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# OVERESTIMATION OF SNOW DEPTH AND INORGANIC NITROGEN WETFALL USING NADP DATA, NIWOT RIDGE, COLORADO

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## ABSTRACT

We evaluated precipitation quantity and inorganic N deposition from wetfall at the Saddle site on Niwot Ridge, an alpine location in the Colorado Front Range of the Rocky Mountains. The chemical content of precipitation was collected with an Aerometrics wet-only deposition collector and precipitation amount was collected in a co-located Fergusson-type weighing gauge with a wind shield. Calculating the actual deposition of snow at a point in alpine areas is difficult because wind transport can cause under sampling or over sampling of the actual precipitation amount. We used a moisture sensor on the wet chemistry collector to account for blowing snow events, categorizing snow and rain collected in the Saddle precipitation gauge as precipitation events when the moisture sensor was "on" and blowing snow and rain events when the moisture sensor was "off". Over a ten-year period, 61% of the winter precipitation was collected when the moisture sensor was "off". Perhaps fortuitously, annual solid precipitation (October-May) of 1514 mm measured at the Saddle was 61% more than the 938 mm measured at an alpine site 2 km away and accounted for the difference in annual precipitation amount at the two sites. Annual inorganic N deposition at the Saddle site was then calculated as the measured summer deposition amount added to the measured winter deposition adjusted for over sampling from blowing snow events. These correction factors resulted in a 32% reduction of annual inorganic N in wetfall for the period 1986-1995, from an arithmetic mean of 4.7 kg $ha^{-1}$ $yr^{-1}$ to 3.2 kg $ha^{-1}$ $yr^{-1}$.

## INTRODUCTION

Critical and target loads for nitrogen (N) deposition in the western US are now being debated [Williams, 1997; Williams and Tonnessen, 1997]. Ambient concentrations of N measured in the early 1980’s at Niwot Ridge in the Colorado Front Range were 30-fold greater than pre-industrial levels [Fahey et al., 1986] and attributed to fossil fuel combustion [Lewis et al., 1984]. Additional measurements of ambient N at Niwot Ridge in the early 1990’s have shown that anthropogenically-fixed N in the atmosphere has since doubled [Rusch and Sievering, 1995]. In response to atmospheric deposition of anthropogenically-fixed N in the Front Range of the Rocky Mountains, there has been a fundamental shift from N-limited ecosystems to N-saturated ecosystems [Williams et al., 1996a]. Furthermore, the most acidic snow found west of the 100th meridian has been measured in the Rocky Mountains [Turk et al., 1995]. Episodic acidification, defined as negative alkalinity, has been reported in headwater catchments of the Rocky Mountains and is associated with elevated concentrations of nitrate ($NO_3^-$) in surface waters [Williams et al., 1996b]. If only modest atmospheric loadings of N in the Colorado Front Range are sufficient to induce N leaching to surface waters, current concepts of critical loads may need to be reconsidered [Williams et al., 1996a].

However, there is some controversy about what the current levels of N deposition are in wetfall to the Colorado Front Range. Niwot Ridge is an alpine site located at 3,500 m in the Colorado Front Range and is a participant in the National Atmospheric Deposition Program (NADP), which collects precipitation chemistry at about 200 cooperating sites in the US [NADP/NTN, 1986-1995]. Williams et al. [1996a] have shown that inorganic N deposition measured from 1991 to 1994 at the Niwot Ridge NADP site of 4.6 kg $ha^{-1}$ $yr^{-1}$ is similar to that of many sites in the northeastern US, such as the Hubbard Brook Experimental Site in New Hampshire. However, Legates and DeLiberty [1993] have suggested a 25% underestimation of precipitation amount for the winter season in the Colorado Front Range, suggesting that the NADP results are an underestimation of inorganic N in wetfall to Niwot Ridge. In contrast, Sievering et al. [1996] attempted to calculate wet and dry fluxes of N on an annual basis to Niwot Ridge and suggested that the actual non-growing season values may range from 10% to as much as 50% lower than measured values.

