

UW-NMS Numerical Simulation of the Diurnal Flow Regime in the Steamboat Springs Mountain Range and Assessment of Upslope Propagation of Local Aerosol Concentrations

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ABSTRACT

The UW-NMS model is used to determine if the diurnal flow regime found in mountainous regions, such as Steamboat Springs, CO, is accurately resolved in a numerical model simulation. In addition, in situ aerosol measurements are examined to determine if the daytime upslope flow is sufficient enough to increase aerosol concentrations at higher elevations along the mountain slopes.

I. Introduction

Mountainous terrain can have a great impact on the local weather as well as the weather of the surrounding area. According to Hernandez et al. (1998), the diurnal cycle of solar heating and long wave radiative cooling in the mountains can often create a hierarchy of interconnected wind regimes. The synoptic-scale flow, small-scale flows such as the valley and slope winds, and the sheltering and deflecting effects induced by the topography may all combine to create a flow that differs a great deal from the large-scale flow, alone. In addition, the small-scale flow patterns, themselves, are a crucial ingredient in producing certain meteorological features. For example, the local diurnal flow regime in the

Rocky Mountains plays a significant role in maintaining the Great Plains dryline. This boundary that separates warm, dry air to the west from cooler, moist air to the east is often the location of convective initiation and strong thunderstorms. Therefore, in order for mesoscale models to correctly simulate convection in and around mountainous terrain, it is crucial that the diurnal valley and slope winds be accurately diagnosed.

Small-scale flow patterns, such as the valley and slope winds associated with mountainous regions can be very difficult to simulate. This is in large part due to the complex terrain features that are often on smaller scales than that of the model grid. As a result, these small-scale topographical features are

smoothed out by the model, creating potentially significant changes in the local wind regime. At the time this research was conducted, the accuracy of the UW-NMS in capturing the local wind regime in the mountains was unknown as it had never before been validated by in-situ measurements. The first portion of this paper will therefore show that the UW-NMS does a reasonable job in resolving the local wind regime in the Steamboat Springs mountain range, primarily due to its high-resolution capabilities in the vertical.

As for the aerosol portion of this research project, there have been an increasing number of studies pertaining to the effect of aerosols on orographic precipitation in the winter. These studies have concluded that anthropogenic aerosols may be causing a decrease in the growth of snow crystals, and therefore a diminished snowfall rate. This of course can carry heavy consequences for the western United States whose main water source is snow-melt from the Rocky Mountains. So far these studies have only dealt with aerosols that are carried from upwind sources by the large-scale flow. Thus, the second portion of this paper will show that the daytime upslope flow in the mountains can be can also be responsible for carrying locally high aerosol concentrations from the cities and towns at the base of a mountain to higher elevations.

II. Methodology

a. Tools and Data

The numerical model to be used in this research project is known as the

University of Wisconsin Nonhydrostatic Modeling System (UW-NMS). This research model was written in 1992 by Dr. Gregory J. Tripoli, and is primarily used to examine how convection interacts with mesoscale and synoptic-scale features. Five nested grids were used in running this simulation (Figure 1). The outermost grid has a horizontal resolution of 60 kilometers and the innermost (fifth) grid has a horizontal resolution of 200 meters. The vertical resolution was 200 meters on all of the grids, with the exception of 25-meter vertical resolution between the base and mountaintop on the innermost grid. This set-up is summarized in Table 1. The UW-NMS model was initialized at 00Z on 16 March 2006 using the GFS model data from NCEP.

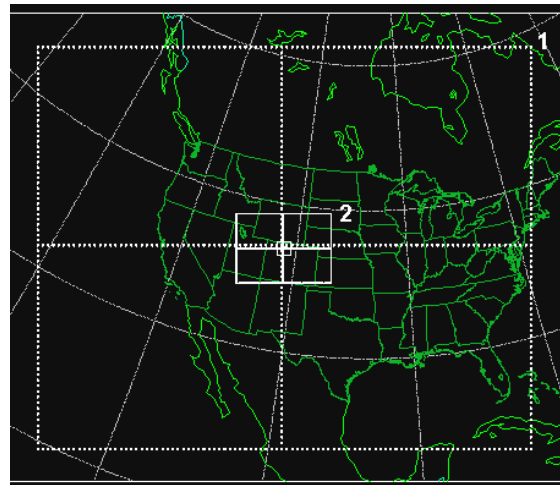


Figure 1a: Outermost grids

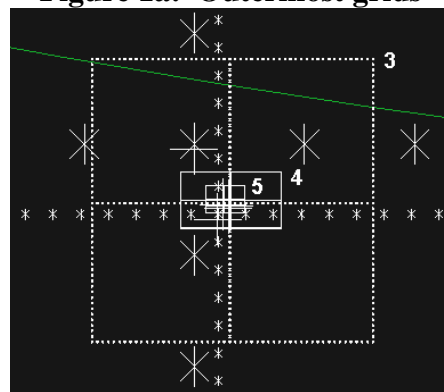


Figure 1b: Innermost grids

Grid Number	Horizontal Points	Vertical Points	Horizontal Resolution (m)	Horizontal Size (km)	Vertical Resolution (m)
1	96x76	30	60000	5640x4440	200
2	74x54	30	15000	1080x780	200
3	52x52	30	3000	150x150	200
4	92x52	30	600	54x30	200
5	107x77	83	200	21x15	200 to 2km; 25 to 3.4km; 50 to 3.6km; 100 to 3.8km; 200 to top

Table 1: UW-NMS grid properties used in the Steamboat Springs simulation.

