1. Introduction

a. *Pollution effects*

As the population of the urban corridor along the eastern Front Range grows at an unprecedented rate (Nichols et al., 2001; Colorado Department of Local Affairs, 2013), concern about pollutant transport into the Rocky Mountains is on the rise. Pollutant gases along the Front Range such as nitrogen oxides (NO_x) from engine combustion and industrial processes, sulfur dioxides (SO_2) from coal combustion and gas processing, and ammonia (NH_3) from agriculture and livestock can convert to particle phases through the following reactions found in Beem (2008), Jacob (1999), and Jacobson (2002):

- Gaseous NH_3 dissolves in water. NH_3 scavenges H^+ in rain/water to form ammonium (NH_4)

$$NH_3\ (g) \Leftrightarrow NH_3\ (aq)\ \text{(dissolved ammonia)}$$

$$NH_3\ (aq) + H_2O(l) \Leftrightarrow NH_4^+\ (s) + OH^-$$

- Nitrate (NO_3) scavenges H^+ ions to form nitric acid (HNO_3). HNO_3 combines with NH_3 to form ammonium nitrate

$$NO_3^-\ (g) + H_2O\ (l) \Leftrightarrow HNO_3\ (g) + OH^-$$

$$HNO_3\ (g) + NH_3\ (g) \Leftrightarrow NH_4NO_3\ (s)$$

- Sulfur dioxide (SO_2) oxidizes in rain droplets to sulfate (SO_4^{2-}) which scavenges H^+ ions to form sulfuric acid (H_2SO_4). H_2SO_4 combines with NH_3 to form ammonium sulfate

$$SO_2\ (g) \Leftrightarrow SO_2 \bullet H_2O$$

$$SO_2 \bullet H_2O \Leftrightarrow HSO_3^- + H^+$$

$$H_2O_2\ (g) \Leftrightarrow H_2O_2\ (aq)$$

$$HSO_3^- + H_2O_2\ (aq) + H^+ \Leftrightarrow SO_4^{2-} + 2H^+ + H_2O$$

$$SO_4^{2-}\ (g) + 2H_2O^+\ (g) \Leftrightarrow H_2SO_4\ (g) + 2OH^-$$

$$H_2SO_4\ (g) + 2NH_3\ (g) \Leftrightarrow (NH_4)_2SO_4\ (s)$$

Pollutants transported into the Rocky Mountains diminish atmospheric visibility (Sisler and Malm, 1994), suppress precipitation (Jirak and Cotton, 2005), decrease biological diversity in terrestrial and aquatic ecosystems through atmospheric deposition (Vitousek et al., 1997; Amon et al., 2001; Baron, 2006), and increase chances for respiratory and cardiovascular illnesses of animals that experience long-term exposure (Gilmour et al., 2001). Mountain ecosystems are assumed to be pristine environments and devoid of anthropogenic influence, which includes direct defacing of mountain surfaces or indirectly degrading land or water by atmospheric pollution. However, the Rocky Mountains have coarse-textured soils (Walthall, 1985) which disallow the uptake nutrient-rich precipitation, allowing most ions in precipitation to reach and store in mountain lakes through runoff streams. Eutrophication of streams and lakes occurs when human-influenced as well as natural-occurring nitrogen, namely NH_4 and NO_3 species accumulate beyond the ability of the biota to process the nutrients. A growing presence of nitrogen-limited algae suggests a lake or stream is eutrophic (Smith and Schindler, 2009). Algal growth along the surface of the water reduces sunlight to the subsurface flora, limiting photosynthesis. With little-to-no photosynthesis, oxygen concentrations under water become too low to sustain life below the surface and the ecosystem slowly dies.

b. *Pollution sources*

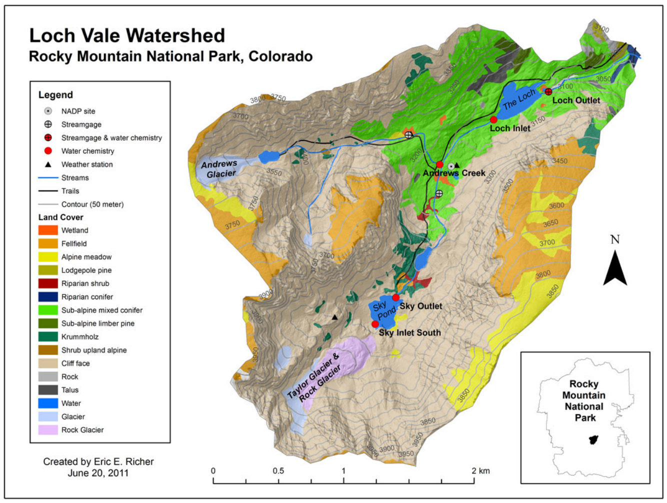
The Colorado Front Range is a major emitter of NO_x, SO_2, and NH_3. With the exception of NO_x emissions in northwest Colorado, the urban corridor between Colorado Springs and Fort Collins, Colorado is Colorado's biggest source region of NO_z and SO_2 relative to other regions in the state (Benedict et al., 2013). Weld County, Colorado has some of the largest confined animal feeding operations (CAFOs) in America with approximately 595,000 head of cattle (Lynn, 2012) in the county. With as many as 300 head of cattle per acre for thousands of acres comes the consequence of overflowing waste. From the CAFOs, notable emitted gases are hydrogen sulfide (H_2S), methane (CH_4), and NH_3. NH_3 can convert to NH_4 from Reaction 2, which can be transported with other aforementioned Front Range pollutants via upslope winds into the Rocky Mountain.

Rocky Mountains are very susceptible to change from the addition of unnatural pollutants such as transported chemical byproducts from Colorado's Front Range. The confluence of mountain meteorology conspires to transport pollutants along the Front Range, including those from the urban corridor and CAFOs. Though winds in Colorado are predominately from the West, thermally induced east winds during spring- and summer-time result from a mountain-valley circulation on the lee side of the Front Range in the event of little-to-no synoptic forcing (Markowski and Richardson, 2010). From daybreak, the mountain tops heat up quicker than eastern-Colorado plains, which creates potential temperature gradients along the mountain slopes that increase with altitude. The higher potential temperatures on the mountain slopes induce a buoyancy-driven wind from the plains westward into the mountains, explained extensively by Wagner (1938), Ekhart (1948), Defant (1951), and Thyer (1966). These upslope, or anabatic winds can travel 2-4 m/s (Defant, 1951) and convectively transport emissions along and east of the Front Range up mountain slopes where pollutants are emptied into mountains either through wet or dry deposition (Baron and Denning, 1993; Benedict et al. 2013).