Interest in climate change at regional and global scales has intensified the intercomparison and interpretation of precipitation quantity and chemistry derived from network data [Neilson et. al., 1989]. Numerous problems exist with interpreting precipitation data from different sites, including different collectors, sampling frequency, sample handling, and analytical techniques [Sisterson et al., 1985]. The NADP was developed to minimize these variables by using the same collectors, sampling frequency, sample handling and analytical techniques for about 200 sites in the United States [NADP, 1986-1995]. However, methodology that is applicable in one climatic regime may require site-specific correction factors in another regime [e.g. Ramundo and Seastedt, 1990]. Here we investigate this problem at a site where snowfall is the primary form of precipitation.

Accurate measurements of precipitation quantity are particularly difficult at Niwot Ridge in the Colorado Front Range. More than 80% of the annual precipitation falls as snow [Caine, 1995] and mean winter wind speeds are are 10-13 $m\ s^{-1}$ with recorded gusts to 69.5 $m\ s^{-1}$ [Greenland, 1989]. Here we attempt to verify the precipitation quantity measured at the Saddle on Niwot Ridge from 1987 to 1996. We then attempt to verify NADP measurements of annual inorganic N in wetfall from 1986 to 1995, the extent of the NADP record at Niwot Ridge. Based on these results, we then calculate the "corrected" wet deposition of N to the NADP site on Niwot Ridge.

## SITE DESCRIPTION

Niwot Ridge is an unglaciated ridge located in the Colorado Front Range of the Rocky Mountains (40° 03’ N, 105° 35’ W) (Figure 1). This site is an UNESCO Biosphere Reserve and a Long-Term Ecological Research (LTER) network site. Treeline is at approximately 3,400 m. The ridge stretches eastward 6.5 km from the Continental Divide and exhibits one of the highest continentality values in North America, with an average of 45 frost-free days per year [Greenland, 1989]. There is a spring maximum in annual precipitation in March, April and May followed by a relatively dry summer period [Greenland, 1989].

The LTER network operates a high-elevation tundra laboratory and the NADP wet precipitation collector at the Niwot Ridge Saddle at an elevation of 3,500 m (Figure 1). The location of the Niwot Ridge LTER research site on the Niwot Saddle has forced the location of the precipitation gauge in a windy site with no natural vegetation or topographic barriers to act as a wind shield. In addition to the Saddle site, the University of Colorado's Mountain Research Station has maintained a meteorological station since 1951 called D1 on Niwot Ridge at an elevation of 3,750 m and two kilometers to the west of the Saddle site. The D1 site is located close to the continental divide in a sheltered lee zone with little wind relative to the Saddle site (Figure 1) [Greenland, 1989].

## METHODS

Calculating the actual deposition of snow at a point in alpine areas is difficult because wind transport of snow can cause under sampling or over sampling of the actual precipitation amount. We addressed this problem by using two different approaches to estimate "true" precipitation amount.

We used a moisture sensor on the NADP wet chemistry collector to distinguish between precipitation events and blowing snow events. The Aerometrics wet chemistry collector is located approximately 10 m to the south of the Belfort precipitation gauge at the Saddle site. When the moisture sensor on the wet chemistry collector is wet, it sends a 12-volt signal to the upper pen in the Belfort precipitation gage so that this pen moves to an "up" position, recording the onset of the precipitation event. The moisture sensor is heated; when precipitation stops the sensor becomes dry, stopping the 12-volt signal and hence recording the end of the precipitation event. The moisture sensor thus provides information on when precipitation events started, stopped, and the duration of the precipitation event. The moisture sensor is mounted facing upward such that precipitation falling vertically causes it to be "on" and precipitation moving horizontally (eg. blowing snow) rarely causes it to be "on". We recognize two confounding factors with this method: (1) blowing snow may be at an angle rather than horizontal with respect to the moisture sensor; and (2) this method does not distinguish between mixed precipitation and blowing snow events. For this analysis, we categorized rain and snow collected in the Saddle precipitation gauge as precipitation events when the moisture sensor was "on" and blowing snow events when the moisture sensor was "off". Field observations have shown this sensor to work surprisingly well. However, we used personal observations in January and February of 1997 to quantify the efficiency of the moisture sensor in discriminating blowing snow events from actual precipitation events by recording the stop and start times of precipitation events and blowing snow events through field observations, and then comparing our field notes to the moisture sensor record.

