution results. The poor results suggest further analysis is necessary (including dew point data quality analysis), which is beyond the scope of this report.
- U-component (x-direction) and V-component (y-direction) winds showed relatively good correlation, especially at upper-levels (875–775 mb or approximately 1200-m above ground level [AGL]), which had 0.785 for U-component 1 km compared with 0.585 U-component 1 km for 10-m height, for example.
- Wind magnitude was determined to be a good approximation for the accuracy of the U- and V-component winds and, thus, could be used for a “first look” at model 1- and 3-km results.

4.2 [Part 2](#)-Location-Based Analysis

As was seen by Johnson (2011) ([1](#)), the initial plots of all data suggested there was not a very large difference between the high-resolution (1 km) and lower-resolution (3 km) results. Looking

at the differences between the two scatter plots seen in figure 3 (Obs versus 1 km) and figure 4 (Obs versus 3 km), it is apparent that at first glance there is certainly a positive correlation for both resolutions. However, there are indications the correlation coefficients between the two model results may not be very different (0.903 and 0.899 for the “total” 1 km versus Obs and 3 km versus Obs, respectively).

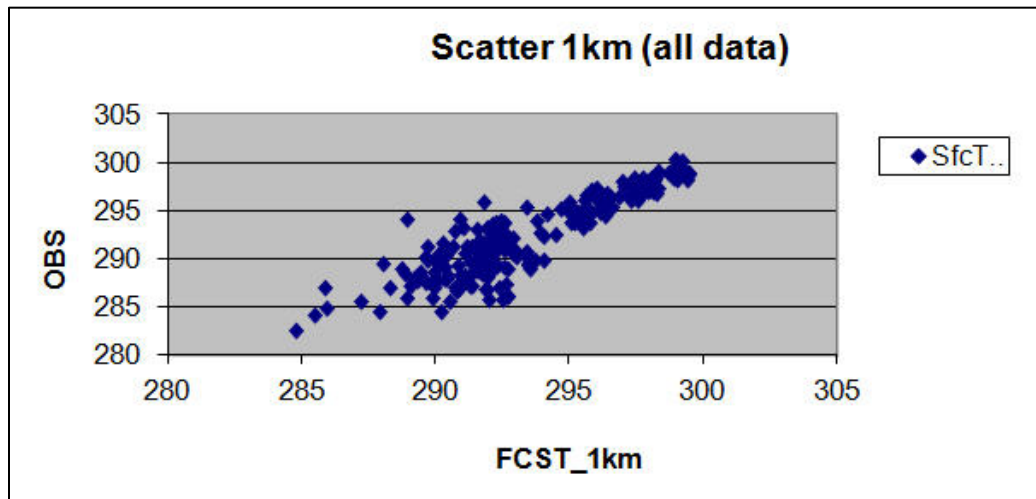


Figure 3. Screenshot of surface temperature (K) data set showing surface observation data versus 1-km model forecast data for all data points (all geographic regions and all times) used in analyses.

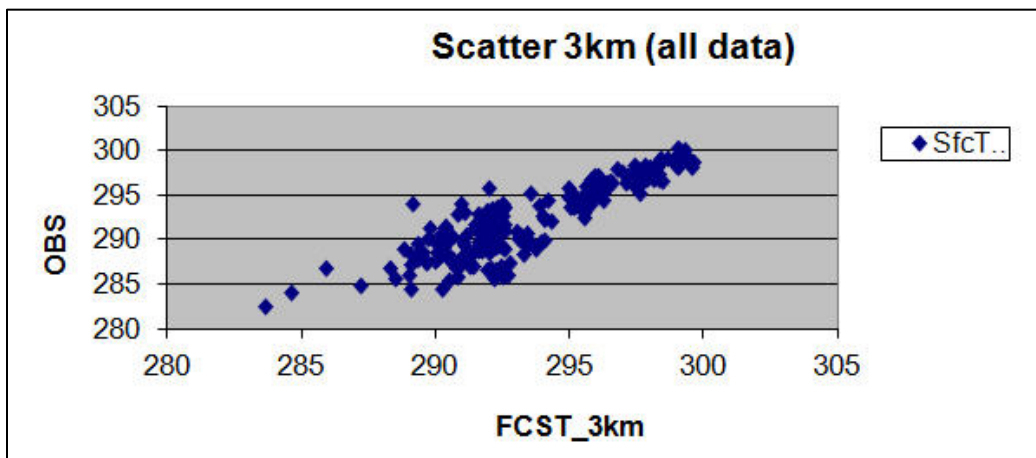


Figure 4. Screenshot of surface temperature (K) data set showing surface observation data versus 3-km model forecast data for all data points (all geographic regions and all times) used in analyses.

4.2.1 Correlation Analysis and T-Tests

Correlation coefficients and variance covariance matrices by geographic location-type ([Part 2](#)) and t-test results of significance of correlation at 95% level of confidence are listed in [appendix B, Part 2](#).

The initial look at individual stations [appendix C](#) showed a large improvement in correlation coefficients when compared to the results from Johnson (2011) ([1](#)). However, in most cases, the 1 km did not outperform the lower-resolution 3-km model results, and if so, by very little. A summary of the findings for each of the geographic location-types:

Valleys: *All stations* showed 1-km correlation coefficients higher than 3-km results.

Plains: *Two of nine stations* showed 1-km correlation coefficients higher than 3-km results.

Mountains: *Three of eleven stations* showed 1-km correlation coefficients higher than 3-km results.

In all cases (Valleys, Plains, and Mountains), t-test results showed (for both 1- and 3-km results) $t > t_{df}$, where df = degrees of freedom. Thus, $\Rightarrow$ *Reject hypothesis of no relationship*. Note that in almost all cases $df = 7$ as there were nine time bins with all stations reporting for nearly all time bins. Exceptions have been noted in [Section 2, Description of Data](#).

Of greater interest, and detailed in [appendix C](#) in this report, were the results encompassing *all data for each of the three categories*. These correlation coefficient results showed that in all cases/categories of geographic regions (Valleys, Plains, and Mountains), the 1-km WRF results were the same (Plains) or better (Valleys and Mountains) and that the positive correlation in all cases was significant. The difference of improvement, however (Valleys and Mountains) was small (<0.01), with ***best 1-km improvement indicated in areas of type “mountain.”***

Examination of probability plots to test for a normal distribution showed that none of the surface temperature data for any of the geographic location-types were normally distributed, as can be seen in figures [5](#), [6](#), and [7](#). This was somewhat unexpected, as it was hypothesized that having regionalized results might (in addition to improving model accuracy) improve the normal distribution fit found by Johnson in the Spring of 2012 ([8](#)), but this was not the case:

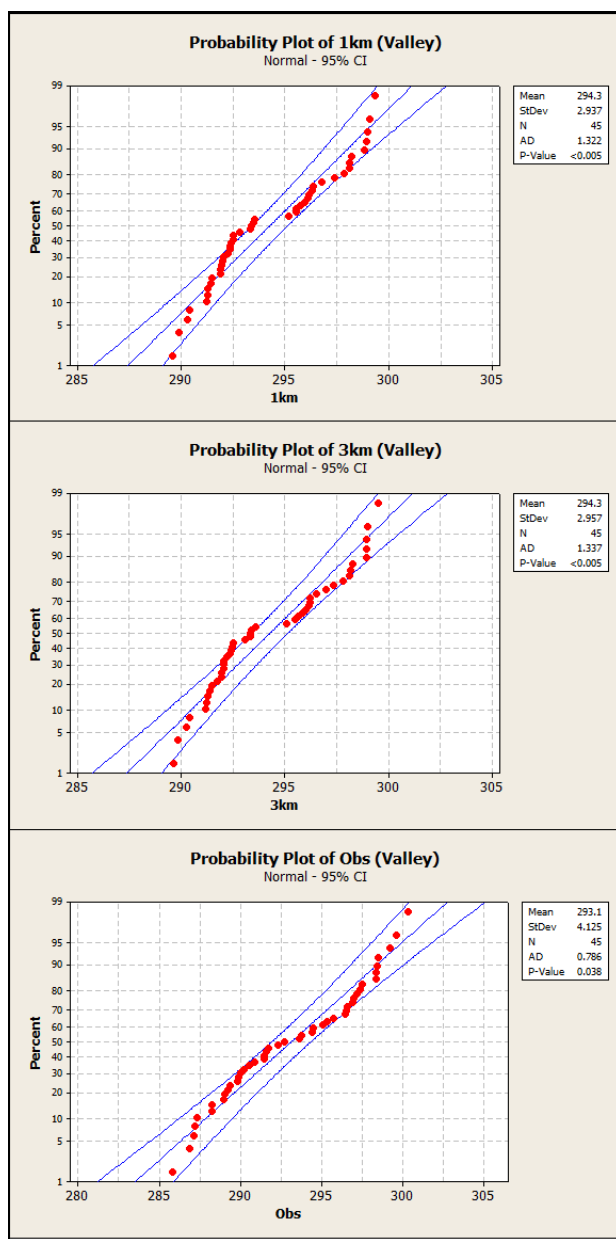


Figure 5. Probability plots for each of 1 km, 3 km, and observation data (Valley). Surface temperature (K) is indicated along the x-axis.

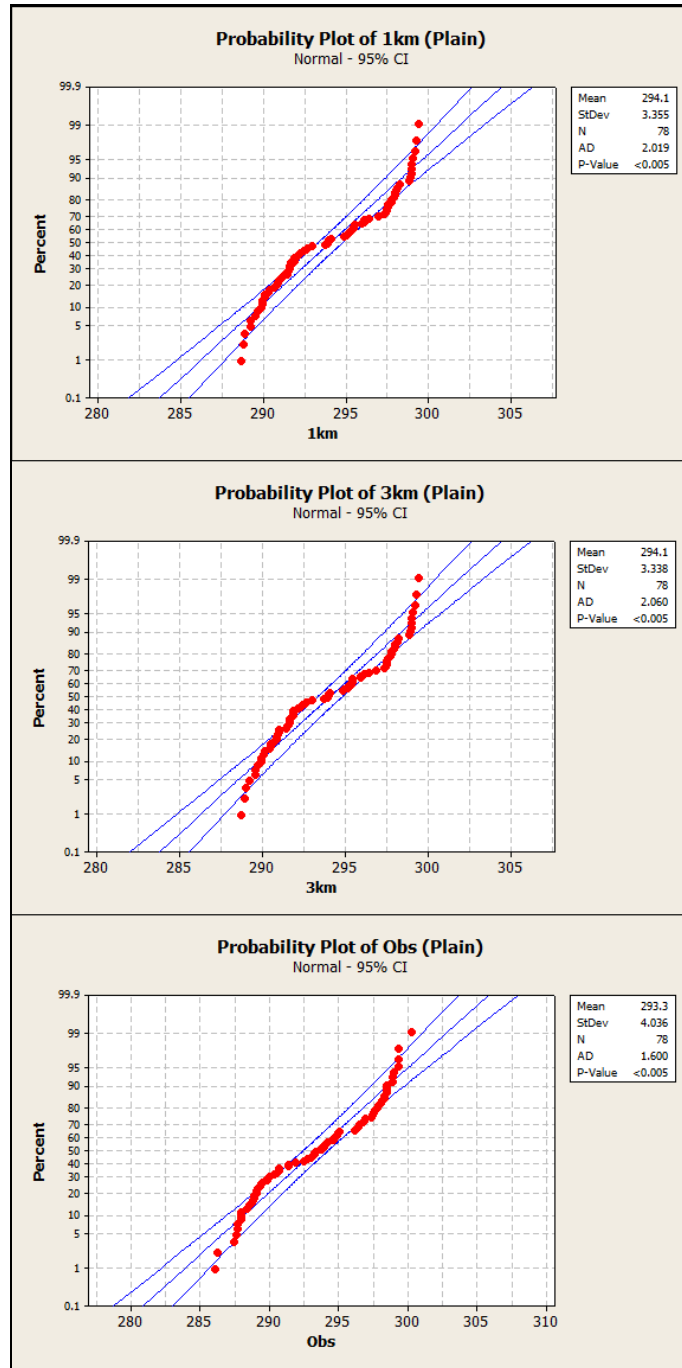


Figure 6. Probability plots for each of 1 km, 3 km, and observation data (Plain). Surface temperature (K) is indicated along the x-axis.

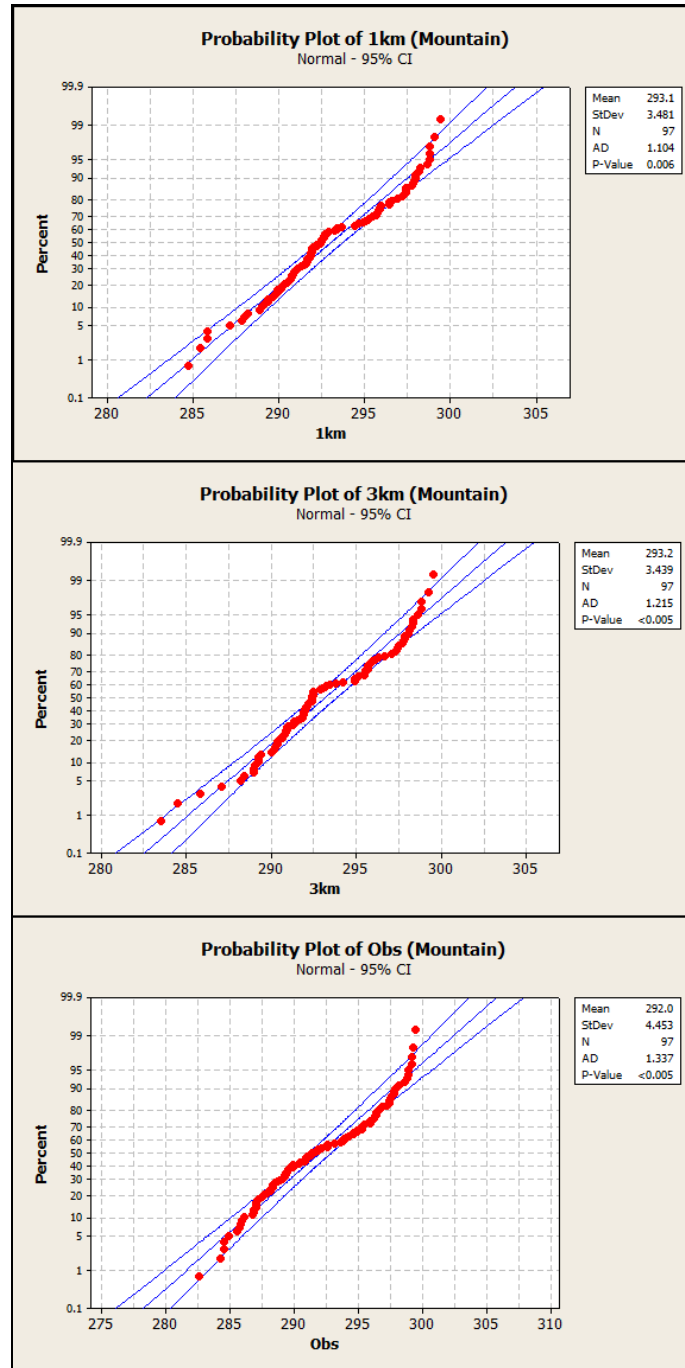


Figure 7. Probability plots for each of 1 km, 3 km, and observation data (Mountain). Surface temperature (K) is indicated along the x-axis.