The focus of this study was to examine the meteorological conditions in which atmospheric deposition of pollutants at two mountain sites was anomalously high due to convective transport. We looked at 19 years (1994-2013) of precipitation and wet deposition data from three National Atmospheric Deposition Program (NAPD) sites in the Rocky Mountains: Beaver Meadows (CO19), Loch Vale (CO98), and Niwot Ridge (CO02). The two sites in Rocky Mountain National Park (RMNP), Loch Vale (3159 m) and Beaver Meadows (2477 m), are located approximately 11 km apart but differ in height by 682 m resulting in different seasonal precipitation composition and totals discussed in Baron and Denning (1993). We then isolated two simultaneous high-deposition events from the three mountain sites. The Advanced Research Weather Research and Forecasting (WRF-ARW, hereafter WRF) model was used to simulate the meteorology at a high resolution for the progression of the upslope event that led to high nitrogen deposition in the Rocky Mountains. Data from the North American Regional Reanalysis (NARR) was used to observe and verify synoptic conditions produced by the WRF model that influenced the high-deposition events.

2. Deposition

Rocky Mountain ecosystems are very susceptible to change from the addition of unnatural pollutants such as transported nitrogen from Colorado's Front Range. The confluence of mountain meteorology conspires to transport pollutants along the Front Range, including those from the urban corridor as well as CAFOs, work to change ecosystems. With 83% bare rock, ice, and boulder, 11% tundra, 5% forest, and 1% subalpine meadow (Arthur, 1992), Loch Vale Watershed in the Rocky Mountains has very little soil to absorb deposited materials during precipitation events. Hence, most deposited ions end up in runoff streams into mountain lakes shown in Figure 1.



Deposition values at Loch Vale are closer to values at sites on the west side of the Continental Divide, whereas values at Beaver Meadows were better correlated with Estes Park data. This suggests Loch Vale deposition has more influence from synoptic-scale frontal disturbances with moisture from the Pacific Ocean carrying pollutants from the western United States. Conversely, deposition at Beaver Meadows is influenced by the transport of urban pollutants along the Colorado Front Range via cyclonic flow near the Texas Panhandle, which contains moisture from the Gulf of Mexico.

Monthly inorganic nitrogen deposition and precipitation amounts from 1994-2012 from Beaver Meadows (2477 m), Loch Vale (3159 m), and Niwot Ridge (3520 m) are shown in Figure 2. Beaver Meadows and Loch Vale both show bimodal precipitation distributions for the year, with a primary maximum in the spring and a secondary maximum in the summer. Interestingly, monthly nitrogen deposition distributions also show a bimodal distribution, however, the primary maximum is in the summer while the secondary maximum occurs in the spring. Warmer temperatures and longer hours of sunlight during summers yield more dynamic atmospheric reactions producing NO_3 and NH_3 (Baron et al., 1992; Hargreaves and Tucker, 2004). The Rocky Mountain Atmospheric Nitrogen and Sulfur (RoMANS) Report, a comprehensive nitrogen and sulfur deposition study from 2006, showed higher deposition associated with lower precipitation during summers is attributed to a few infrequent upslope events with large ambient nitrogen concentrations while lower deposition with higher precipitation during springs is due to prevailing west winds with low emissions from faraway sources.

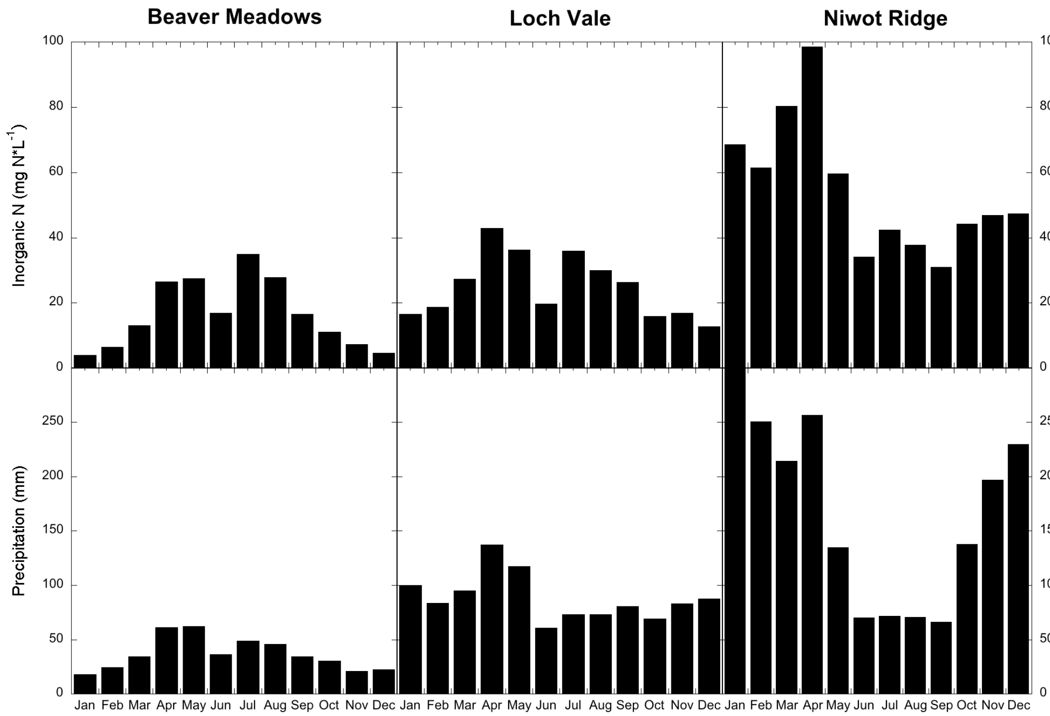
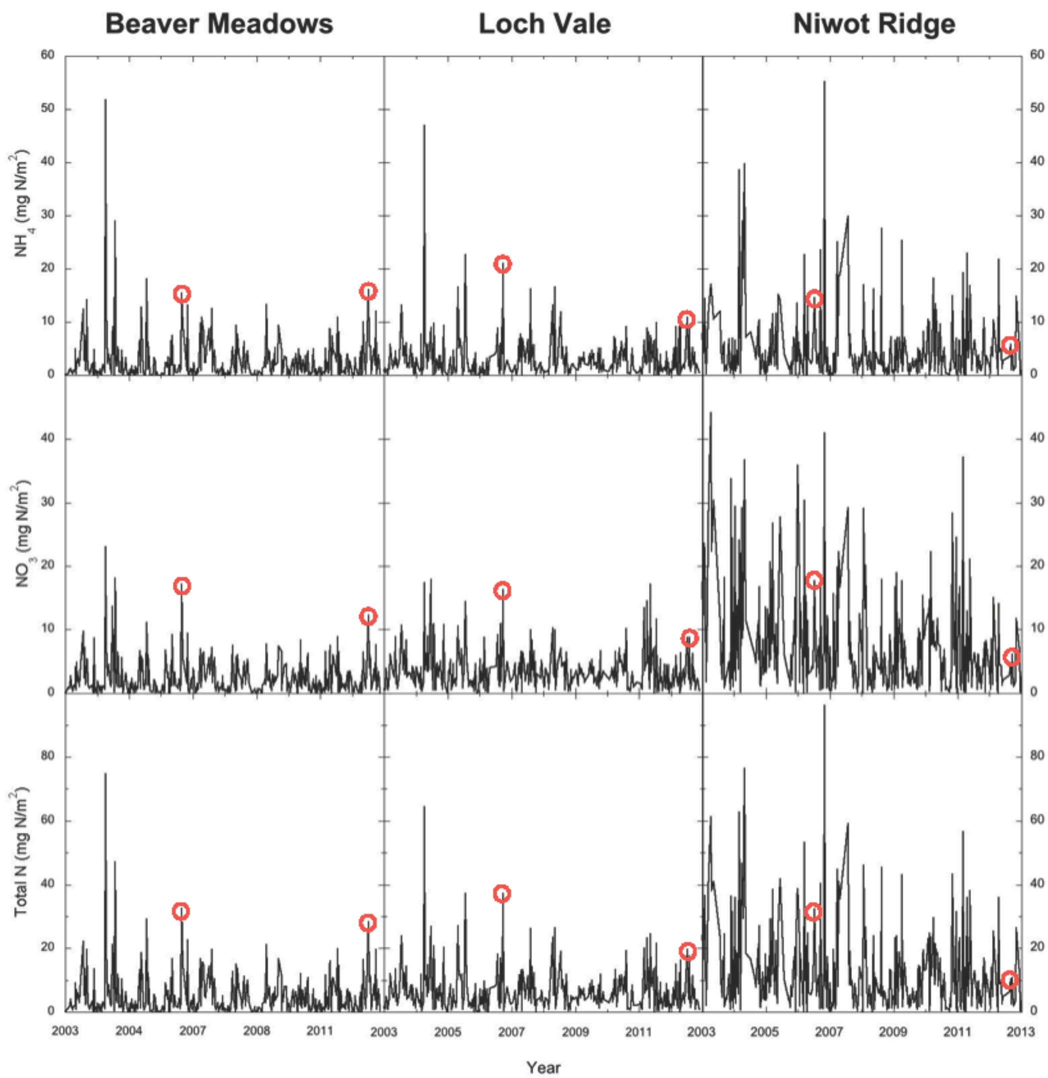