Precipitation is collected continuously at both the Saddle site and D1 with a standard, shielded, Fergusson-type weighing rain gauge made by Belfort. Both gauges contain antifreeze, to prevent snow from blowing out of the gauge, to melt the snow for more accurate measurements, and to reduce evaporation losses. The precipitation gauge at the Saddle is inspected about daily and the chart changed weekly. The precipitation gauge at D1 is inspected less frequently and the chart changed weekly to biweekly. Here we compare precipitation measurements at the Saddle site to the precipitation measurements at D1, from 1987 to 1996. We define rainfall as precipitation occurring during the summer months of June through September and snowfall as precipitation occurring in fall, winter and spring from October through May. Fifteen years of field observations by staff climatologist Mark Losleben (personal communication) have shown that rainfall rarely occurs in winter and spring but that snowfall can occur at any month.

Precipitation events were collected for precipitation chemistry in an Aerometrics wet-only chemistry collector at the Saddle site, following the standard NADP collection protocol. Precipitation chemistry was collected weekly at the Saddle site and analyzed for chemical concentrations at the NADP analytical laboratory. Wet deposition or solute loading was calculated as chemical concentration in wetfall multiplied times precipitation amount collected in the co-located Belfort precipitation gauge at the Saddle site.

## RESULTS and DISCUSSION

### Precipitation Amount

For January and February, 1997, we removed the blowing snow events from the precipitation record using our field observations to verify the accuracy of the moisture sensor. The 675 mm of precipitation measured in the Belfort gauge was 69% more than the 399 mm of adjusted precipitation (Figure 2). Clearly, the Belfort precipitation gauge at the Saddle site measures snowfall when the moisture sensor does not register any precipitation. Most likely, the difference between measured and corrected precipitation amount was the contribution from blowing snow. At D1 over the same time period, the 321 mm of precipitation measured was within 20% of the corrected precipitation amount at the Saddle site (Figure 2). These results suggest that the D1 site may provide an independent measurement of snowfall amount for Niwot Ridge.

About 61% of winter precipitation amount each year from 1987 to 1996 was collected in the Belfort gage when the moisture sensor recorded no precipitation event (Figure 3), similar to the 69% we measured in January and February of 1997 (Figure 2). We interpret the significant ($p < 0.001$) overcatch of solid precipitation when the NADP precipitation sensor was closed as blowing snow events. In contrast to solid precipitation events, a paired t-test shows that there was no significant difference between summer precipitation amount collected at the Saddle and summer precipitation amount collected when the precipitation sensor was open ($p = 0.62$, $n = 10$). Interestingly, in the summers of 1990 and 1994 no precipitation was collected in the Belfort precipitation gauge when the moisture sensor was dry. The moisture sensor appears to do an excellent job of sensing when rainfall events occur and to do a reasonable job of distinguishing snowfall events from blowing snow events.