In-situ measurements were provided by both the Storm Peak Lab and the mesonet network of weather stations positioned at various locations throughout the Steamboat Ski area. The mesonet weather stations record data every fifteen minutes, while the Storm Peak Lab records data every five minutes.

Aerosol concentrations were recorded using the portable PTrak Ultrafine Particle Counter. This instrument detects particles as small as 0.02 micrometers and has a concentration range of 0 to 500,000 particles per cubic centimeter. For the purposes of this study, the particle

counter recorded aerosol concentrations at an interval of one-second.

b. Implementation

In order to study a true diurnal wind regime in the mountains, clear skies and light ambient winds are needed over at least a 24-hour period. For most of the week at the Storm Peak Lab, conditions were cloudy and often snowy. Finally, high pressure began to move in during the early morning hours of 16 March (as seen by Figure 2) and the clouds began to dissipate. The conditions remained mostly clear until the afternoon of the next day, with wind speeds averaging to roughly 10 miles per hour at the top of the mountain.

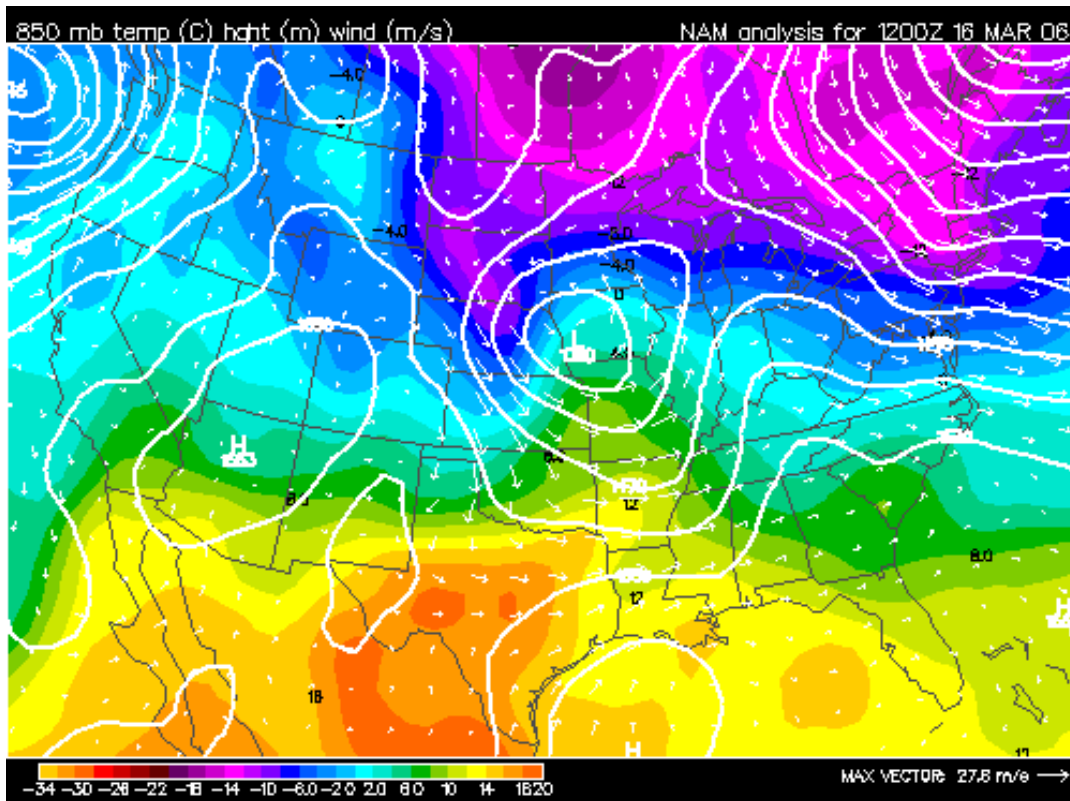


Figure 2: 850mb heights (m) and temperature (degrees Celsius) at 12Z 16 March 2006. Notice the high pressure moving in over the Four Corners region.

A UW-NMS simulation was therefore set up for the period ranging from 00Z 16 March 2006 to 18Z 17 March 2006. Temperature, wind speed and wind direction data from the Storm Peak Lab and two of the mesonet stations was used to validate the simulation results. Aerosol concentrations were recorded using the portable particle counter at selected times during the morning, afternoon and night. Daytime measurements were recorded while riding three different chair lifts up the western side of the ski area (Christie Lift, Thunderhead Express, and Storm Peak Express). Evening measurements of aerosol

concentrations were taken by way of snowmobile, from Storm Peak Lab to the base of the ski area. Table 2 gives the elevation of the Storm Peak Lab (SPL) and the two mesonet weather stations (W0 and W5), while Figure 3 shows the locations of these sites as well as the three chair lifts (solid yellow lines) used in this research.

Weather Station	Elevation
W0	6,930ft / 2112m
W5	8450ft / 2575m
Storm Peak Lab	10,568ft / 3221m

Table 2: Elevation of weather stations used in this research.