Figure 2. Inorganic nitrogen deposition and precipitation amounts for three NADP sites, Beaver Meadows (2477 m), Loch Vale (3159 m), and Niwot Ridge (3520 m), from 1994-2012

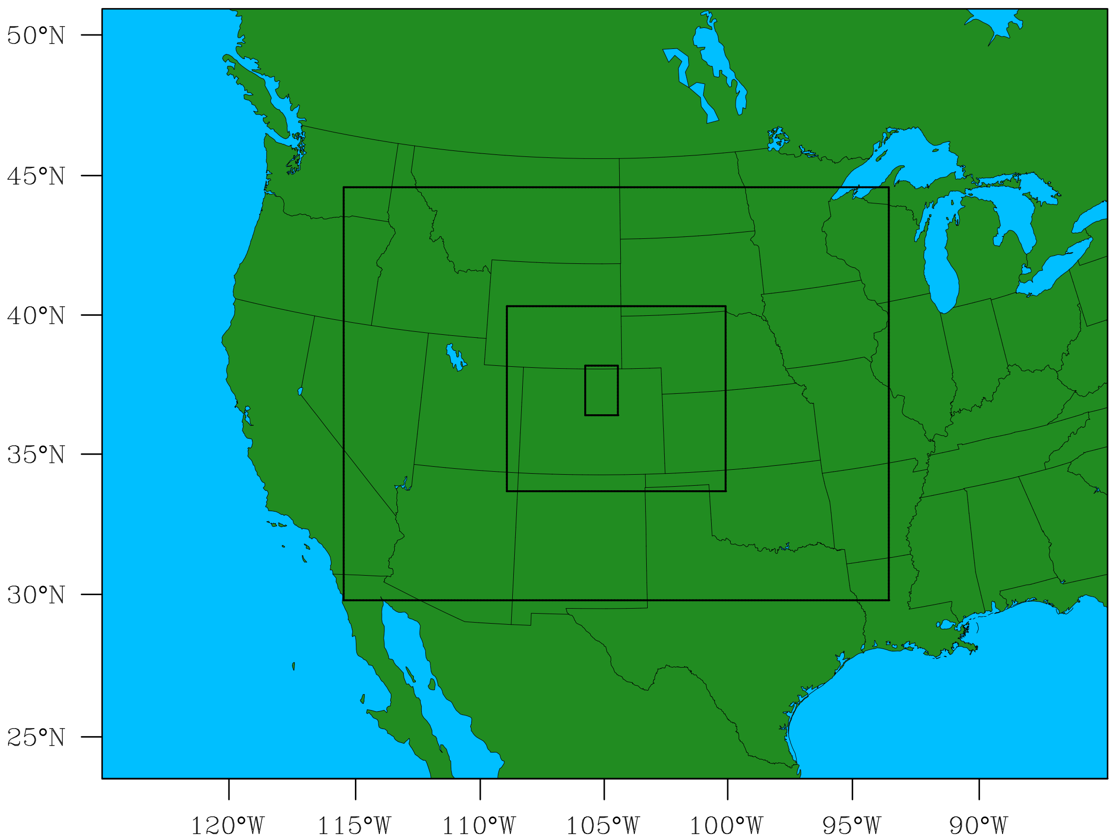
Figure 3 shows a decade (2003 Jan 1 – 2013 Jan 1) of weekly N deposition associated with NH_4^+ and NO_3^- ions as well as the total N deposition from NH_4^+ + NO_3^- from Beaver Meadows, Loch Vale, and Niwot Ridge sites. This study focused on the meteorological set-up that favored large nitrogen deposition in the Rocky Mountains during the summertime. The highest peaks in Figure 3 were springtime deposition events and, therefore, not taken into account for this study. We looked at two anomalously high deposition events that occurred 18-20 August 2006 and 06-08 July 2012 (circled red peaks in Figure 3).