A comparison of annual precipitation totals from 1987 through 1996 show that the average precipitation amount of 1854 mm measured at the Saddle site was 54% greater than the 1200 mm measured at D1 (Figure 4). A paired t-test shows that this difference was significant at the alpha = 0.05 level ($p = 0.002$, $n = 10$). Furthermore, the standard deviation of annual precipitation at the Saddle of 580 mm was about twice that of the 206 mm at D1. A paired t-test shows that winter precipitation amount at the Saddle was significantly greater than at D1 ($p = 0.001$, $n = 10$). Perhaps fortuitously, annual solid precipitation (October-May) of 1514 mm measured at the Saddle was 61% more than the 938 mm measured at D1, similar to the winter overcatch estimated using the moisture sensor. Rainfall during the summer months does not appear to explain the higher annual precipitation amount at the Saddle site compared to D1. Annual rainfall amounts (June-September) over the ten years were similar at the two sites: 222 mm at the saddle compared to 217 mm at D1 ($p = 0.82$, $n = 10$).

Generally, precipitation amount increases with elevation in the Colorado Front Range [Barry, 1973]. We hypothesize that the larger precipitation amount collected at the lower-elevation Saddle site compared to D1 was caused by blowing snow. The higher standard deviation in annual precipitation amount at the Saddle site compared to D1 is also consistent with more blowing snow at the Saddle site. Wind speed, available snow, and surface hardness are the three main variables controlling snow redistribution and are highly variable with time.

To our knowledge, this is the first report of oversampling of solid precipitation. The oversampling of solid precipitation at the Saddle site may be caused by factors unique to this high-elevation site. Consistent with other results, prior research at the Saddle site has shown that collection of snowfall decreases with increasing wind speed during storm events [Bardsley and Williams, 1997 (in press)]. However, as storms clear, strong winds ($> 20\,\mathrm{m\,s^{-1}}$) characteristically sweep the Saddle site because of the large fetch combined with no natural shielding from either topography or vegetation. Large amounts of blowing snow are produced at this time because of the combination of high winds, new snow available for transport, and the low surface hardness of the recent snowfall. Consequently, the Belfort precipitation gauge continues to collect blowing snow under clear sky conditions. The collection of blowing snow more than compensates for the undercollection of snow during snow events and results in overcollection of precipitation amount on an annual basis.

## Inorganic Nitrogen Deposition

We can use the results from the revised precipitation amount to recalculate inorganic N wetfall to the NADP site at the Saddle. No change was made for summer deposition amount, since there was no significant difference in summer precipitation amount between D1 and the Saddle site and when the moisture sensor was "on" and "off". We decreased the inorganic N deposition from the NADP reports from October through May of each year by 61%. Annual inorganic N deposition at the Saddle site was then calculated as the measured summer deposition amount added to the adjusted winter deposition. These adjustment factors resulted in a 32% reduction of annual inorganic N in wetfall for the period 1986-1995, from an arithmetic mean of $4.7\,\mathrm{kg\,ha^{-1}\,yr^{-1}}$ to $3.2\,\mathrm{kg\,ha^{-1}\,yr^{-1}}$ (Table 1).

Comparison of the adjusted amount of inorganic N in wetfall to Niwot Ridge to other NADP sites places these results in perspective. The adjusted N wetfall to Niwot Ridge from 1986 to 1995 was about 30% more than the 2.7 kg $ha^{-1}$ $yr^{-1}$ at the 3159 m Loch Vale site in Rocky Mountain National Park, located about 50 km north of Niwot Ridge (Table 2). Both Loch Vale and Niwot Ridge have companion NADP sites in montane locations at lower elevations, Sugarloaf at 2524 m on North Boulder Creek (the same drainage as Niwot Ridge) and Beaver Meadows at 2490 m in Rocky Mountain National Park (Table 2). Inorganic N deposition to Sugarloaf of 2.5 kg $ha^{-1}$ $yr^{-1}$ is similar to that of Loch Vale and about 70% more than the 1.5 kg $ha^{-1}$ $yr^{-1}$ at Beaver Meadows. It does appear that inorganic N in wetfall is greater in the Boulder Creek drainage than in nearby Rocky Mountain National Park.