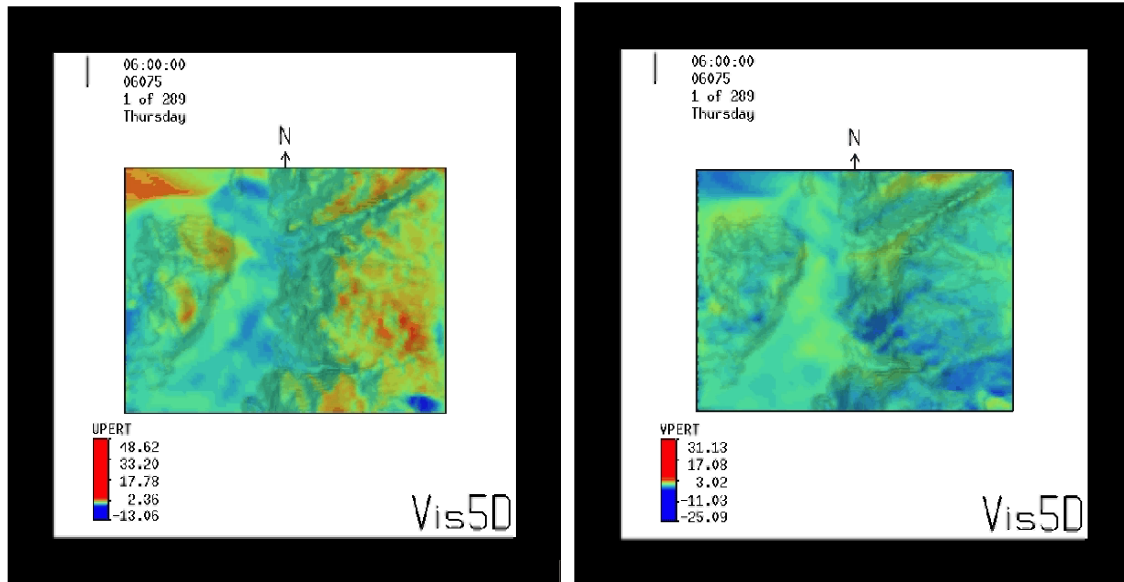
Figure 3: Locations of the Storm Peak Lab and mesonet weather stations (magenta) as well as the chair lifts (solid yellow lines) used in this research.

III. Results

a. Modeling the Diurnal Flow Regime

In order to best depict the diurnal wind regime along the slopes of the Steamboat Springs mountain range, animations were made showing the perturbation u-component (Animation

1a) and v-component (Animation 1b) of the wind field overlaid on the topography, starting at 06Z 16 March and ending at 06Z 17 March in the inner grid. Double-clicking on the corresponding images, below, will begin each animation (these are .AVI animations, so most Windows machines should be able to play them).

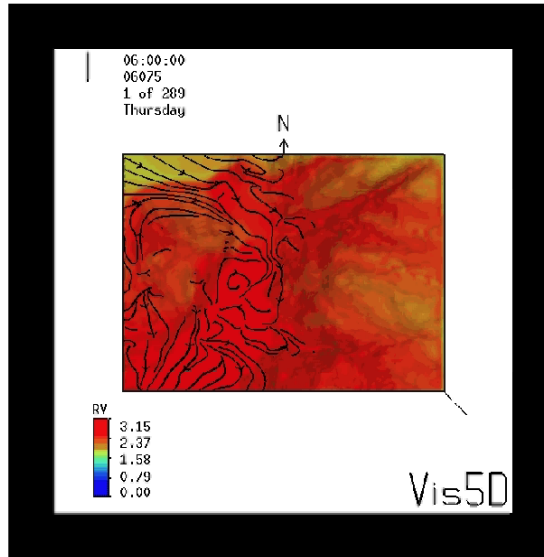


Animation 1: Perturbation wind field (m/s) overlaid on topography. (a) U-component, (b) V-component.

As seen from these animations, downslope flow does appear to be occurring along the mountain slopes and in the Yampa River Valley from 06Z to approximately 14Z. At 14Z, the winds become increasingly variable as they begin to shift into an upslope pattern. By 17Z an upslope flow is seen most prominently moving southward up the valley floor. An interesting feature found in these animations is what appear to be gravity waves forming around 1530Z on the eastern slopes of the Rockies, and in the valley at 1830Z. The gravity waves seem to weaken slightly around nightfall (00Z), when the downslope flow returns.

Another way of determining the diurnal wind regime in the mountains is to look at a conservative variable and see where it is advected. Since moisture is a

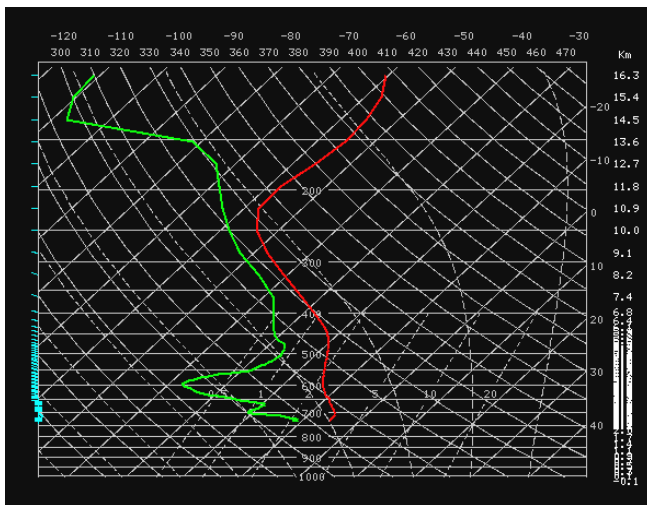
conservative variable, mixing ratios are overlaid on the topography in Animation 2, for the same time frame as in the previous animations. Also in Animation 2 are the horizontal perturbation streamlines at 2.3km (just above the valley floor). One can see clearly from this animation that a downslope flow has developed by 08Z, and is advecting a plume of higher moisture from the Yampa River down into the valley. In addition, drier air can be seen advancing down both sides of the mountains until approximately 1445Z. At this time, the upslope flow is forming and the dry air begins to retreat back up the slopes of the mountains, while the moist air is advected back up the valley floor. The gravity wave features mentioned previously are also visible in this moisture field.