Beaver Meadows
Loch Vale
Niwot Ridge
NH4 (mg N/m2)
NO3 (mg N/m2)
Total N (mg N/m2)
Year

3. WRF-ARW

We used version 3.4.1 of the Advanced Research WRF (ARW) (Skamarock et al., 2008) to examine the meteorological setup for two high-deposition events in August 2006 and July 2012, mentioned in Section 2. WRF was configured with one-way boundary conditions between four domains (shown in Figure 1) at a 3:1



parent-to-nest ratio.

The coarse domain had grid spacing set to 27 km with a time resolution of 96 s (1 km grid spacing for the finest domain with a time resolution of 3.56 s). The initial conditions and boundaries were provided by the National Centers for

Environmental Prediction Operational Model Global Tropospheric Final Analyses (National Centers for Environmental Prediction, National Weather Service, NOAA, U.S. Department of Commerce, 2000). The vertical grid had 50 layers with a ceiling at 50 mb.

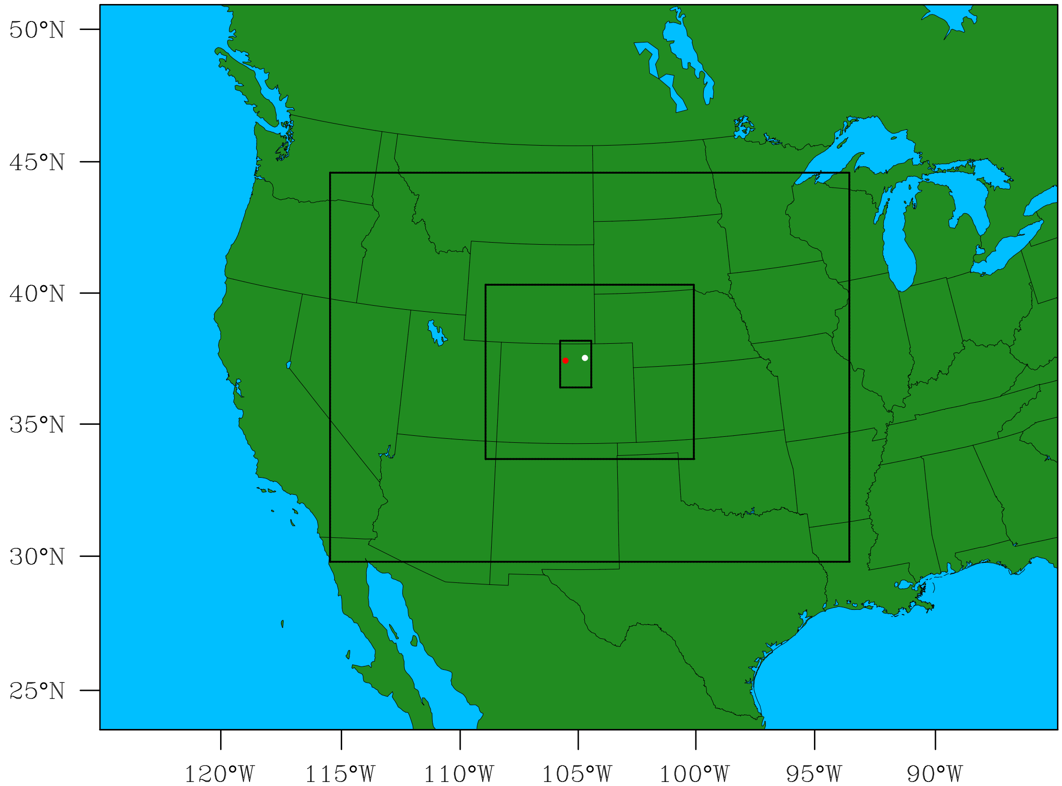
The physics options used in this study were similar to the physics options demonstrated in Nehrkorn et al. (2010).

- Microphysics: Lin et al. scheme
- Radiation: RRTMG scheme for longwave radiation and the New Goddard scheme for shortwave radiation at 10 minutes between each radiation physics call (radt = 10 min)
- Planetary Boundary Layer: Yonsei University (YSU) scheme for domain 1 and the Mellor-Yamada-Janjic scheme for domains 2, 3, and 4 to include TKE. The YSU scheme for domain 1 is coupled with the Noah Land Surface Model and the MM5 similarity theory-based surface layer scheme while the Mellor-Yamada-Janjic scheme for domains 2, 3, and 4 is coupled with the Noah Land Surface Model and the Eta similarity theory-based surface layer scheme.
- Convection for domains 1 and 2: Grell 3D scheme.

We included a passive tracer discussed in Barth et al. (2012) in a 2x2 grid of domain 4 (tracer_opt = 2 in the dynamics section of namelist.input). The unitless passive tracer, released from a 2x2 grid at every time step (dt = $3.\overline{55}$ s), represented emissions from Kuner Feedlot managed by JBS Five Rivers Cattle Feeding LLC in

Weld County, CO, shown by the white dot in Figure 2. At each time step, the surface of the approximate location of the feedlot was set to a tracer value of 1. Concurrently, winds advected and dispersed the tracer into the 3D space of the 4th domain.

For each August 2006 and July 2012 case, WRF was run for 48 hours with an output time interval of 10 minutes for each domain. We initialized WRF at 06 UTC to avoid erroneous spin-up meteorological features (Weiss et al., 2008). Additionally, the spin-up of WRF at 06 UTC allowed for realistic meteorology by the time daytime heating started around 12 UTC.