The uncorrected annual inorganic N deposition of 4.7 kg $ha^{-1}$ $yr^{-1}$ to Niwot Ridge is in-between the 3.7 kg $ha^{-1}$ $yr^{-1}$ reported for Acadia National Park in Maine and the 5.1 kg $ha^{-1}$ $yr^{-1}$ at Hubbard Brook in New Hampshire (Table 2). However, the corrected inorganic N in wetfall to Niwot Ridge of 3.2 kg $ha^{-1}$ $yr^{-1}$ is much lower than both Acadia National Park and Hubbard Brook NADP sites. Inorganic N in wetfall to the Colorado Front Range from 1985 to 1996 ranged from 2.7 kg $ha^{-1}$ $yr^{-1}$ at the Loch Vale watershed in Rocky Mountain National Park to 3.2 kg $ha^{-1}$ $yr^{-1}$ at Niwot Ridge, about half that of montane catchments in the northeastern US such as Acadia National Park and Hubbard Brook. Given that episodic acidification of surface waters is now occurring in the Niwot Ridge drainage [Williams et al., 1996b] and that the Loch Vale watershed in Rocky Mountain National Park appears to be at Stage 2 of N saturation [Williams et al., 1996a], inorganic N in wetfall of about 3.0 kg $ha^{-1}$ $yr^{-1}$ to the Colorado Front Range appears sufficient to cause adverse environmental damage. High-elevation catchments in the western US appear to be sensitive to lower amounts of atmospheric deposition of N than catchments in the eastern US.

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Table 1. Measured and Corrected Annual Wet Deposition of Inorganic Nitrogen to Niwot Ridge NADP Site, 1986-1995

| Year | Measured (kghayr) | Corrected (kghayr) | Percent Change (%) |
|---|---|---|---|
| 1986 | 3.59 | 2.42 | 32 |
| 1987 | 2.34 | 1.62 | 30 |
| 1988 | 2.93 | 1.95 | 33 |
| 1989 | 5.56 | 3.74 | 32 |
| 1990 | 7.46 | 4.95 | 33 |
| 1991 | 4.60 | 3.18 | 30 |
| 1992 | 4.68 | 3.20 | 31 |
| 1993 | 4.85 | 3.28 | 32 |
| 1994 | 4.57 | 3.05 | 33 |
| 1995 | 6.80 | 4.56 | 32 |
| Mean | 4.74 | 3.20 | 32 |

Table 2. Comparison of Annual Inorganic Nitrogen Deposition from Selected NADP Sites, 1986-1995

| Site | State | Elevation (m) | N Deposition ($\mathrm{kg\ ha^{-1}\ yr^{-1}}$) |
|---|---|---|---|
| Niwot Ridge: Measured | CO | 3,520 | 4.7 |
| Niwot Ridge: Corrected | CO | 3,520 | 3.2 |
| Loch Vale, ROMO | CO | 3,159 | 2.7 |
| Sugar Loaf | CO | 2,524 | 2.5 |
| Beaver Meadows, ROMO | CO | 2,490 | 1.5 |
| Acadia National Park | MA | 129 | 3.7 |
| Hubbard Brook | NH | 250 | 5.1 |