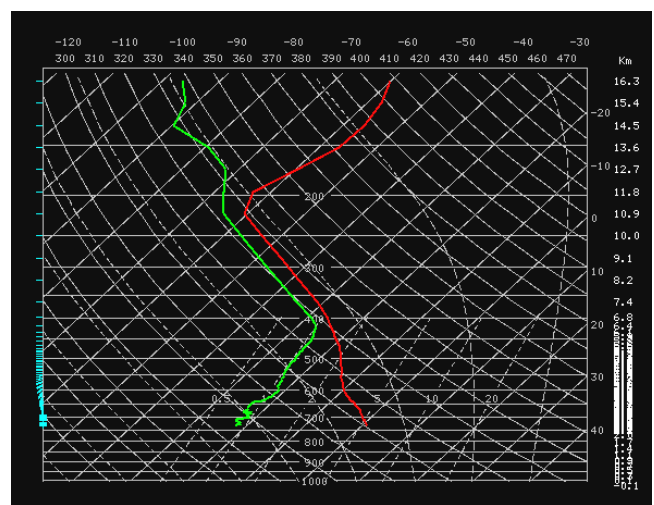
Animation 2: Mixing ratio (g/kg) and horizontal perturbation streamlines overlaid on topography.

The ability of the UW-NMS to capture this diurnal shift of the winds, especially in the valley, is in part due to the high vertical resolution on the innermost grid. This allowed the model to adequately resolve the surface radiation inversion that formed during the night, inducing the downslope flow. In addition, the model was able to resolve the eroding of this inversion after

sunrise, giving way to the upslope shift in winds. Figures 4a and 4b show the model-derived soundings taken in the Yampa River Valley towards the end of the downslope phase at 14Z and during the upslope phase at 20Z, respectively. Notice the radiation inversion at 14Z and how it has been almost completely smoothed out by 20Z



(a)



(b)

Figure 4: Model-derived soundings taken in the Yampa River Valley at (a)14Z and (b)20Z

While the UW-NMS simulation looks reasonable, validation of the model temperatures, wind speed and wind direction with the Storm Peak Lab and mesonet data show that the model is not resolving these variables with a great amount of accuracy at all locations. Figure 5 is a 24-hour graph of hourly temperature readings on 16 March from the Storm Peak Lab (SPL) and mesonet sites (W0 and W5) compared to those from the UW-NMS model at the same

locations. While the model did reasonably well at the SPL site, there are rather large discrepancies at the W0 and W5 sites. The largest discrepancies are found at the W0 site, which is at the base of the mountain. This leads one to believe that other factors, such as very small-scale terrain, vegetation and possibly buildings from the ski resort, are causing variations in the temperature field that are not being captured in the model.

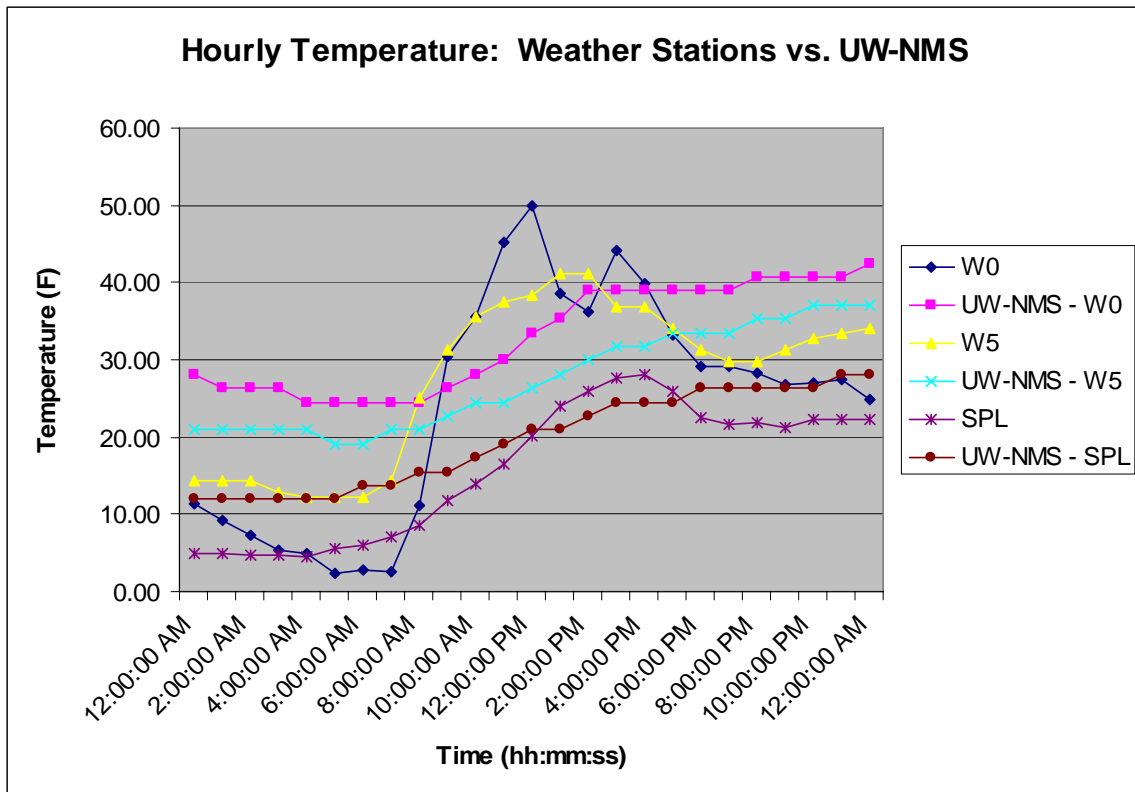


Figure 5: Hourly temperature readings (degrees Fahrenheit) taken from the Storm Peak Lab and mesonet weather stations and compared to the UW-NMS output at the same locations.