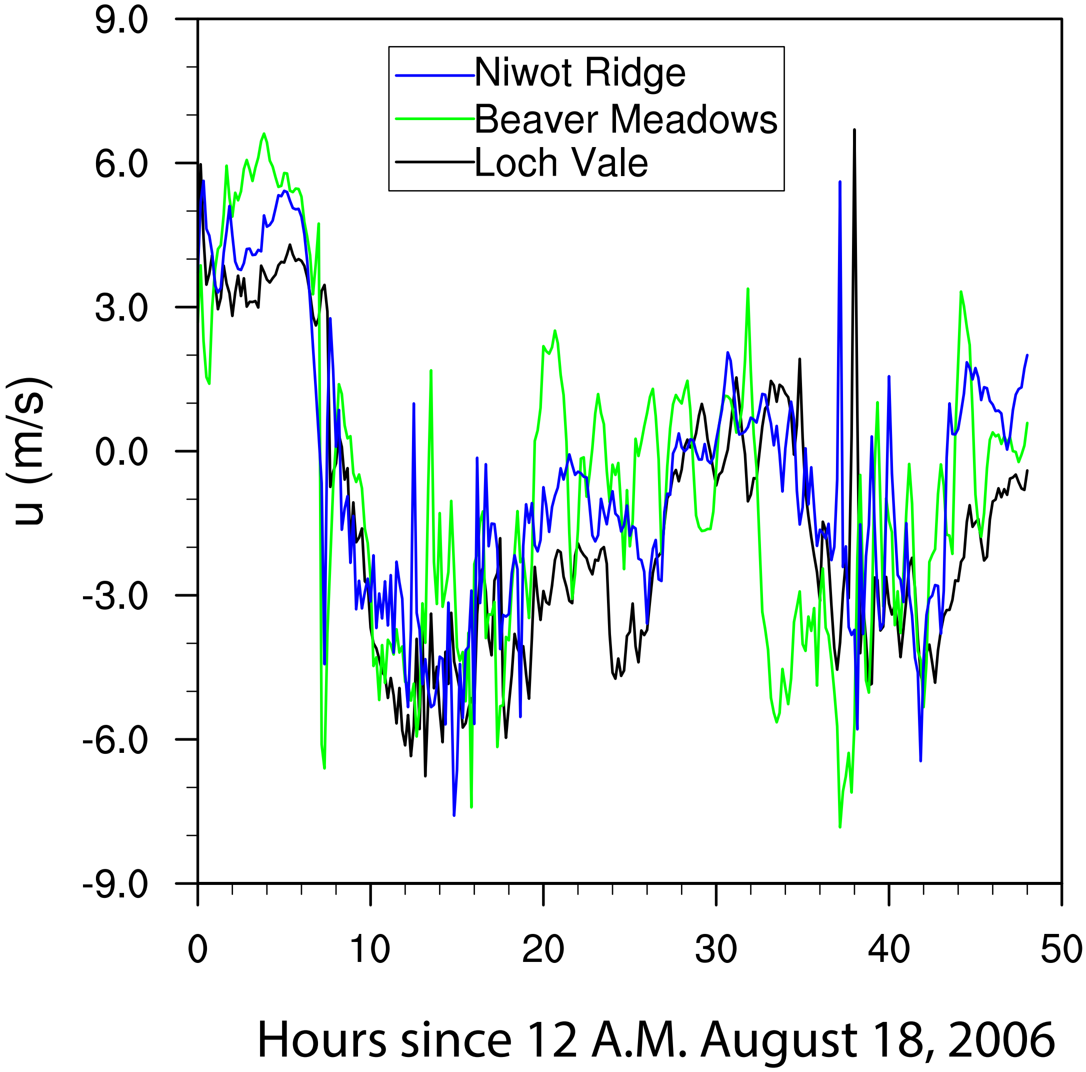
We then compared domains 1 and 4, which used parameterized and resolved convection, respectively, to test the importance of moist convection on high-deposition events.

5. Discussion

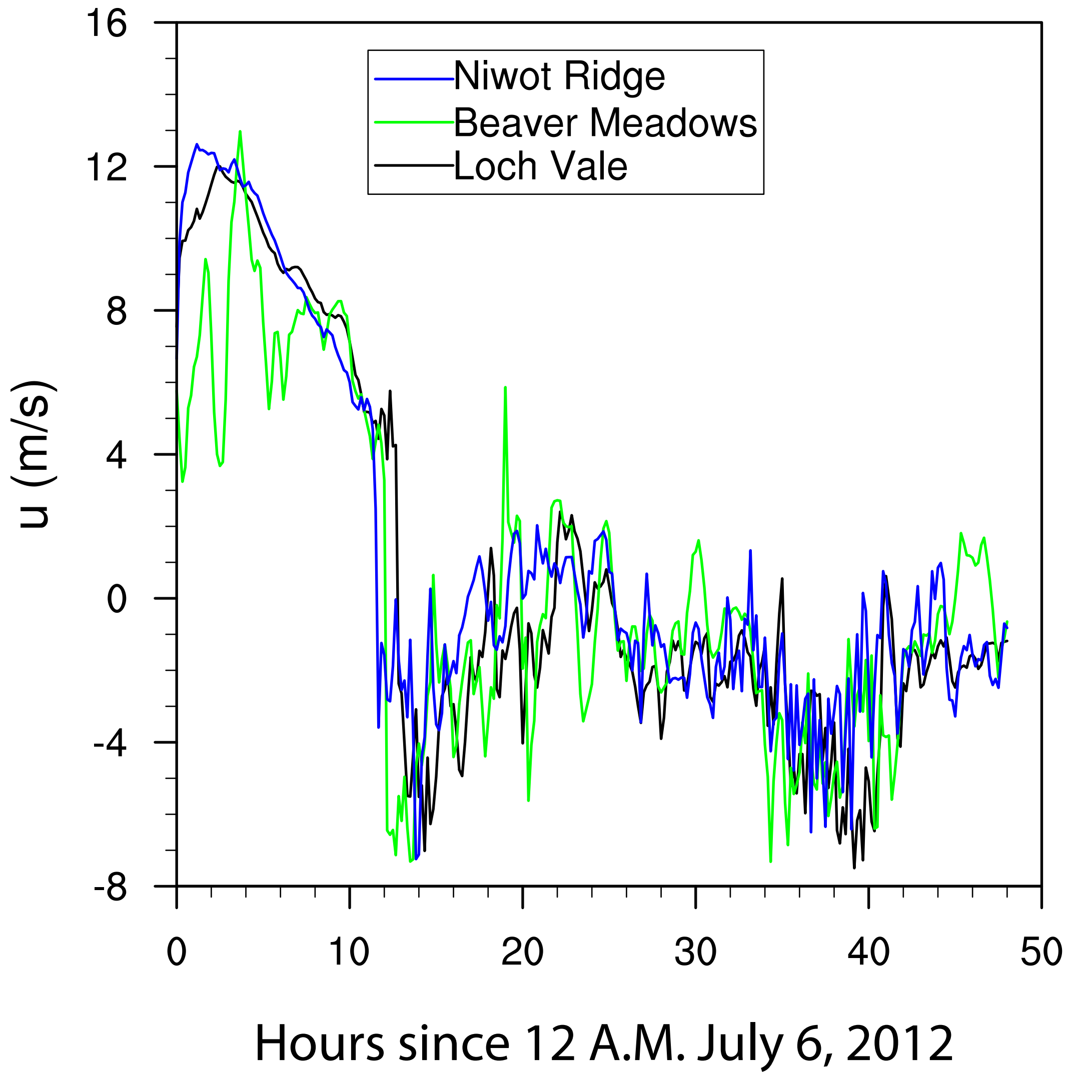
We simulated meteorology with WRF at 1-km grid spacing for two high wet deposition events in August 2006 and July 2012. Specifically, zonal wind direction and speed along with precipitation adjacent to the Colorado Front Range were of interest. North American Regional Reanalysis (NARR) data were also used to examine the synoptic meteorological conditions at different layers of the atmosphere leading up to the high wet deposition events.