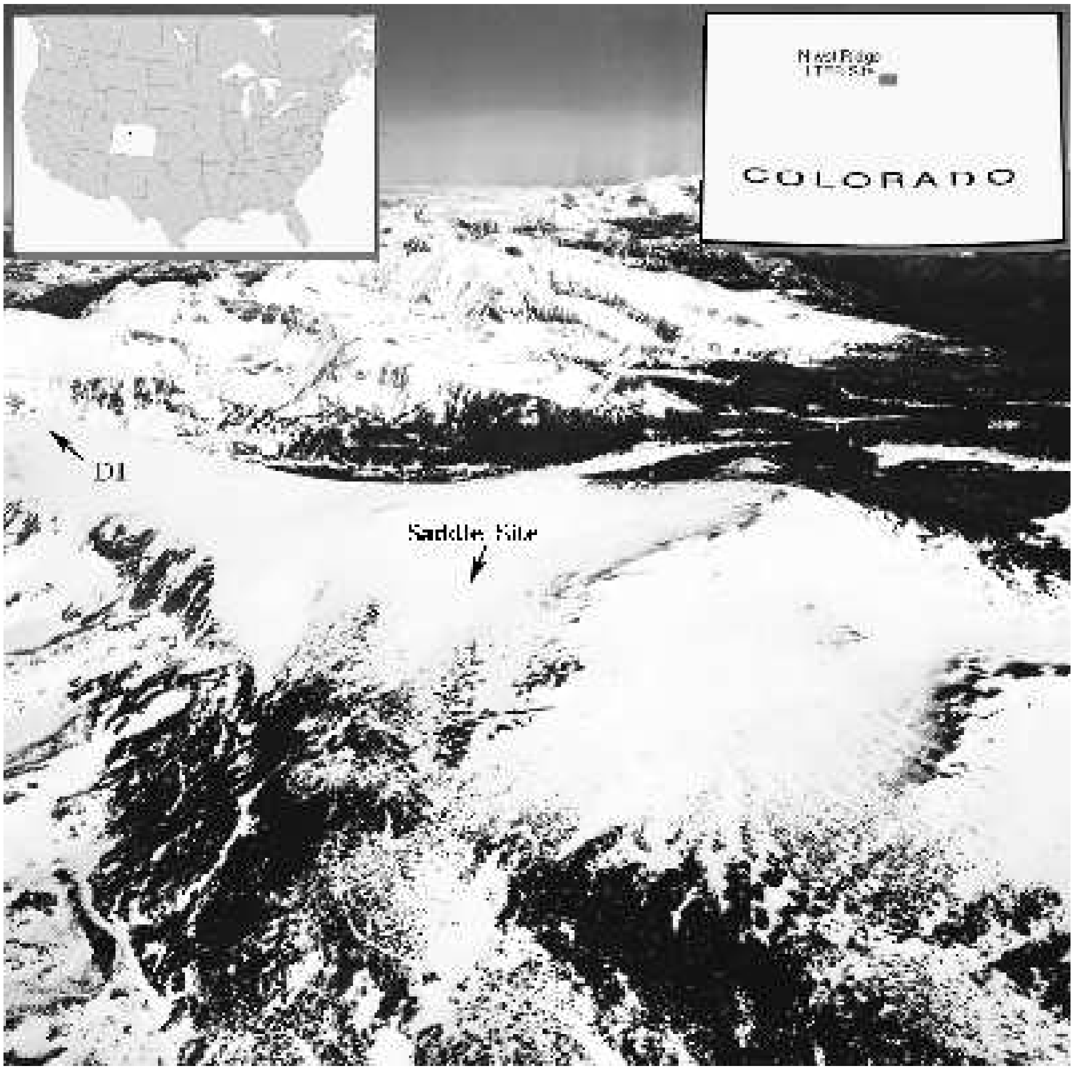
ROMO is Rocky Mountain National Park

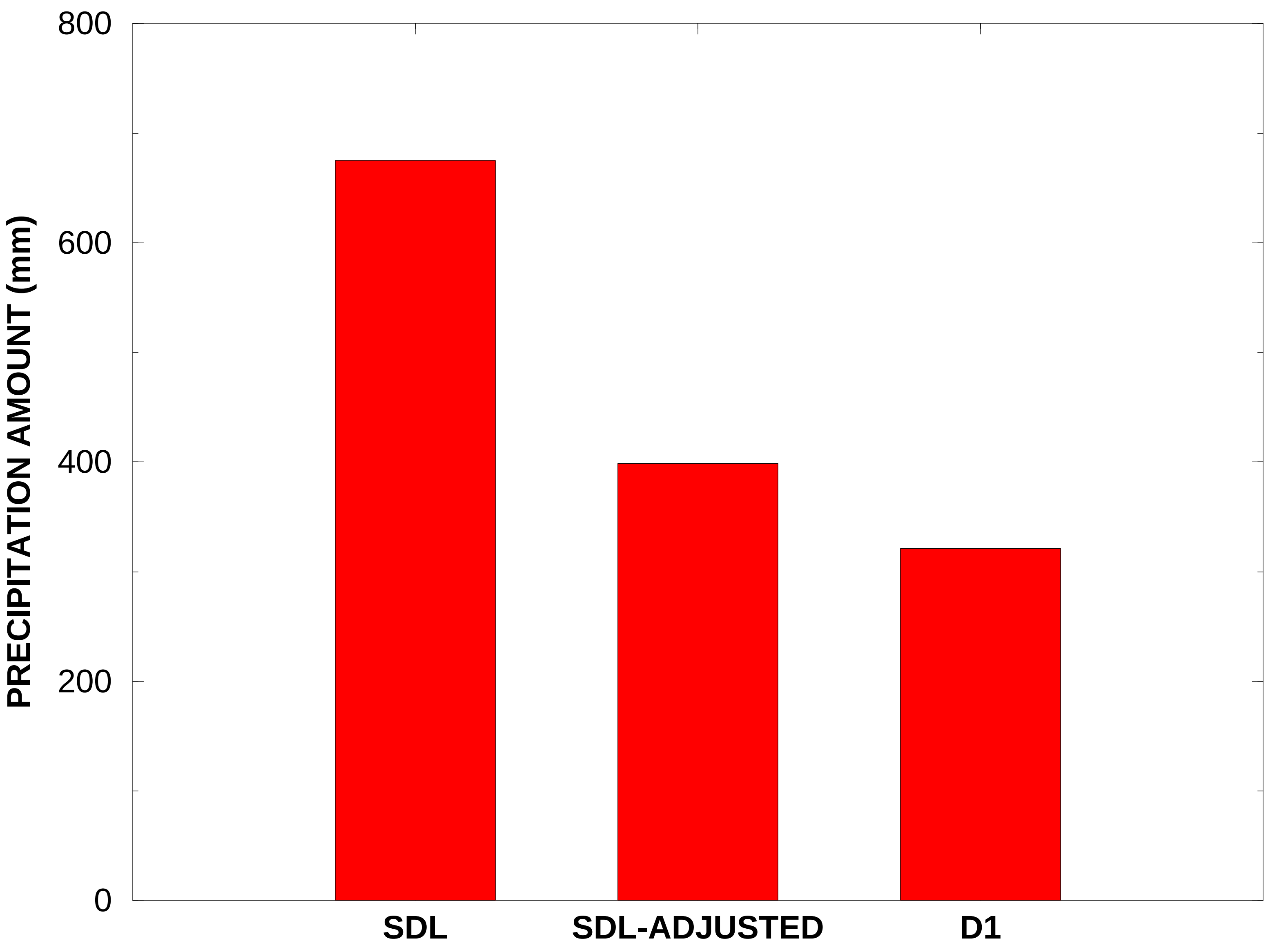
Figure 1. Location of study site and aerial view of Niwot Ridge during the snow-covered season. Precipitation recording gauges were located at D1 (3,749 m) and at the Saddle on Niwot Ridge (3,515 m).