In addition, the surface temperature histogram results of each geographic location-type seen in figures [8](#), [9](#), and [10](#) are still showing the bimodal distribution as noted by Johnson (2012) ([8](#)). As stated earlier, spatial and temporal influences are thought to be the cause, and are reason for suggested future analyses:

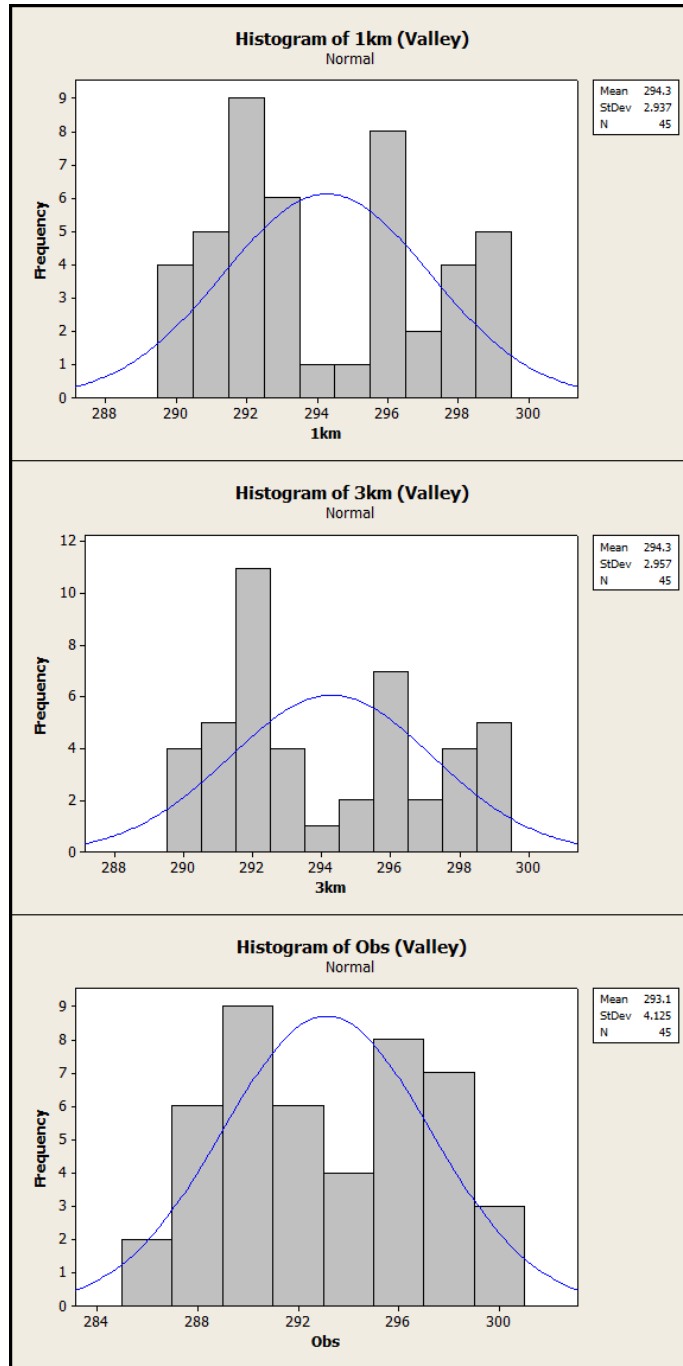


Figure 8. Histogram plots for each of 1 km, 3 km, and observation data (Valley). Surface temperature (K) is indicated along the x-axis.

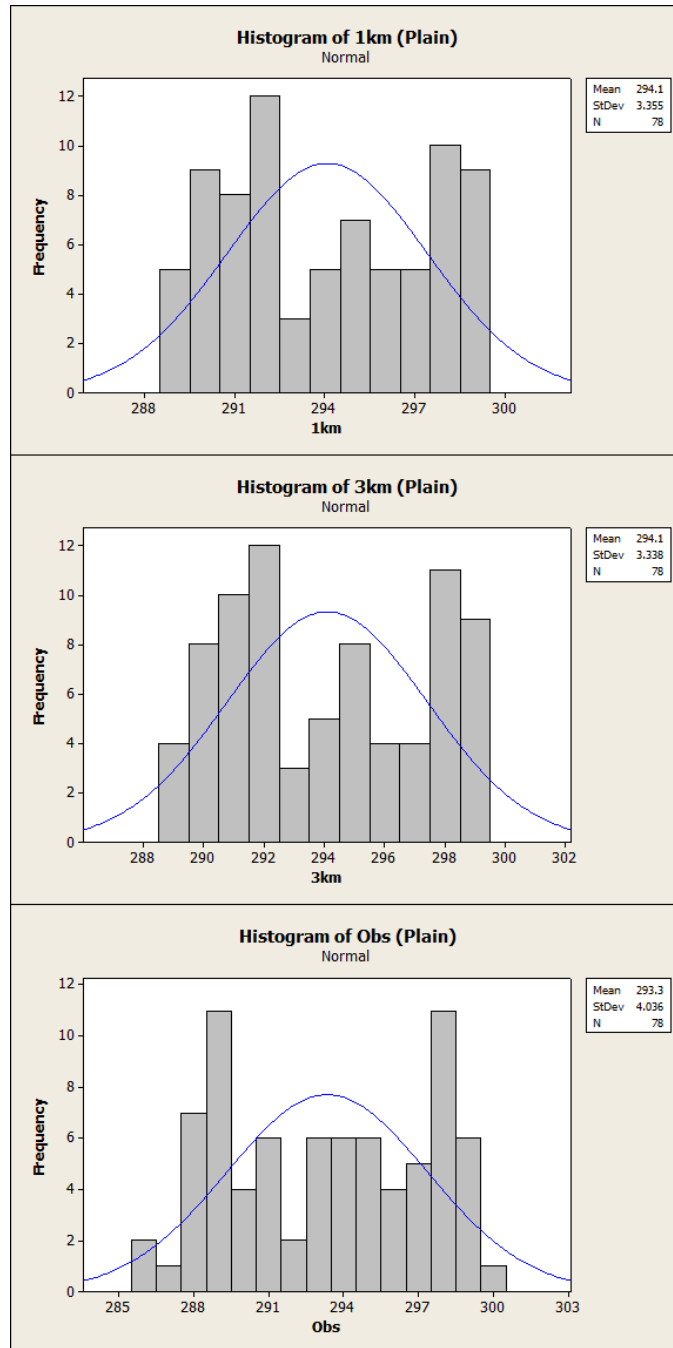


Figure 9. Histogram plots for each of 1 km, 3 km, and observation data (Plain). Surface temperature (K) is indicated along the x-axis.