a. WRF

From Figures 1 and 2 show 48-hour time series of zonal wind from WRF output for 3 NADP sites, Niwot Ridge, Beaver Meadows, and Loch Vale during the

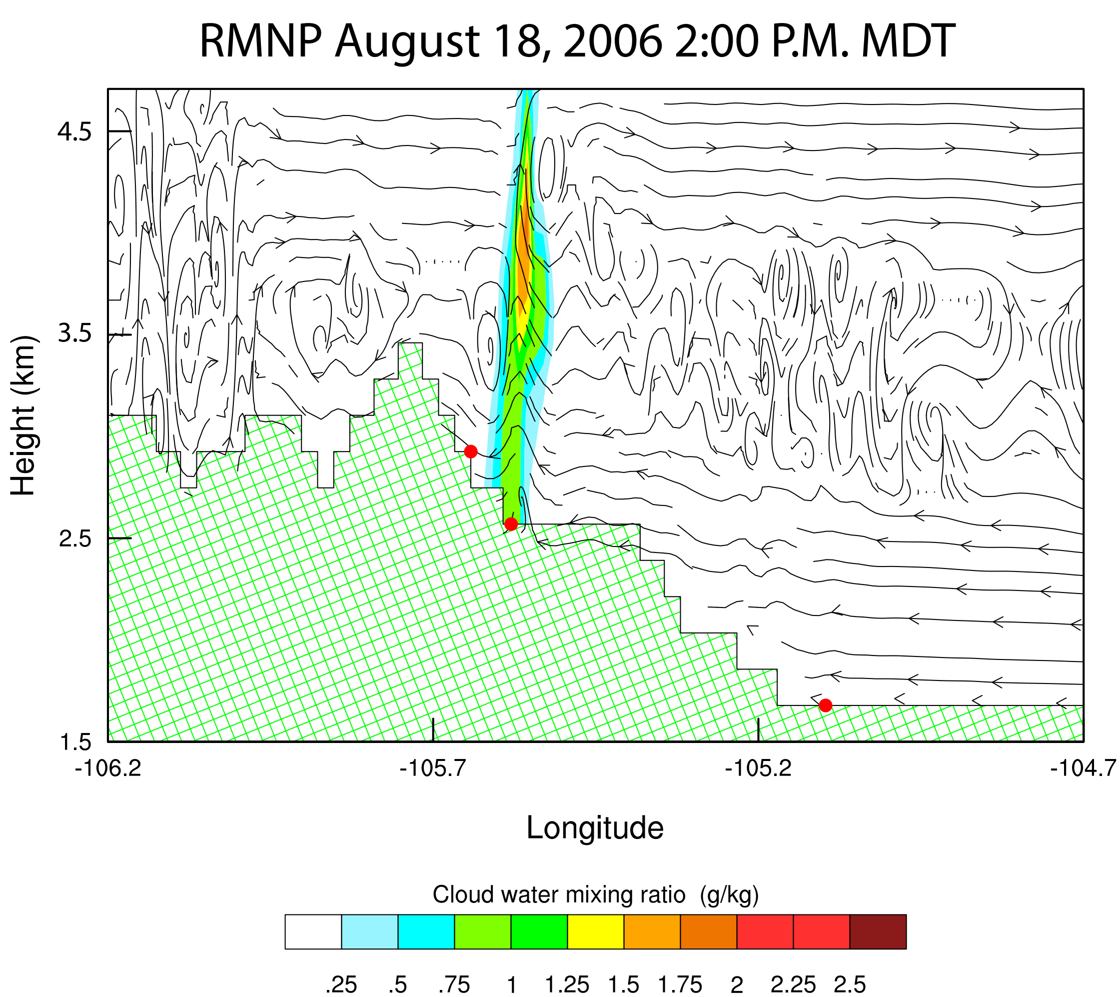


August 2006 and July 2012 high wet deposition events, respectively. Because both simulations started at midnight, hours 0-23 were considered "Day 1" while hours 24-47 were considered "Day 2".

