Variability of Cloud Base Heights in Yampa River Valley during a Wintertime Snow Event

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ABSTRACT

The common understanding is that NW flow is ideal for Steamboat Springs, Colorado to experience orographic clouds and snow. The hypothesis that was tested in this experiment is how accurate the NW assumption is in relation to Steamboat Springs. The findings of this experiment disagree and agree with the understanding that NW is ideal for Steamboat Springs, Colorado. First, the agreement that NW on the synoptic scale is essential for the moisture to reach Steamboat and not be deposited on upstream mountains such as the San Juan's, Sierra Nevada's and the mountain ranges of Utah. However, on the mesoscale, NW flow is not ideal, where W to WNW is best for Steamboat Springs to experience moderate to heavy amounts of snow and experience low cloud bases causing Storm Peak Laboratory to be in cloud. If the flow is greater then 315 degrees, Steamboat is in the shadow of Elk Head Mountain thus reducing the amount of snow and orographic clouds experienced.

Introduction

In the winter months of North America a phenomenon known as upslope precipitation occurs, producing heaving snow in mountainous regions. Upslope precipitation is important not only ski resorts but the southwest United States. The deep snow pack that forms over the higher elevations melts every spring, providing water for drinking, recreation, entertainment and agriculture to the drier southwest. Water struggles have persisted for decades, and likely will continue well into the future. Upslope precipitation is when flow collides with a barrier, in this case a mountain range, which often lifts the entire layer of air. As the air rises it cools and condenses forming clouds and precipitation with sufficient moisture present. 700mb streamlines and relative humidity is a good proxy for determining which mountain ranges will be favored for significant snowfall. For example, if the flow is from the SW, the San Juan and Flattops should expect heavy snow. Westerly winds will favor the mountains near Salt Lake City and resorts in Colorado such as Copper Mountain and Vail.

Northwesterly flow is perfect for producing “champagne powder” at Steamboat Springs, Colorado the location of this experiment. The combination of NW flow, moisture and typically cold 700mb temperatures produces a very light (ie low density) snow perfect for skiing and snowboarding. The purpose of this experiment is determining a range of wind directions for which Steamboat sees orographically enhanced or purely orographic snowfall and more specifically clouds. This will be looked at from an observational standpoint as well as using a high resolution simulation. It is commonly known that NW winds at 700mb is favorable for orographic snow and low cloud bases at Steamboat, however there has been little done to investigate what range of wind directions and moisture produce snow and low cloud bases. This experiment will test the hypothesis that NW flow is ideal on both the synoptic and mesoscale for producing low cloud bases and heavy snow at Steamboat Springs, Colorado.

Wintertime Snow in Steamboat Springs, Colorado

Steamboat Springs is known for its "Champagne Powder" a very light and fluffy snow. Studies have been conducted in Colorado and Wyoming to explore this claim and have found that Steamboat Springs does indeed have dry, light fluffy snow. It was found that Steamboat Springs occasionally has snow with exceptionally low density and of the six sites in the experiment consistently experienced low density snow (Judson & Doesken 2000). This is not however surprising as if you compare the San Juan Mountains with the NW facing slopes that Steamboat Springs are located. When the San Jaun Mountains experience large orographic snow falls the flow is from the southwest bringing moisture but also warmer temperatures from the Pacific, producing heavy snow but also a more dense snow fall. Compared to Steamboat Springs, where the moisture is still from the Pacific but is often associated with cold air advection (CAA) on the back side of an upper trough producing heavy snow, but also a lower density snow.

The timescale of orographic precipitation is highly variable that produces snow at Steamboat Springs. Simplified box models allow for a connection to be made based on multiple factors such as mountain width, moisture, temperature and wind speed. One example is that if the mountain width were to be increased this would allow for an increase in the advective timescale increasing the efficiency of the hydrometeor formation (Jiang & Smith). It has been concluded that orographic clouds are highly variable and can begin with timescales on the order of hours to days and quickly become convectively unstable and be on the order of seconds to minutes. If the clouds are of a longer timescale a more homogeneous precipitation total will result. Compare this to if the flow becomes unstable and has embedded convection. Then the snow will be highly variable over just a few kilometers.