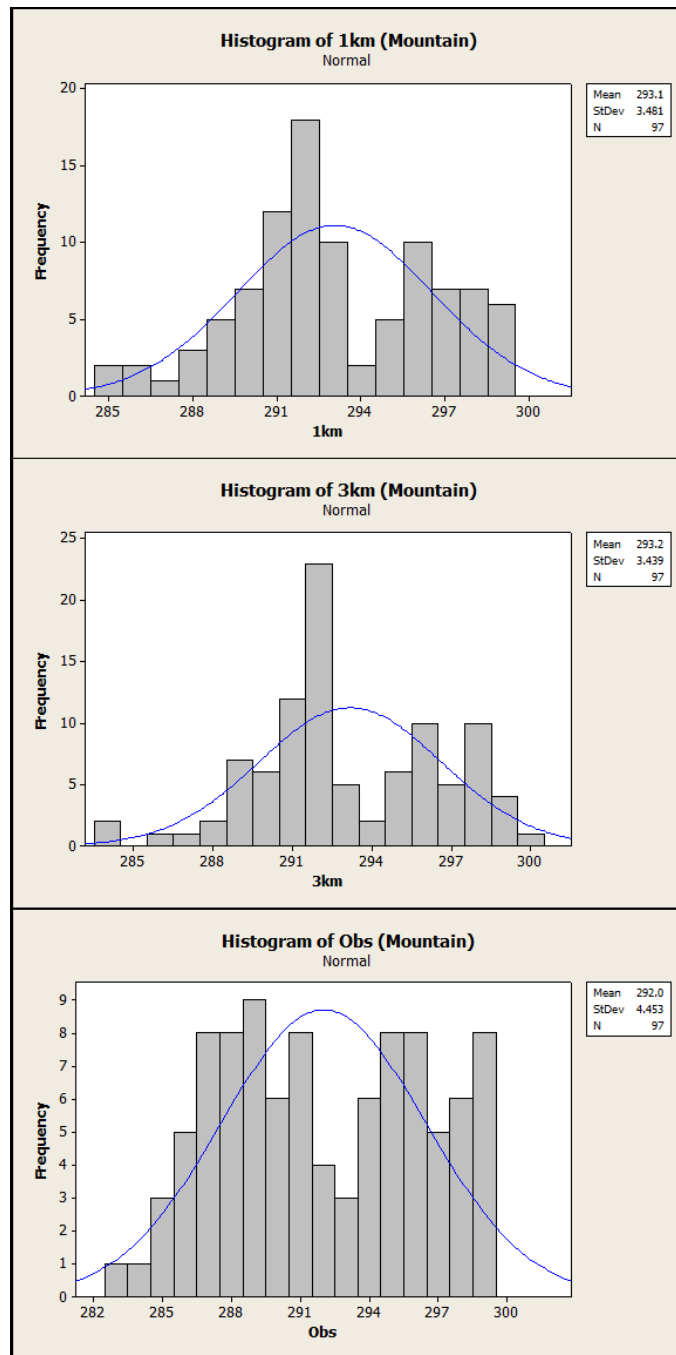


Figure 10. Histogram plots for each of 1 km, 3 km, and observation data (Mountain). Surface temperature (K) is indicated along the x-axis.

Though the data sample did not clearly fall into a normal distribution, with evidence of a bimodal distribution, surface temperature data have been shown to still be reasonably close to normal ([11](#)).

5. Conclusions

This research was an extension to analysis performed by Johnson in 2011 (8). This phase, described here as “Phase 2,” incorporated a two-fold plan: (1) analysis of additional atmospheric variables as potential for analysis of 1 and 3-km WRF model output, and (2) analysis of geographic location-types of observation stations (ground truth sample points), and divided into three location-types: Valleys, Plains, and Mountains.

The analysis of different variables showed that the existing variable of “surface temperature” far outperformed other variables in terms of correlation coefficient results. Only one other variable type, winds, showed some promise for analysis. Specifically, U-component and V-component (and, accordingly, wind magnitude) winds, with best performance at upper-levels (875–775 mb, or approximately 1200-m AGL), but still with lower-correlation coefficients than were seen with surface temperature.

The analyses performed using geographic location-types resulted in higher-overall correlation coefficients for all location-types (Valleys, Plains, and Mountains). However, the differences in 1 km versus 3 km were present only in the “Valley” and “Mountain” cases. Though differences in 1 km and 3 km were present (favoring 1-km improved accuracy), they were minimal.

The bimodal distribution for both the results by Johnson (2011) (1), as well for this more recent analysis, remains. Reducing the sample set to a uniform distribution of observation stations, as well as segregating the sample set of observation stations into geographic location-types had minimal effect. Thus, the authors believe both spatial as well as temporal effects are playing a role in this result, suggesting further research into this area is necessary.

Based on the results from Johnson (2011, 2012), which examined 1- versus 3-km WRF model performance over different forecast hour time bins (1), and showed that geographic location-type analysis may show improved WRF model performance (8), new studies have since been designed to further explore sub-domains. These studies involve the use of larger volumes of data consisting of hourly forecast-observation matched pairs data, such as that used for the above work, over a period of 10 case study days over complex terrain. An automated approach is planned to insure quality controlled observational data and error-free data handling. The analysis of the data will be performed using a Geographic Information System (GIS) with high-resolution terrain data. The focus of the analysis will be to reveal spatial and temporal influences on model forecast errors.

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Appendix A. Snippet of the MET Output Data