Figure 6 is a graph of hourly wind speed observations by the Storm Peak Lab and the W5 weather station (the W0 weather station does not record wind observations) compared to the UW-NMS model output at the same locations. The date and time period of this graph are the same as in Figure 5. The UW-NMS compares reasonably well with the W5 site, with the exception

of two large discrepancies at 1:00am and 10:00pm where the UW-NMS overshoot the observed wind speeds.

Unfortunately, the model did not do as well at capturing the observed wind speeds at the SPL site, as one can see from the graph that the data points are largely out of sync. The reason for this is not fully understood.

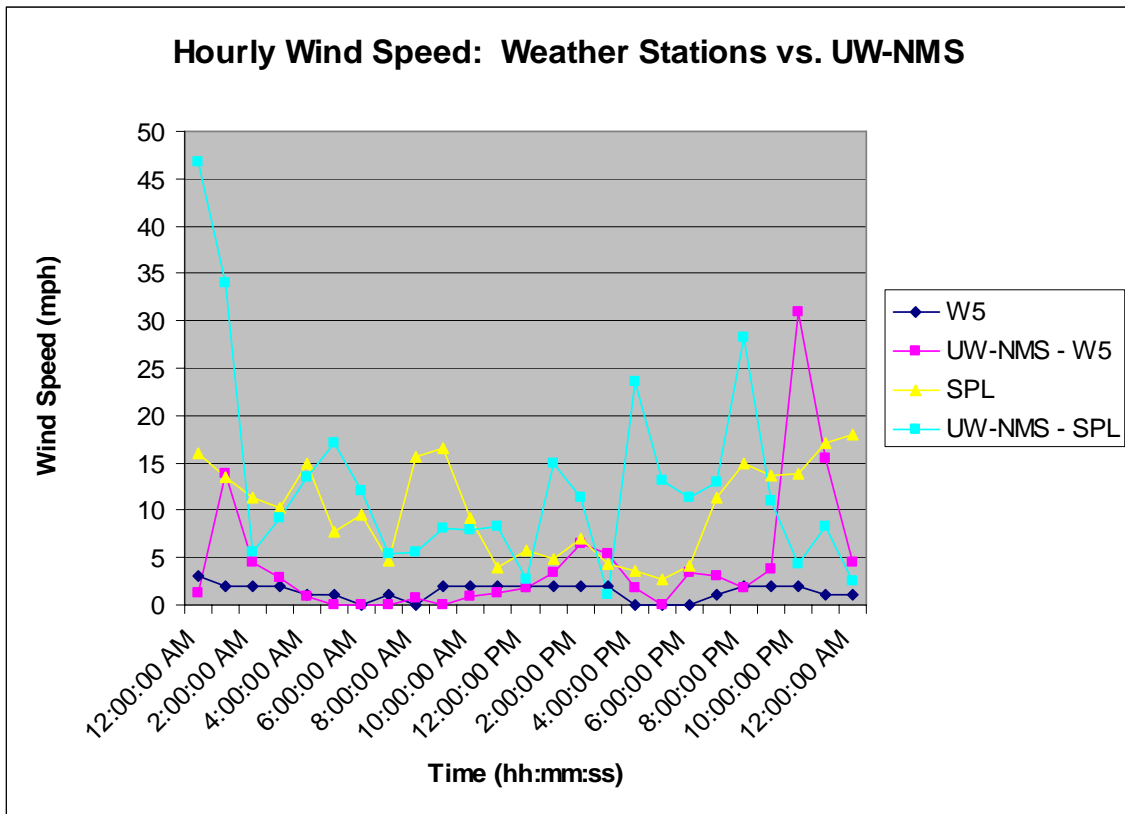


Figure 6: Hourly wind speed readings (mph) taken from the Storm Peak Lab and W5 mesonet weather station and compared to the UW-NMS output at the same locations.

Lastly, Figure 7 is a graph of hourly wind direction observations taken from the SPL and W5 weather stations and compared to the UW-NMS model output at the same locations. It is clear from this graph that the UW-NMS model did a much better job capturing the wind direction at the SPL site than it

did at the W5 site, where there are very large discrepancies. This is most likely due to the fact that the W5 site is located in the middle of the mountain amidst varying small-scale topography and vegetation, such as tall trees, that may not be resolved adequately in the model.