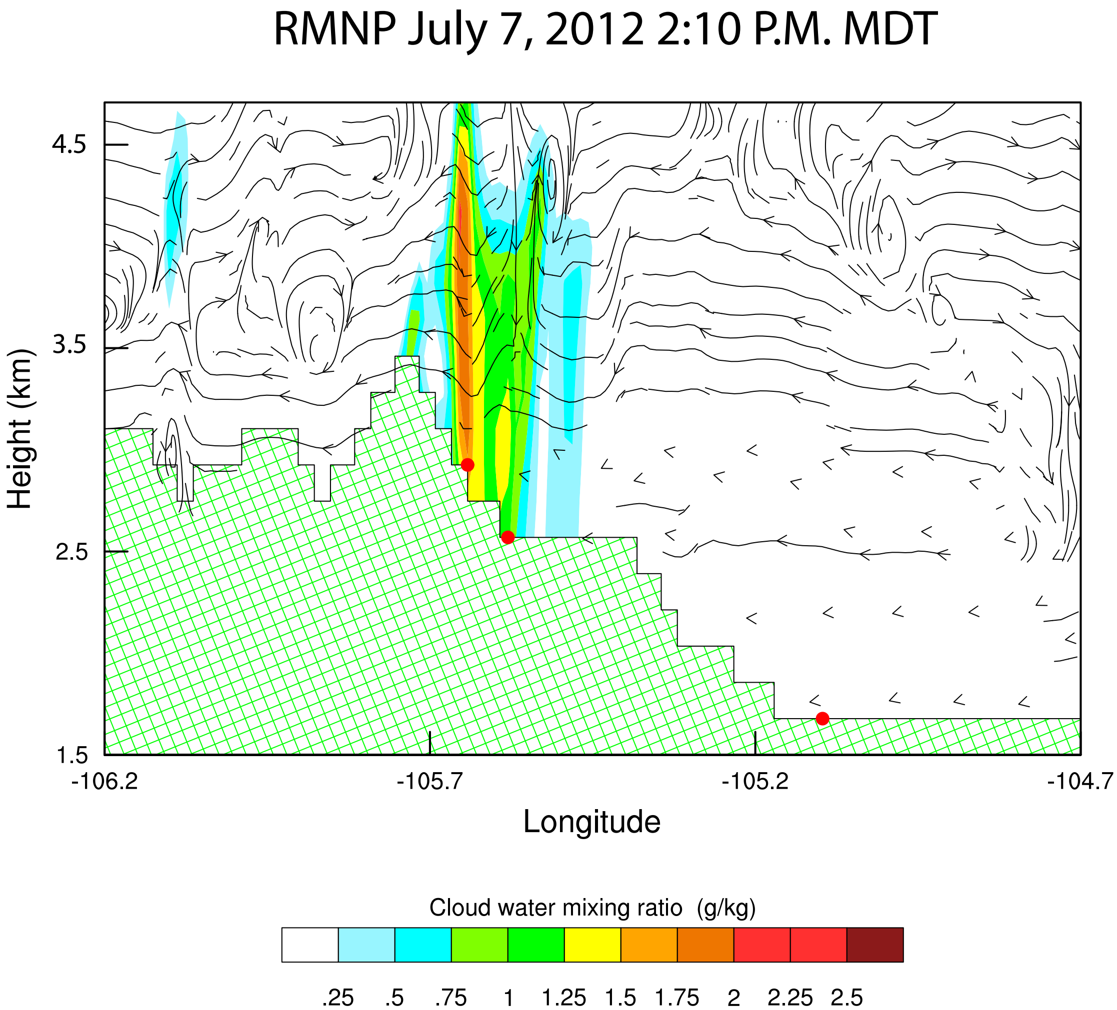


For both time periods shown in Figures 1 and 2, a diurnal cycle of anabatic/katabatic winds is evident with a higher magnitude on Day 1. At all locations for 2006 and 2012, the peak east wind occurred around 2 P.M. local time on Day 1. Around 2 P.M. of Day 2 hour 38), Niwot Ridge and Loch Vale experienced maximum west winds at the same time Beaver Meadows experienced maximum east winds. The wind speeds at all three locations were approximately the same. The opposite direction of concurrent maximum winds for the three locations on the afternoon of Day 2 in 2006 suggested a synoptic wind influence for the higher locations, Niwot Ridge and Loch Vale. On Day 2 of the 2012 event (Figure 2), winds were predominately from the east for all three locations for the entirety of the day, which suggested widespread upslope as a result of a more robust synoptic wind pattern relative to the 2012 event.

Figures 3 and 4 show cross sections of wind streamlines and contoured cloud water mixing ratios along the average latitude of Loch Vale and Beaver Meadows in



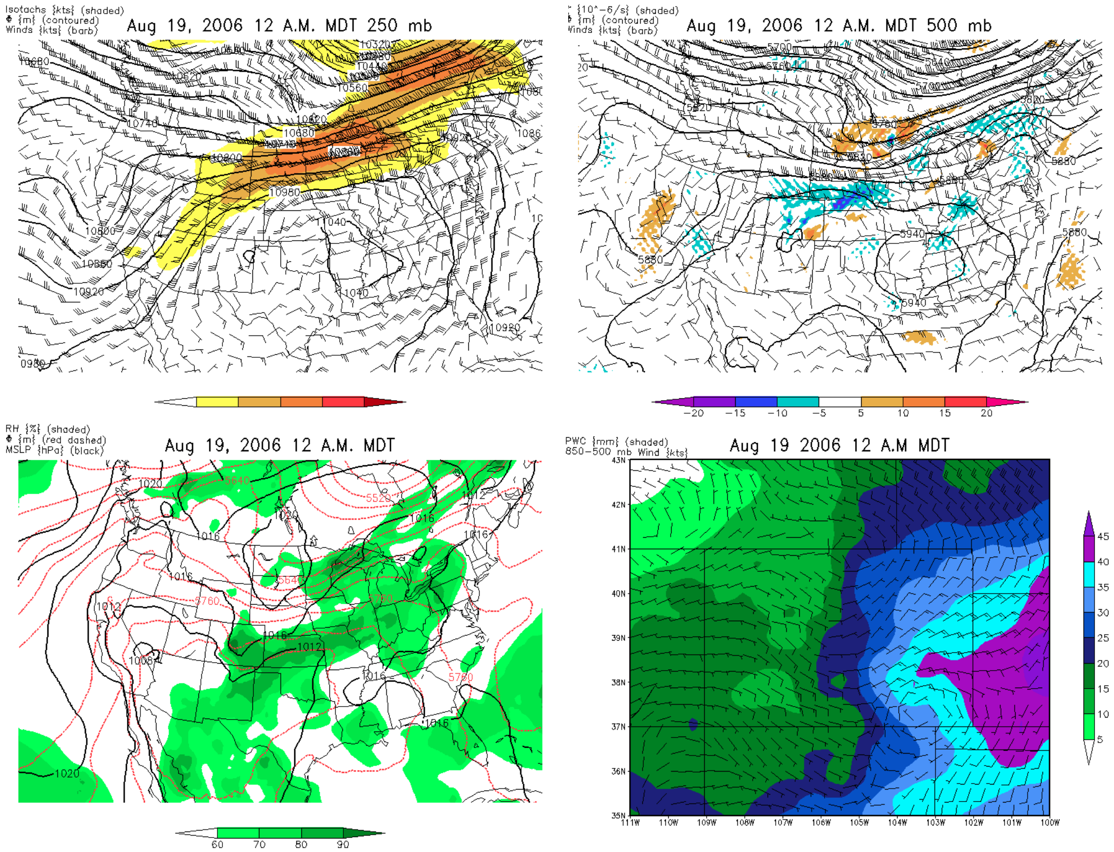
Rocky Mountain National Park at a particular afternoon time. The red dots from west to east are the nearest gridpoints that represent Loch Vale, Beaver Meadows, and a CAFO in eastern Colorado, respectively. August 18, 2006 at 2 P.M. MDT was a textbook example of the mountain circulation resulting from differential sensible heating between mountain slopes and the eastern plains, shown in Figure 3. Buoyancy over the mountain slopes led to surface easterlies, carrying any surface pollutants towards the mountains. As the surface easterlies rose along the mountainside, precipitating clouds formed in the presence of atmospheric moisture. Westerlies ~3 km above the eastern-plains ground level completed the mountain circulation. July 7, 2012 at 2:10 P.M. MDT showcased a deep upslope wind, shown in Figure 4. Deep upslope winds, with a vertical extent of 2.5 km from the plains ground level into the atmosphere, in the presence of moisture from a surface low pressure led to enhanced convection over the mountains. Interestingly, this rain event was largely responsible for the extinguishment of the High Park Fire West of Fort Collins, CO and subsequent flash flooding around the High Park Fire burn scar. The deep easterlies allowed for the transport and deposition of pollutants from eastern Colorado into the higher NADP locations, as shown in Figure 4.