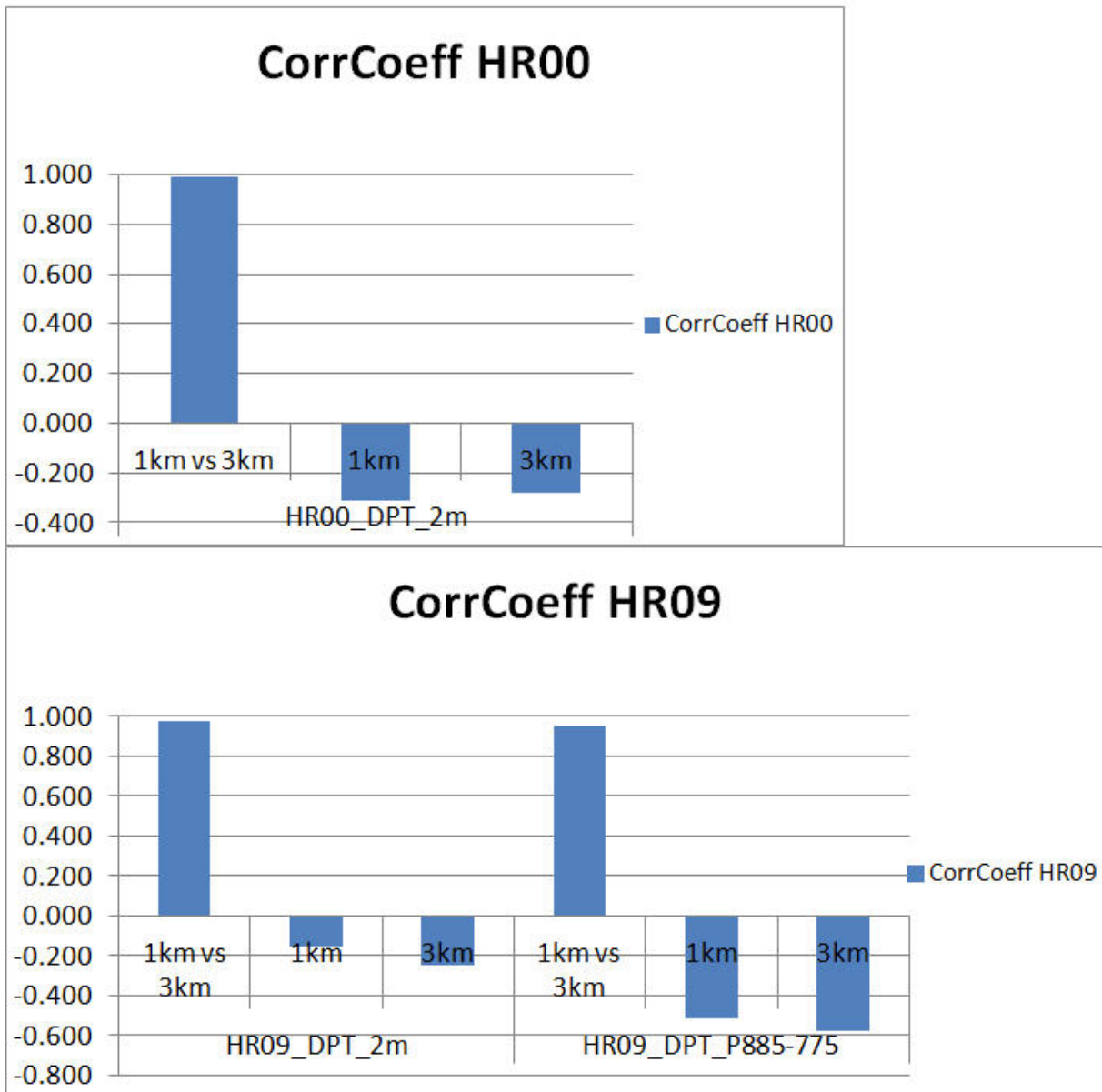
Raw data snippet from 4 July 2010, MET output, 00HR/06Z, WRF@1-km resolution:

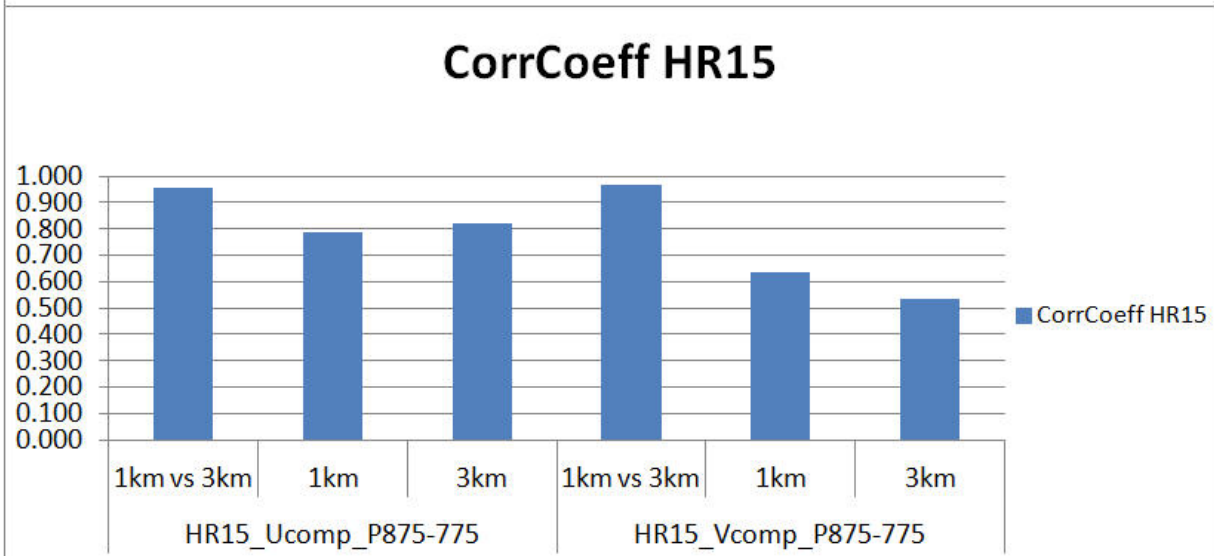
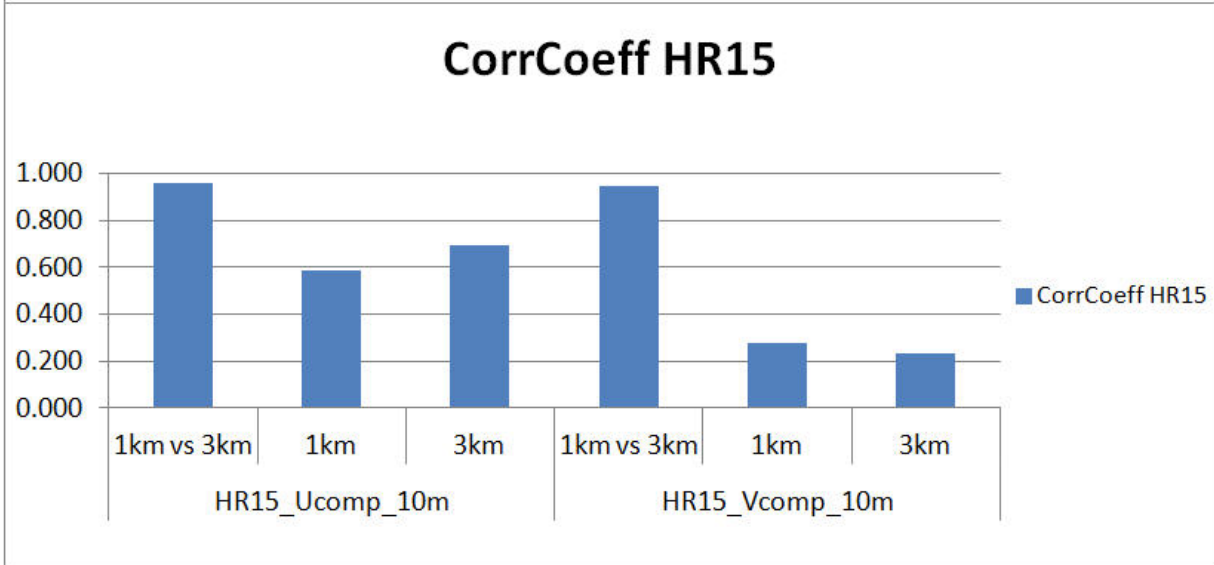
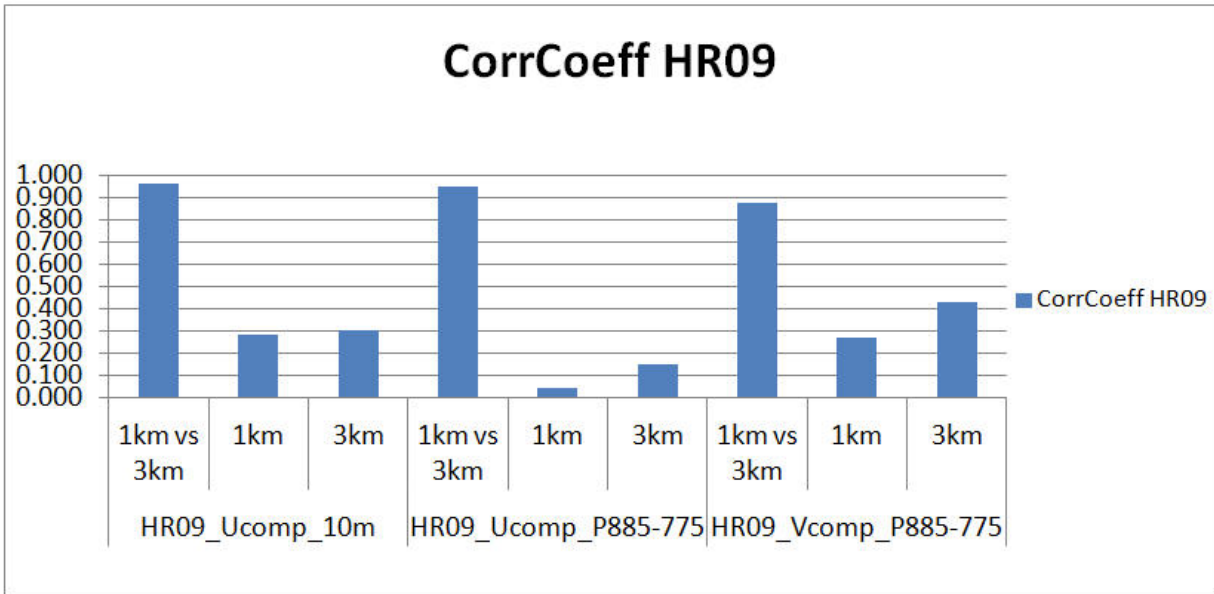
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OBS_ELV FCST OBS CLIMO
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20100704_054000 20100704_062000 TMP P875-775 TMP P875-775 ADPSFC
FULL DW_MEAN 4 NA NA NA NA MPR 17 5
40.24000 -113.09000 866.95001 1304.50000 295.05644 293.73889 NA
V2.0 WRF 000000 20100704_060000 20100704_060000 000000
20100704_054000 20100704_062000 TMP P875-775 TMP P875-775 ADPSFC
FULL DW_MEAN 4 NA NA NA NA MPR 17 6
40.18000 -113.02000 866.34003 1308.80005 294.91416 291.86111 NA
```

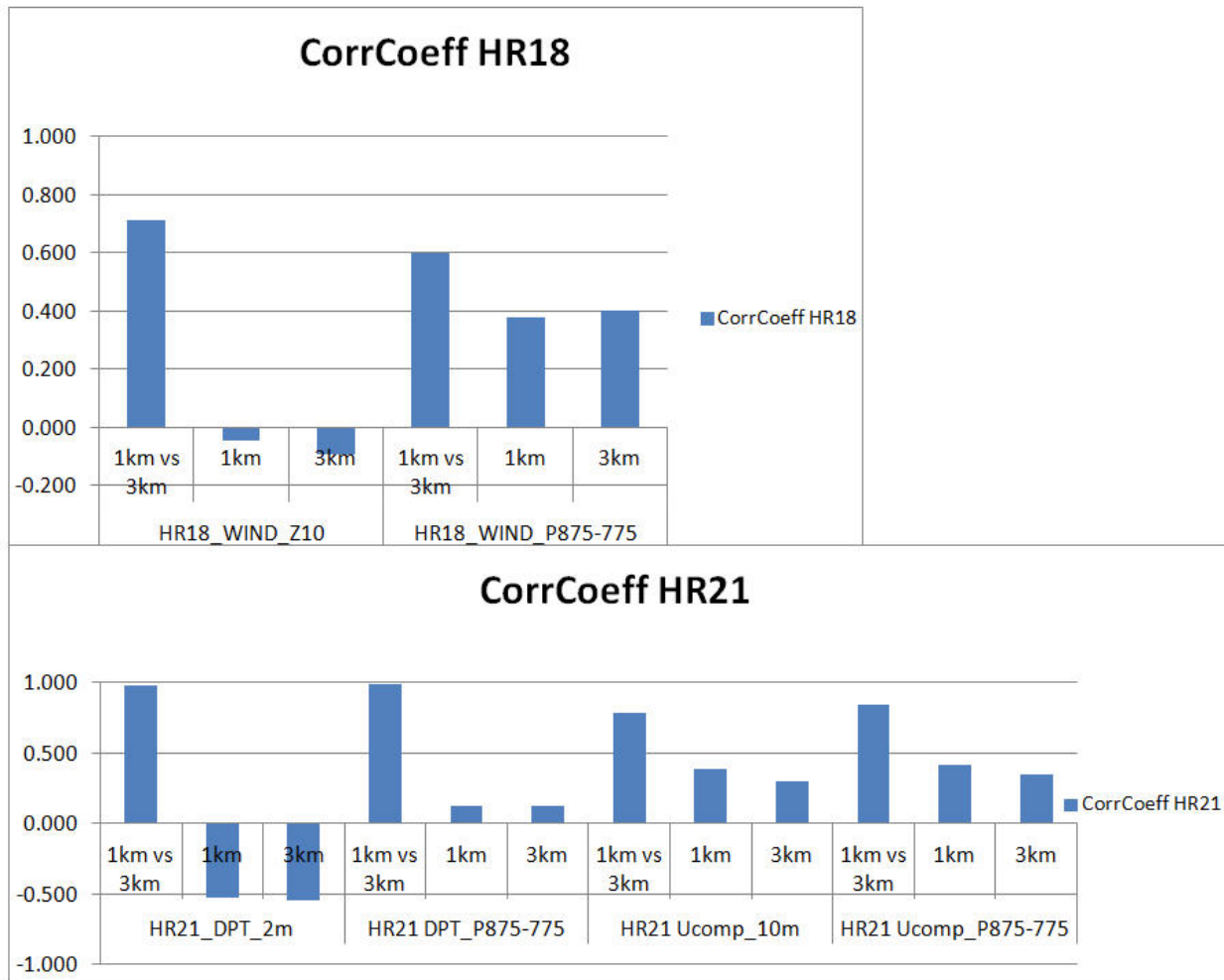
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Appendix B. Detail Plotted Correlation Coefficient Results

Part 1: From the Microsoft Excel spreadsheet (Phase 2_Variables_Summary_4July2010DPG.xls).
Selected time bins shown are results of the first phase of the study (not detailed in this report). Thus,
only certain time bins are shown.







Part 2: Correlation coefficients and variance covariance matrices by geographic location-type ([Part 2](#)) and t-test results of significance of correlation at 95% level of confidence (from the Microsoft Excel spreadsheet *Phase2_ALL_LocationBased_4July2010DPG.xls*).

(Note: 1 = 1 km, 2 = 3 km, 3 = Obs)

Location-type **Valley:**

r_{12} (corr coeff) =	0.999		
r_{13} (corr coeff) =	0.896		
r_{23} (corr coeff) =	0.894		
S =	8.63	8.68	10.86
	8.68	8.74	10.90
	10.86	10.90	17.02
$n =$	45		
$df =$	43		
$tv(0.05) =$	1.682		
t_1km =	5.822		
t_3km =	5.805		

In both 1- and 3-km cases, $t > t_{43}(0.05) \Rightarrow$ **Reject hypothesis** of no relationship.

Location-type **Plain:**

r_{12} (corr coeff) =	1.000		
r_{13} (corr coeff) =	0.920		
r_{23} (corr coeff) =	0.920		
S =	11.26	11.19	12.46
	11.19	11.14	12.39
	12.46	12.39	16.29
$n =$	78		
$df =$	76		