The final ingredient in understanding orographic clouds and precipitation is the cloud top temperatures. It has been discussed in the past that the cloud top temperature directly influences precipitation rates and characteristics (Rauber 1987). As a result it can be concluded that precipitation rates and amounts are dependent on the timescale of the orographic clouds, moisture, advective properties, mountain width and cloud top temperature.

Data

For this experiment numerous sources of data were used, beginning with the University of Wisconsin-Madison's Nonhyrdostatic Modeling System. As described by Greg Tripoli(1992), the model uses nonlinear theory without making Boussinesq approximations. This allows for non-geostrophic processes on the mesoscale to be modeled, such as upslope precipitation in mountainous regions. In this particular simulation the emphasis was to locate moisture in the Yampa

River Valley in an attempt to draw conclusions about moisture, wind direction and cloud base heights. It was initialized off of the GFS 18z analysis and a high resolution topography map, to capture the orographic's that produce snow and clouds at Steamboat Springs, Colorado. Run at 3km resolution, this simulation was initiated at 1800 UTC 31 APR 2010 and run out to 48 hours to capture the full duration of the snow event. The actual model simulation figures were plotted using Vis5d, a program that is customized for overlaying parameters in a cross section or horizontal plots for UW-NMS output. Multiple loops of the 48 hour simulation were also created though not depicted using Vis5D.

Scanning Mobility Particle Sizer (SMPS) data was acquired using Storm Peak Laboratory (SPL) archive page which is courtesy of Western Regional Climate Center. This data was used as a proxy for when the lab is in or out of cloud. In addition figures were created using Surface plots, though not depicted, were created using the National Weather Service Hydrometeorological Prediction Center archive surface maps page to locate surface features, such as the embedded surface cyclone and the front that brought a quick burst of snow early Thursday Morning. Upper air plots were created using the National Weather Service's Storm Prediction Center to locate the upper trough, vorticity at 500mb, vertical motion fields at 700mb and 700mb moisture and winds. Finally, sounding data was extracted from the University of Wyoming's archive sounding data page, to better understand the vertical structure of the atmosphere March 31st-April 3rd, 2010.

Orographic Cloud Experiment

Based on observations some interesting conclusions can be made from the orographic snow event on Thursday April 1st and Friday April 2nd. The storm had three significant wind shifts and will be the focus for this section. At 2:13am local standard time (LST) the wind shifted from SE to W and was directly correlated with a decrease of the number of particles being counted by the SMPS machine. The wind was highly variable in direction between 2:15am LST and 2:35 LST which can be seen in the SMPS data, suggesting there is a direction which Steamboat is no longer blocked by higher terrain to the west. Looking at the two data outputs every 5 minutes and comparing, a westerly threshold between 265-270 degrees seems to exist.

The wind shifts back to SSE at 5:25am LST but the SMPS data is well behind and does not increase until 6:53am LST. This is likely due to the light and variable winds present at SPL between 5:25am and 6:53am. At 6:45am the winds increase from ~12mph to over 30mph at 6:50am LST and scour out the moisture and cloud present at SPL, which is clear in the SMPS data at 8:21am LST. From an observational standpoint, visibilities were under a ½ mile at 6:30am LST while at 7:15am LST the valley was visible. The third major wind shift was at 8:20am LST and matches with the SMPS data indicating that SPL was in cloud. This is also evident as the lab was not visible from the top of Storm Peak Express lift at 9:45 LST with small triangular graupel falling and significant rhiming occurring. Interestingly, the SMPS data was highly variable and while some of the variability does correlate to wind direction changes, some appears unexplained. A hypothesis is that, in the post frontal, colder air mass, there was less total moisture then in the southerly, prefrontal air. As a result fewer aerosols were being used as CCN. This is strictly a hypothesis, and requires further investigation, and an entirely new experiment. To conclude, from an observational standpoint and the SMPS data there is a southern threshold. This threshold, approximately 270 degrees, where anything greater then 270 degrees Steamboat is in cloud, while less then 270 degrees Steamboat is blocked upstream by the San Juan and Flattop Mountains.