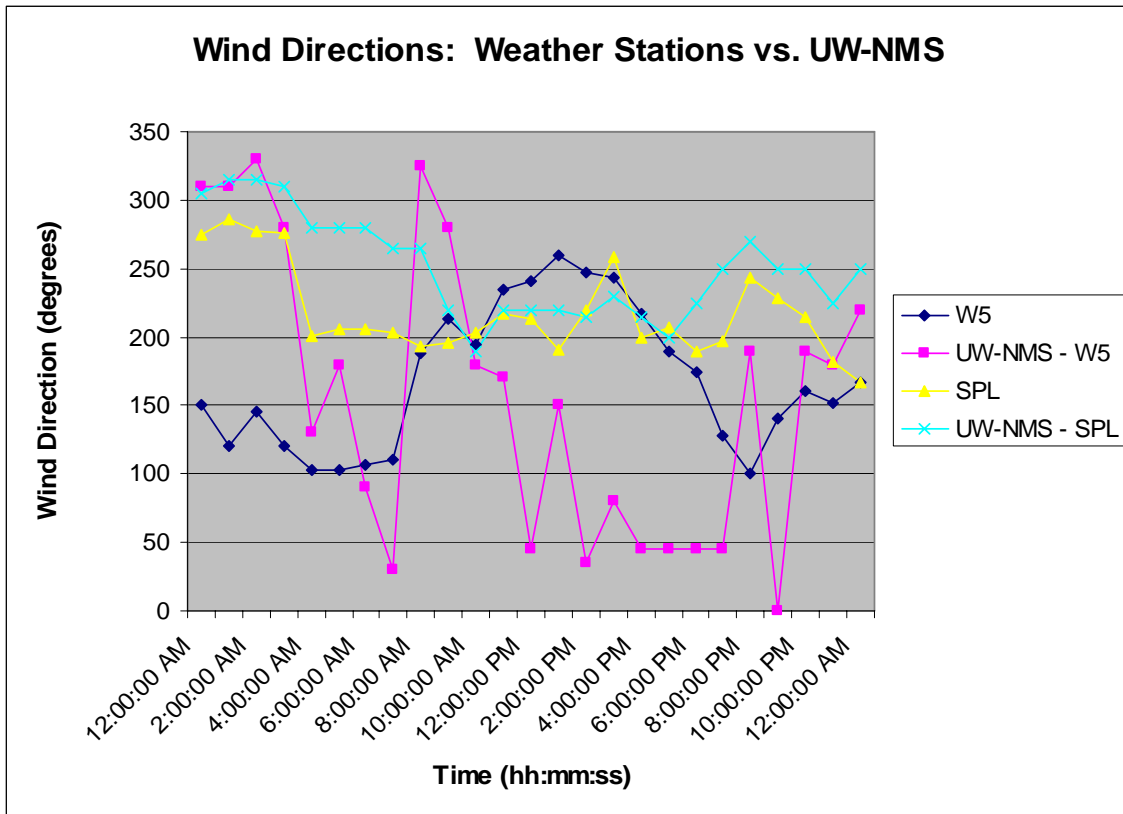


Figure 7: Hourly wind directions (degrees) taken from the Storm Peak Lab and W5 mesonet weather station and compared to the UW-NMS output at the same locations.

b. Upslope Propagation of Aerosols

As shown in the previous results, an upslope flow did in fact form in the daytime hours of 16 March, while a downslope flow was shown to form after sunset. From Figures 8, 9 and 10, it is clear that daytime aerosol concentrations decrease with time and elevation as measurements were taken while riding chair lifts up the mountain.

Unfortunately, it is not completely clear what caused the dip in aerosol concentrations in Figure 9, from

approximately 10:50am to 10:54am. It is possible that the chair lift passed over a small valley at that time, therefore increasing the height of the lift above the ground and decreasing aerosol concentrations. On the other hand, it may simply be human error. Figure 10 shows a large spike in aerosol concentration (going off the charts) between 11:10am and 11:11am MST. It was at this time that the chair lift passed over the Four Points Hut, where plenty of cheeseburgers and French fries were being cooked for the lunch hour!

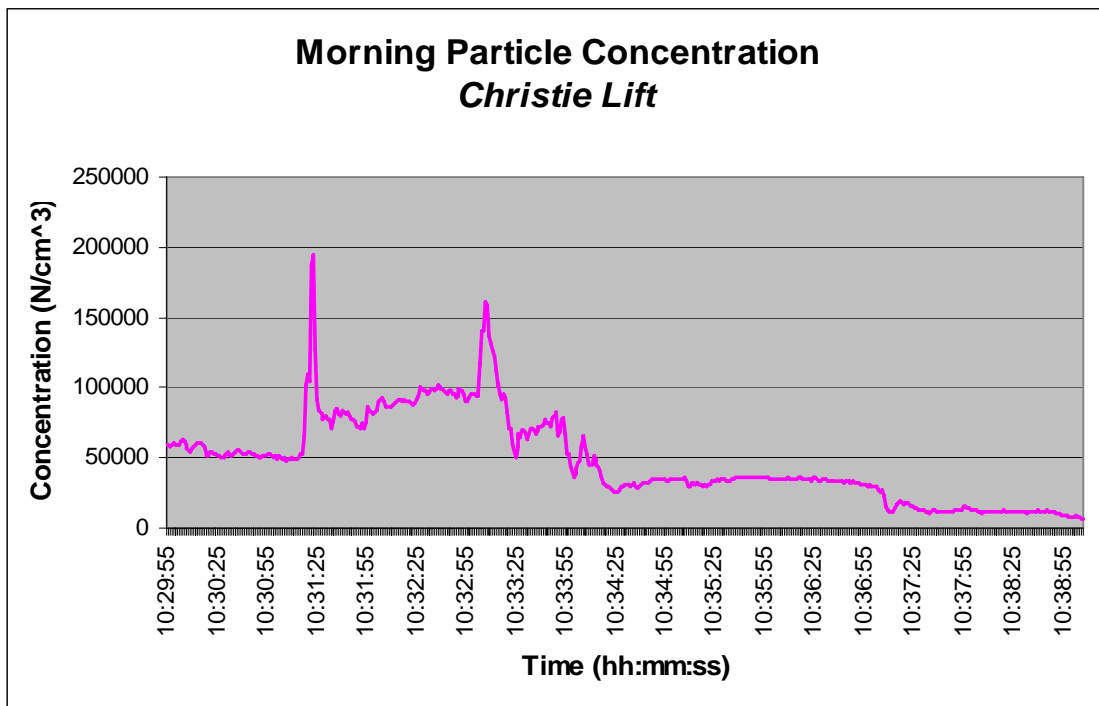


Figure 8: Daytime aerosol concentrations (N/cubic centimeter) taken from the Christie Lift.