$tv(0.05) =$	1.668		
t_1km =	7.979		
t_3km =	7.974		

In both 1- and 3-km cases, $t > t_{76}(0.05) \Rightarrow$ **Reject hypothesis** of no relationship.

Location-type **Mountain**:

$r_{12} \text{ (corr coeff)} = 0.989$			
$r_{13} \text{ (corr coeff)} = 0.893$			
$r_{23} \text{ (corr coeff)} = 0.885$			
S =	12.12	11.84	13.85
	11.84	11.83	13.56
	13.85	13.56	19.83

$n =$	97
$df =$	95
$t_{v(0.05)} =$	1.663
t_1km =	8.669
t_3km =	8.594

In both 1- and 3-km cases, $t > t_{95}(0.05) \Rightarrow$ **Reject hypothesis** of no relationship.

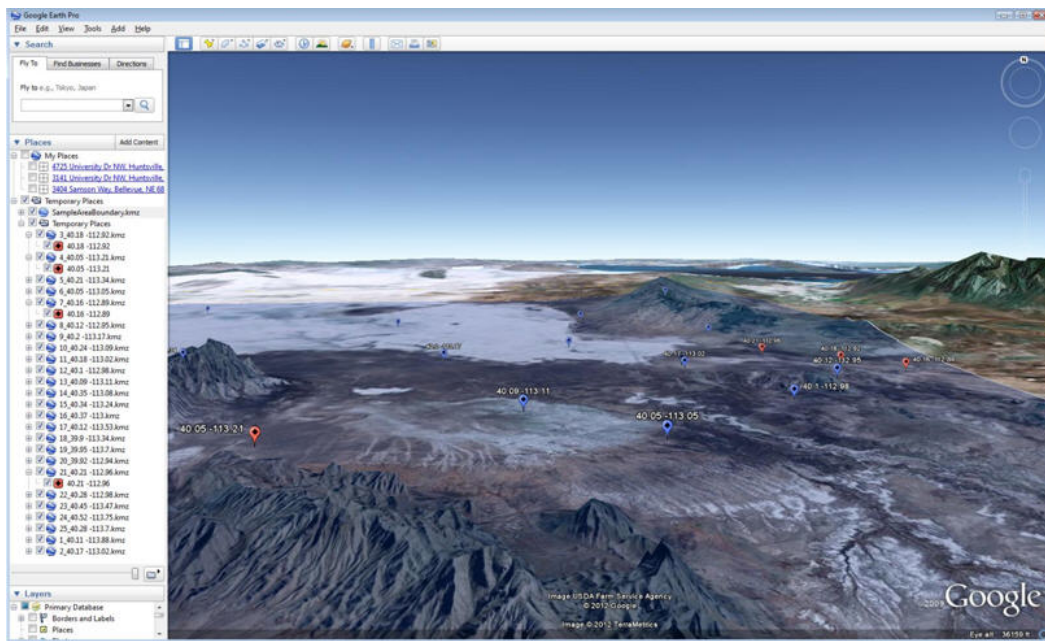
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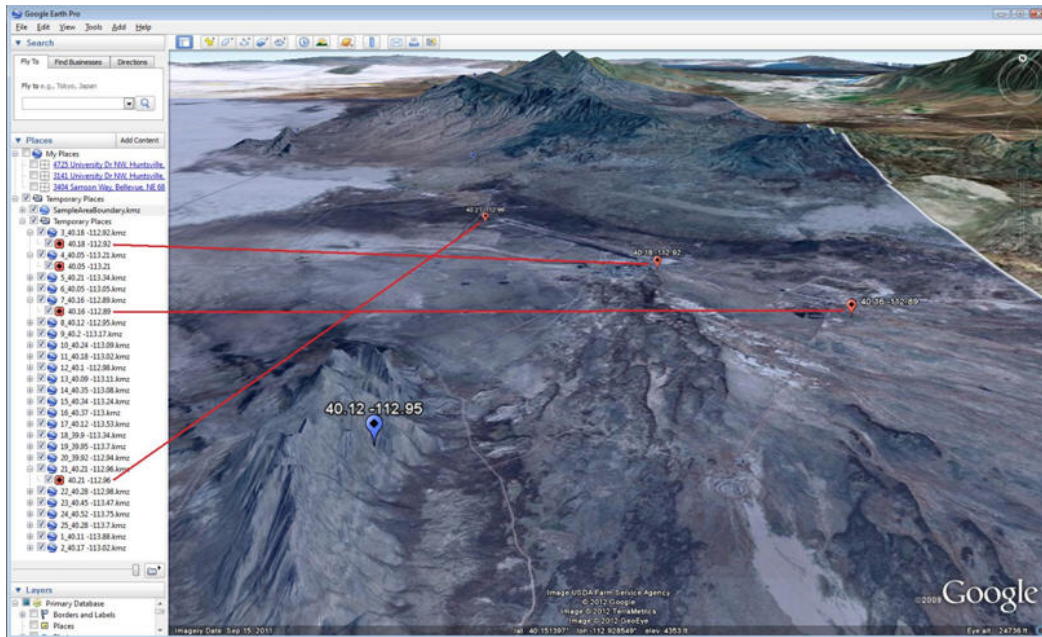
Appendix C. Individual Stations

Correlation coefficients for WRF model 2-m temperature data against observed surface temperature data. The Google Earth images show the specific station locations (highlighted with red icons) for each of the geographic location types (Valleys, Mountains, and Plains).

In the tables that follow each category, “1 km” is the correlation coefficient result for 1-km resolution WRF data versus the observed data. The “3 km” is the correlation coefficient result for 3-km resolution WRF data versus the observed data. The “1 km and 3 km” is correlation between the model itself at the two different model resolutions analyzed in this research.

Valleys:





Station 3

<i>1 km vs. 3 km</i>	0.999
<i>1 km</i>	0.894
<i>3 km</i>	0.885

Station 4

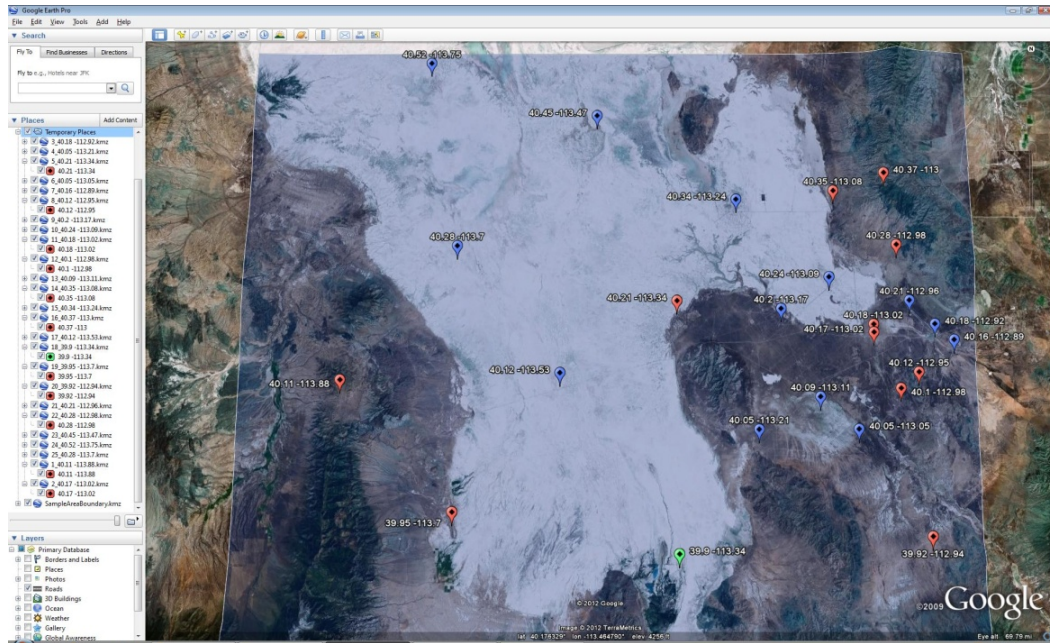
<i>1 km vs. 3 km</i>	0.999
<i>1 km</i>	0.967
<i>3 km</i>	0.962

Station 7

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.877
<i>3 km</i>	0.875

Station 18 (new data point, green in image below)

1km vs. 3km	1.000
1 km	0.952
3 km	0.949



Station 21

1 km vs. 3 km	0.999
1 km	0.896
3 km	0.895

Plains:



Station 6

1 km vs. 3 km	1.000
1 km	0.992
3 km	0.990

Station 9

1 km vs. 3 km	1.000
1km	0.952