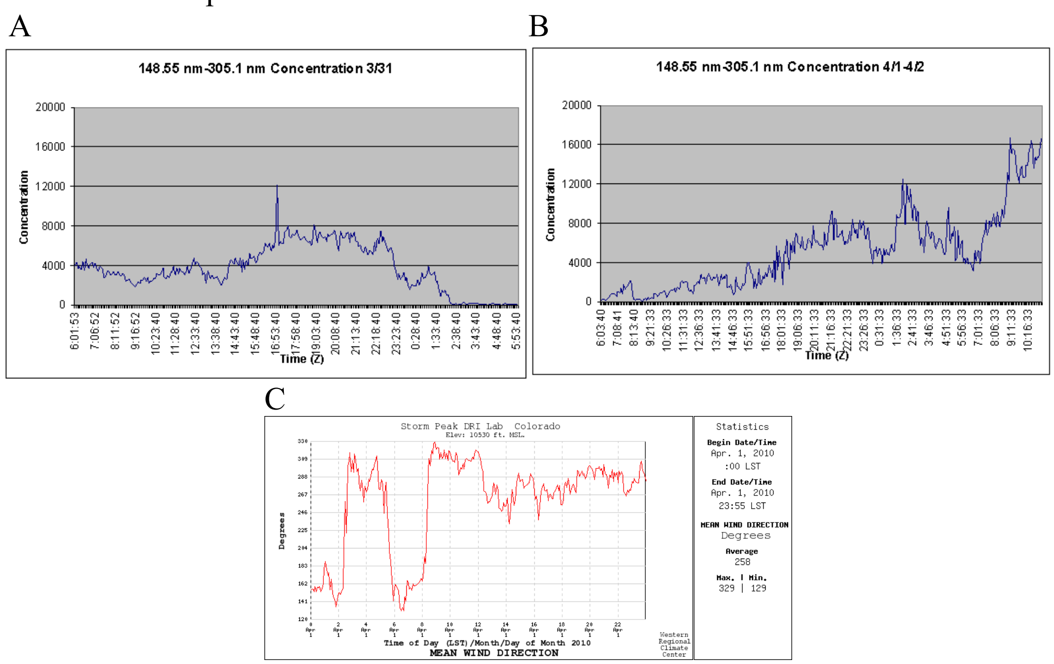

Figure 1. A. Scanning Mobility Particle Sizer data from 6:03 LST March 31st 2010-5:53 LST April 1st, 2010 from 148.44nm-305.1nm. B. Same as A, except 6:03 LST April 1st, 2010-10:16 LST April 2nd 2010. C. Wind direction at Strom Peak Laboratory from 00:00 LST April 1st, 2010-23:55 LST April 1st, 2010, (Data courtesy of Western Regional Climate Center.)

Moving to the model simulation many of the same relationships remain. The model initializes with SW flow and mountain shadowing can be seen at Steamboat Springs with downsloping in the valley (Fig. 2A). As the winds shift more westerly with the passage of a weak front clouds appear at SPL just as the winds reach 270 degrees (Fig. 2B). The simulation continues and the winds shift to NW at around 300 degrees with orographic clouds at SPL (Fig. 2C). Towards the end of the simulation though it appears there is a northern threshold on the wind direction. As the wind becomes northerly the clouds dissipate at SPL despite sufficient moisture in the flow (Fig. 2D). This suggests that there is a very small window that is favorable for Steamboat Springs to experience orographic clouds and snow. Less then 270 degrees the Flattop and San Juan Mountains leave Steamboat in their shadow with downsloping in the Yampa River Valley. If the wind veers too far north Elkhead Mountain receives the orographic clouds and snow. The high resolution simulation also shows the variability of orographic clouds. The different time scales of the clouds were directly dependent on wind direction, moisture and wind velocity. Also, thought not depicted, in the post frontal flow there was less total moisture, but due to a colder air mass persistent clouds and snow were present over SPL. This experiment despite for only a single wintertime snow event provides insights into the different flow and moisture regimes that produce cloud bases low enough that SPL is in cloud at 10,525ft.