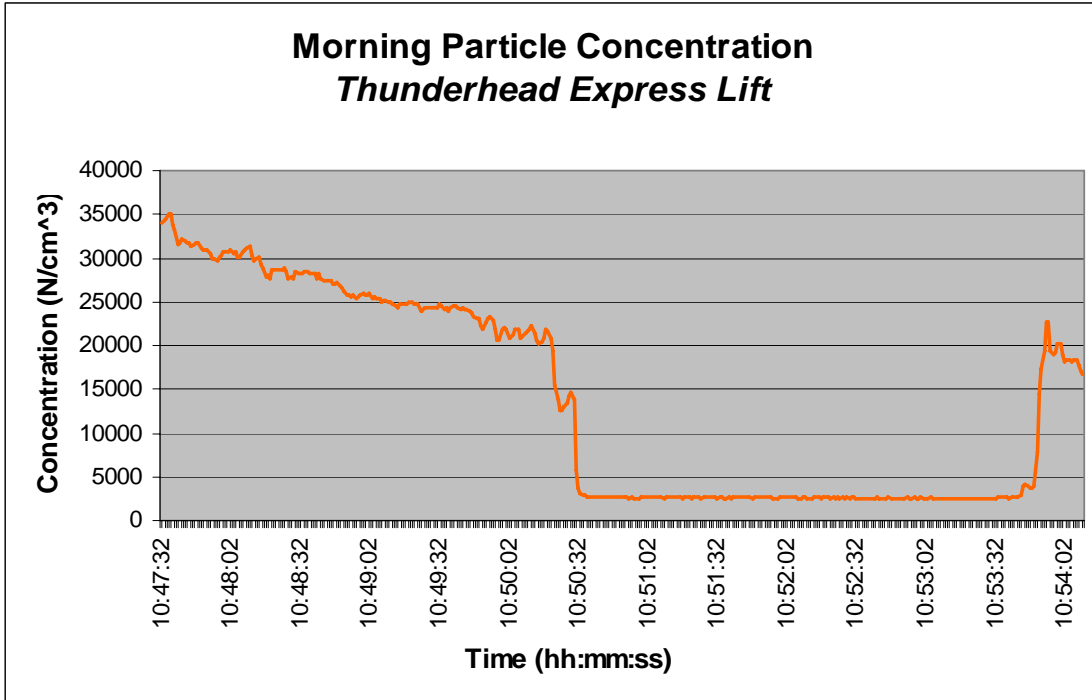


Figure 9: Daytime aerosol concentrations (N/cubic centimeter) taken from the Thunderhead Express.

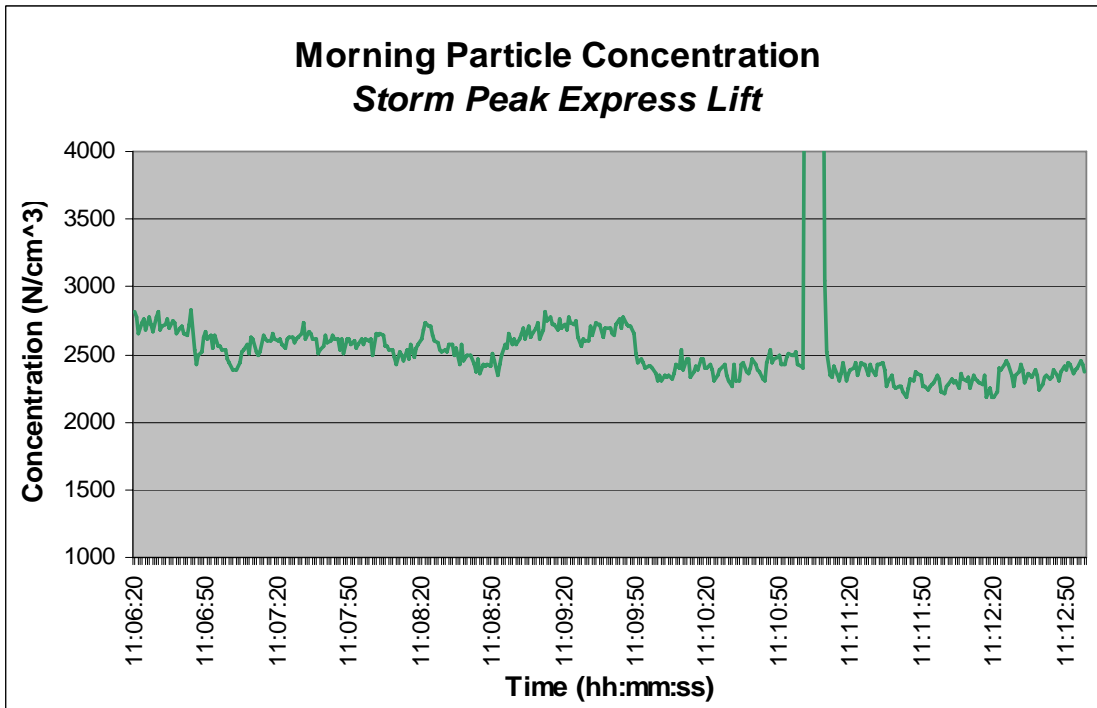


Figure 10: Daytime aerosol concentrations (N/cubic centimeter) taken from the Storm Peak Express.