3km	0.955

Station 10

1 km vs. 3 km	0.998
1 km	0.933
3 km	0.930

Station 13

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.943
<i>3 km</i>	0.945

Station 15

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.949
<i>3 km</i>	0.951

Station 17

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.949
<i>3 km</i>	0.949

Station 23

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.959
<i>3 km</i>	0.959

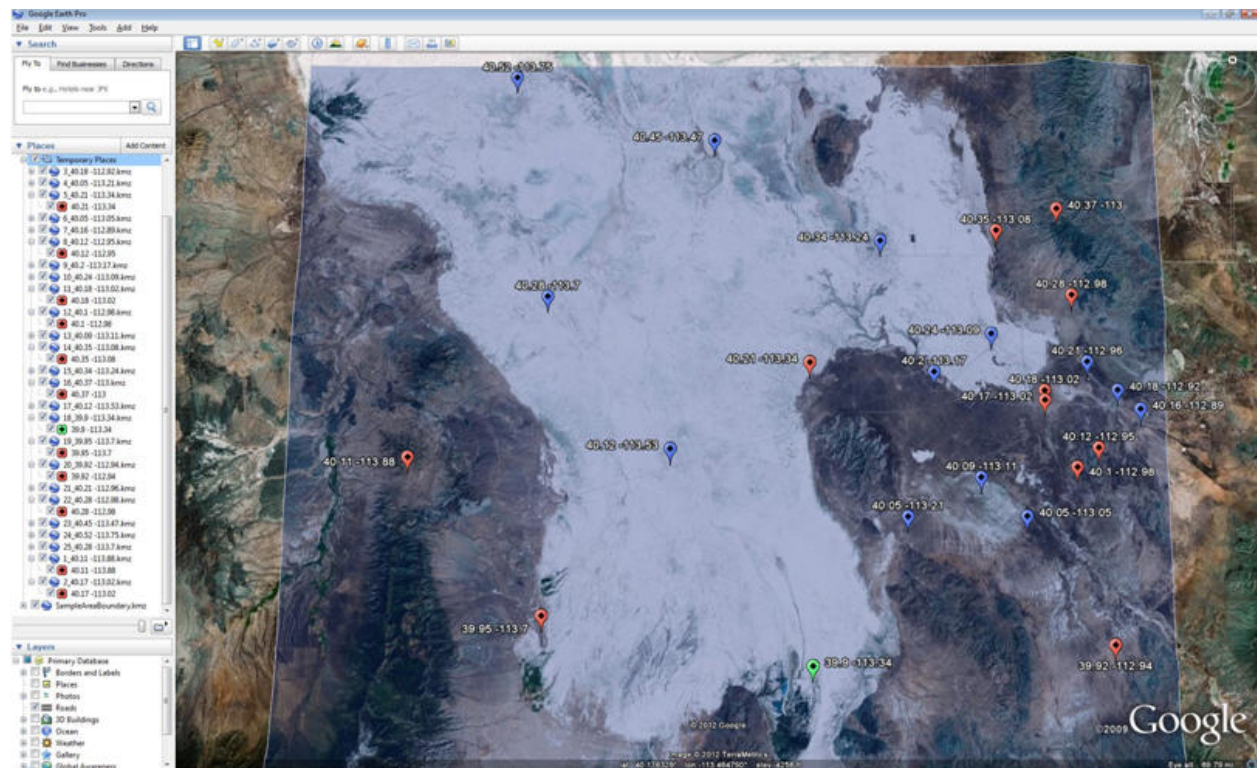
Station 24

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.940
<i>3 km</i>	0.941

Station 25

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.916
<i>3 km</i>	0.916

Mountains:



Station 1 (1946 m)

1 km vs. 3 km	0.995
1 km	0.880
3 km	0.898

Station 2 (1316 m)

1 km vs. 3 km	1.000
1 km	0.957
3km	0.959

Station 5 (1288 m)

1 km vs. 3 km	1.000
1 km	0.928
3 km	0.925

Station 8 (1548 m)

1 km vs. 3 km	0.988
1 km	0.921
3 km	0.880

Station 11 (1309 m)

<i>1 km vs.. 3 km</i>	0.999
<i>1 km</i>	0.940
<i>3 km</i>	0.947

Station 12 (1325 m)

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.922
<i>3 km</i>	0.928

Station 14 (1327 m)

<i>1 km vs. 3 km</i>	0.995
<i>1 km</i>	0.934
<i>3 km</i>	0.941

Station 16 (2150 m)

<i>1 km vs. 3 km</i>	0.984
<i>1 km</i>	0.693
<i>3 km</i>	0.754

Station 19 (1381 m)

<i>1 km vs. 3 km</i>	0.998
<i>1 km</i>	0.911
<i>3 km</i>	0.907

Station 20 (1416 m)

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.973
<i>3 km</i>	0.975

Station 22 (1370 m)

<i>1 km vs. 3 km</i>	1.000
<i>1 km</i>	0.917
<i>3 km</i>	0.917

List of Symbols, Abbreviations, and Acronyms

AGL	above ground level
ARL	U.S. Army Research Laboratory
DPG	Dugway Proving Ground
DTC	Developmental Testbed Center
GIS	Geographic Information System
K	kelvin
MET	Model Evaluation Tools
NCAR	National Center for Atmospheric Research
WRF	Weather Research and Forecasting

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