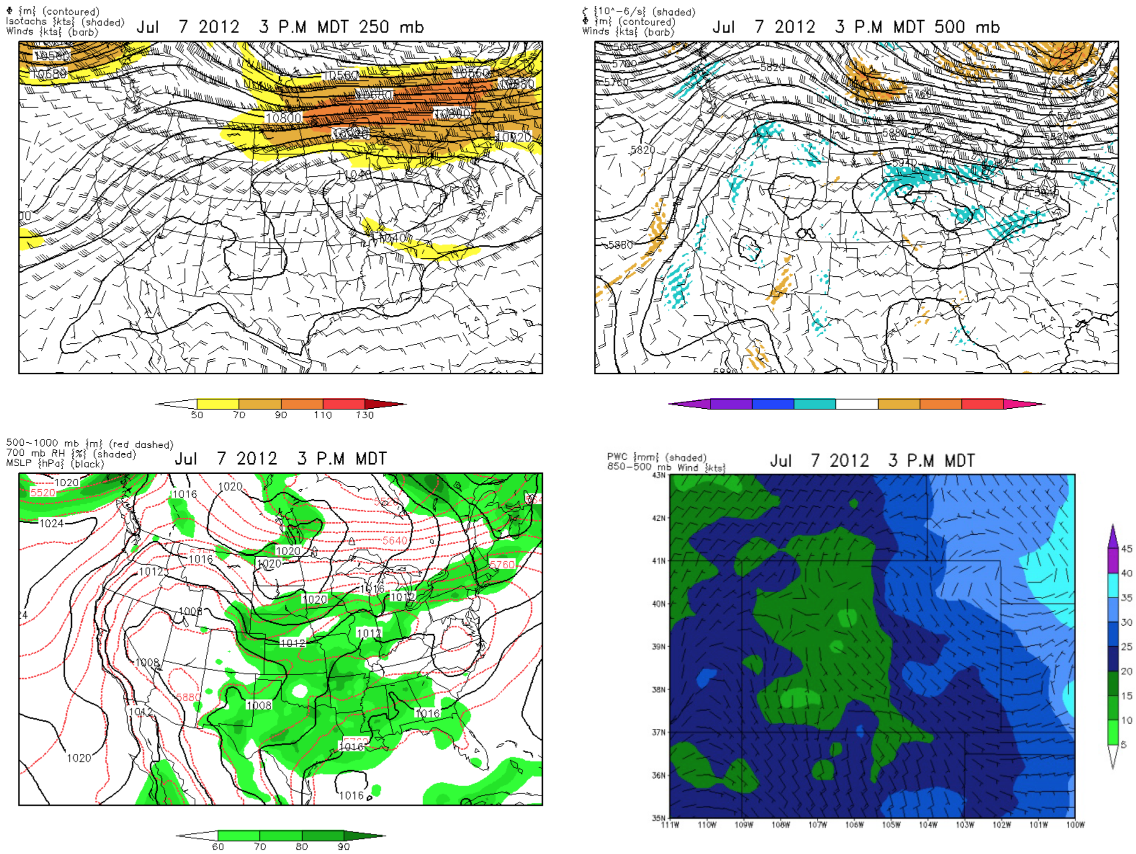
b. NARR

Figures 5 and 6 are four-panel plots of meteorology at different height levels using NARR data for the August 2006 and July 2012 high wet deposition events, respectively. For both figures, the top left panel is a CONUS 250-mb map with wind barbs, contoured geopotential heights, and shaded isotachs; the top right panel is a CONUS 500-mb map with wind barbs, contoured geopotential heights, and shaded relative vorticity; the bottom left panel is a CONUS map of contoured 1000-500 mb heights (red), contoured mean sea-level pressure (MSLP; black), and shaded 700-mb relative humidity (RH); the bottom right panel is a map of Colorado and its surrounding area with 850-500 mb wind barbs removed from the August mean wind values (i.e. wind barb value = wind at specified time – average August wind value) and shaded precipitable water content values.

From the top left panel of Figure 5 (August 2006 event), an upper-level cold front skirted northern Colorado around midnight. At 500 mb, an anti-cyclone and a cyclone simultaneously developed over the Colorado-Wyoming-Nebraska triple point and southeastern Colorado. The circulation pattern at low-mid levels, best shown in the bottom right panel as well as from the lee trough from MSLP contours in the lower left panel, was a recipe for enhanced pollutant transport from eastern Colorado into the Rocky Mountains. High RH values in the bottom left panel showed there was ample atmospheric moisture at low-mid levels for deposition into the mountains.



A broad high-pressure circulation was retrograding from the central U.S. to the Mountain-West states at the time of the still CONUS maps shown in Figure 6 (July 2012 event). The location of the broad upper-level ridge of high pressure, shown in the upper panels, allowed for moist, southerly flow into Colorado. Similar to the August 2006 case, circulation patterns such as anomalous southerly winds from the location of the broad upper-level high pressure concurrently with a mid-level anti-cyclone located in northeastern Colorado (shown in the lower right panel), were once again responsible for the enhanced pollutant transport into the Rocky Mountains. And like the August 2006 high wet deposition event, lee troughing, shown by MSLP contours in the lower left panel, played a role in the circulation patterns of the low-mid atmosphere.



6. Conclusions and Future Work

We isolated two recent anomalously high wet deposition events of nitrogen into the Rocky Mountains using NADP data. We then simulated the meteorological set-up of the deposition events using WRF over northern Colorado with 1-km grid. From WRF output alone, we were able to differentiate between mesoscale and synoptic influences. For example, from Figures 1 and 3, we verified the diurnal cycle was mostly responsible for the mountain convection, which led to pollutants depositing at Loch Vale and Beaver Meadows. Conversely, from Figure 2, we deduced a major synoptic influence from wind direction and magnitudes for three different sites at different altitudes. Using NARR data, we were able to identify circulation at low, mid, and upper levels as the key player for deposition in the Rocky Mountains. Using NARR data helped identify which meteorological set-ups were easy to point out as possible high deposition days when viewing weather forecasts.

Building off this study, we will use WRF output as input to the Stochastic Time Inverted Lagrangian Transport (STILT) model to geo-locate eastern Colorado feedlots that are responsible for high nitrogen emissions. To mitigate nitrogen deposition in the Rocky Mountains, findings from this study (i.e. circulation patterns), will be used to develop a warning system for ranchers in eastern Colorado to refrain from turning manure piles for a brief period of time.

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