After nightfall, aerosol concentrations were recorded while on a snowmobile from the Storm Peak Lab to the base of the mountain (the Christie Lifts area). Figure 11 shows the results from this excursion. Unfortunately, human error led to the large spike between 7:15pm (19:15) and 7:17pm (19:17), as the particle counter was

taking in air too near to the snowmobile exhaust pipe. Despite this error, it is clear that aerosol concentrations are much lower along the mountain slope at night, with the exception of a couple areas of much higher concentrations. These areas may be due to aerosols being trapped underneath an inversion in shallow valleys along the mountain.

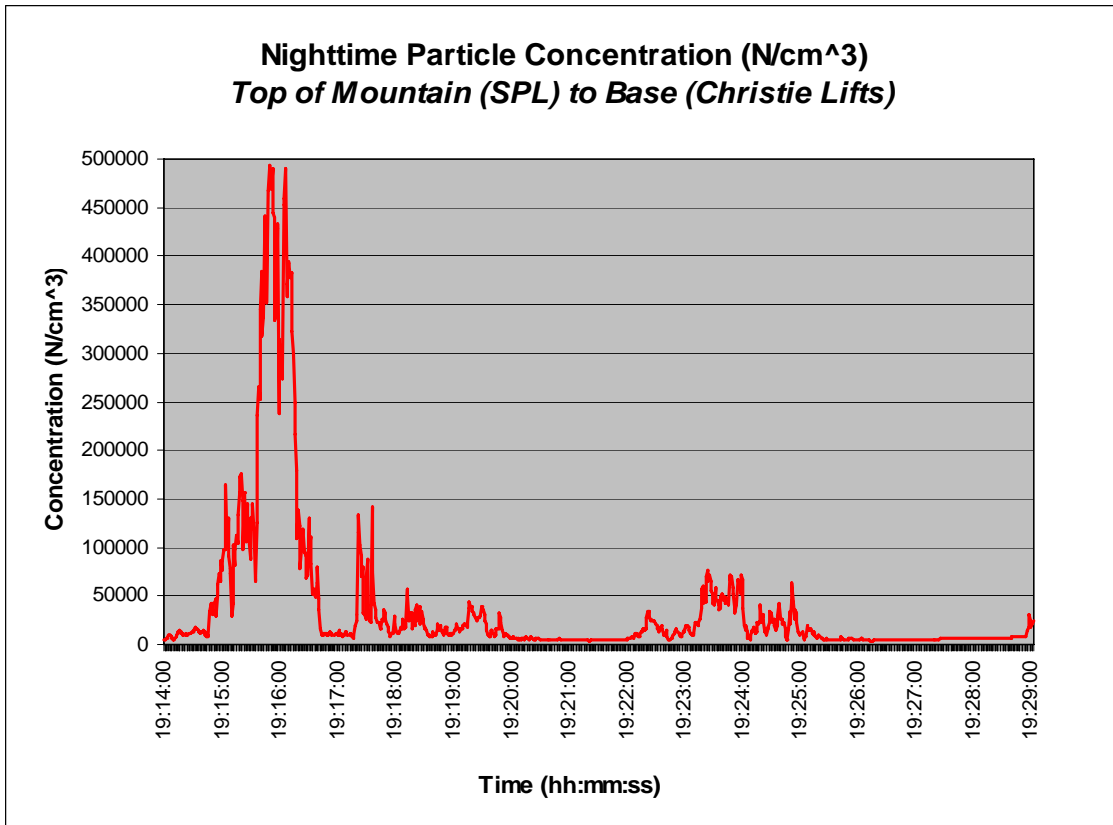


Figure 11: Nighttime aerosol concentrations (N/cubic centimeter) from the Storm Peak Lab to the base.

IV. Conclusion

In conclusion, this research has shown that the UW-NMS model did reasonably well in simulating the diurnal wind regime in the Steamboat Mountains. This is primarily due to the vertical nesting capabilities of the model which allowed the vertical resolution to increase to 25m between the mountaintop and base. Therefore, the creation and erosion of the surface radiation inversion, a necessary component for the diurnal flow in the mountains, was adequately resolved in the model. Despite this seeming success, there were some large discrepancies when the model was validated with temperature and wind data from the Storm Peak Lab and mesonet sites. This may be due to very small-scale topographic features, as well as vegetation (such as tall trees), that are not being captured in the model.

In addition, it was found that locally high aerosol concentrations at the base of the mountain seemed to propagate upslope during the daytime. After nightfall, these concentrations along the mountainside decreased, with

the exception of a couple pockets of higher concentrations. These pockets may be shallow valleys where daytime aerosols become trapped underneath an inversion.

V. References

Bader, D. C., and T. B. McKee, Dynamical model simulation of the morning boundary layer development in deep mountain valleys, *Journal of Applied Meteorology*, 22, 341 – 351, 1983.

Borys, R. D., D. H. Lowenthal, S. A. Cohn, and W. O. J. Brown, Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rate, *Geophysical Research Letters*, 30, 45-1 – 45-4, 03.

Griffith, D. A., M. E. Solak and D. P. Yorty, Is air pollution impacting the winter orographic precipitation in Utah? *North American Weather Consultants, Inc.*, Sandy, Utah.

Hernandez, E., J. de las Perras, I. Martin, A. Rua and L. Gimeno, A field case study and numerical simulation of mountain flows with weak ambient winds, *Journal of Applied Meteorology*, 37, 623 – 637, 1998.

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