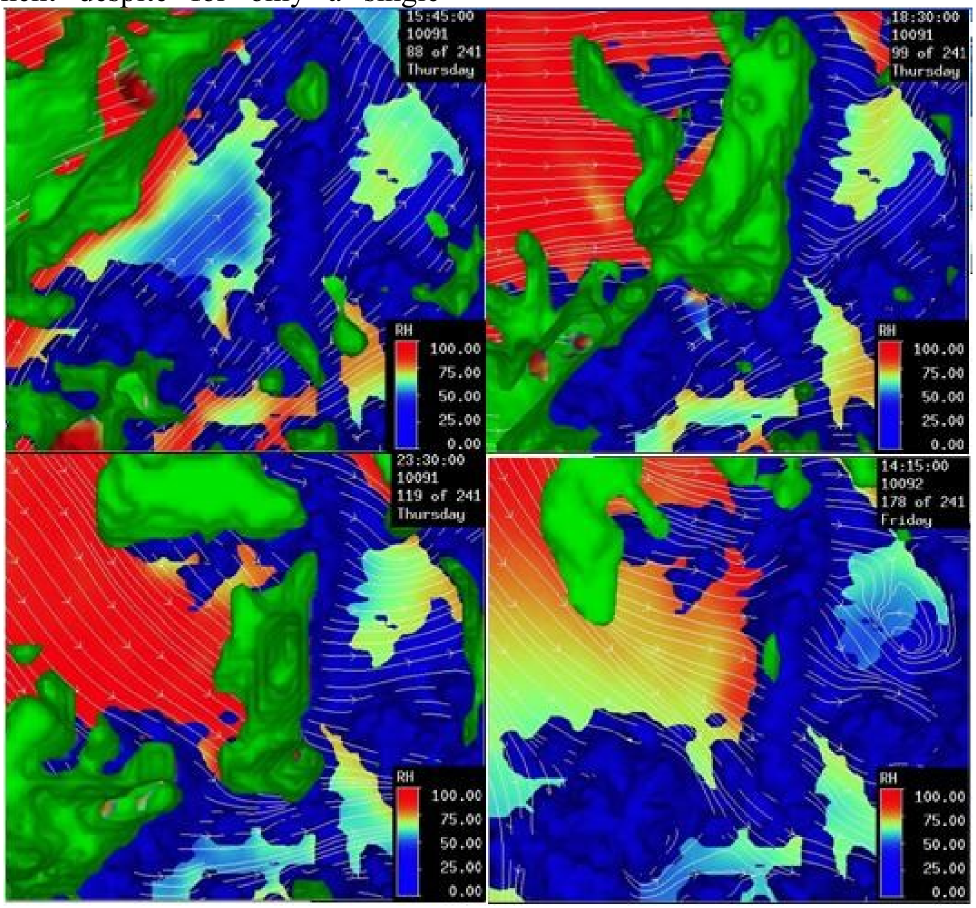

Figure 2 – A. NMS Simulation with SW flow. Streamlines plotted in white, relative humidity (RH) in color fill with warm colors high RH and cool colors low RH and topography plotted in blue. B. Same as A, except westerly flow. C. Same as A, except WNW Flow. D. Same as A, except NNW flow.

Conclusion

Despite only being a single experiment for a snow event in northern Colorado some very interesting results have been found. The original hypothesis was that NW flow was ideal on the mesoscale and synoptic scale for Steamboat to experience orographic snow and low cloud bases at SPL. This hypothesis was proven in correct on the mesoscale but withheld on the synoptic scale. For the mesoscale it was found based on observations, that a southern threshold existed near 270 degrees to no longer be in the shadow of the Flattop and San Juan Mountains. The numeric simulation was in agreement of a southern threshold near 270 degrees but also found a northern threshold. This was located near 315 degrees to get out of the Elkhead mountains shadow. As a result, on the mesoscale it has been found that W (270) to NW(315) is the favorable wind regime at 700mb. Further experiments should be conducted in the future to build upon these initial findings from the April 1st and 2nd orographic snow event.

Acknowledgments

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