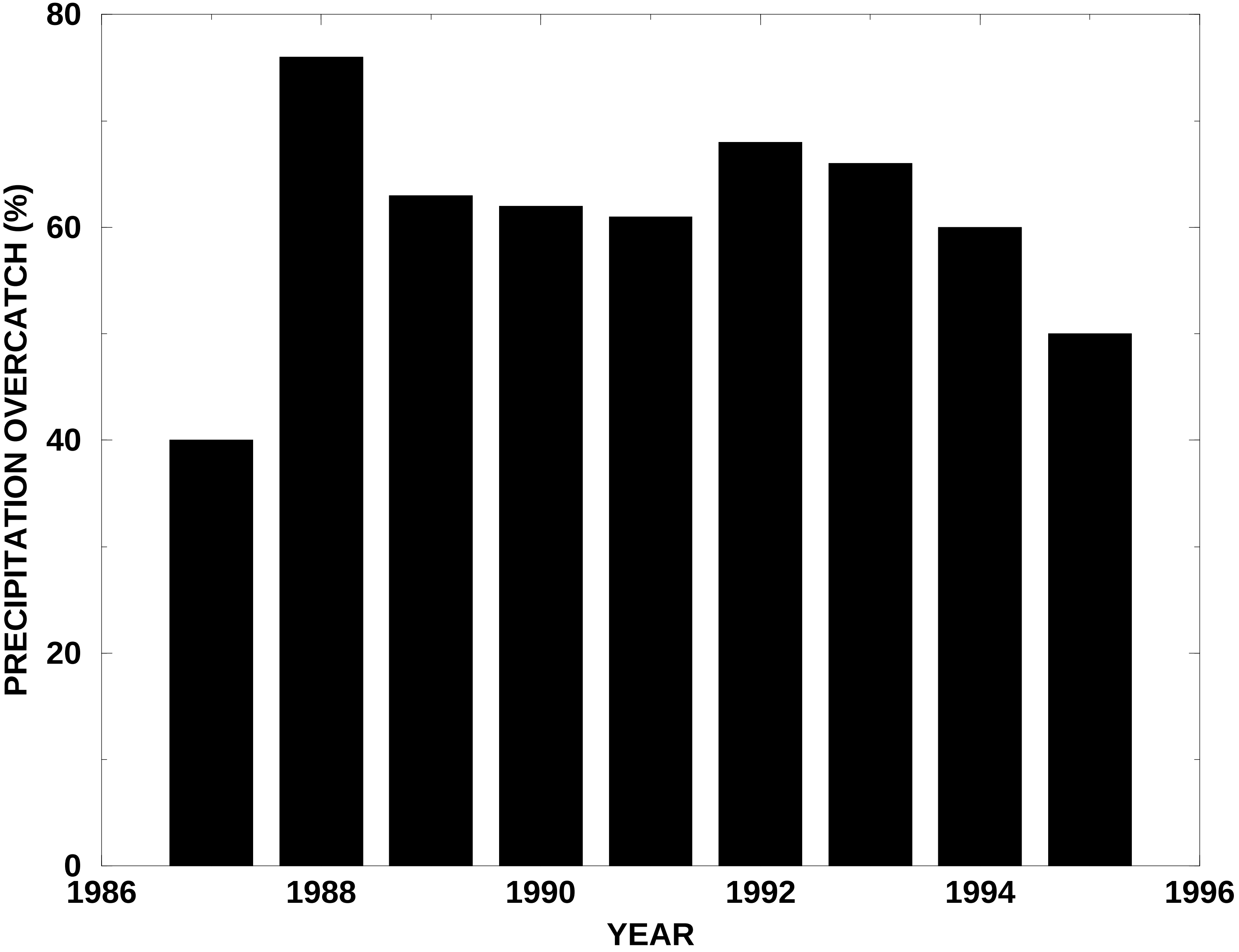
Figure 2. The adjusted January and February 1997 precipitation amounts, with the recorded precipitation amount at the Saddle being 69% greater than the adjusted values. The adjusted precipitation amount at the Saddle site was about 20% greater than the measured precipitation amount over the same time period at D1. Our field validation shows that the moisture sensor on the NADP gauge works surprisingly well.

Figure 3. Overcollection of solid precipitation amount inferred from NADP moisture sensor. About 61% of winter precipitation amount each year from 1987 to 1996 was collected in the Belfort gage when the NADP precipitation sensor was closed, which we interpret as blowing snow events.

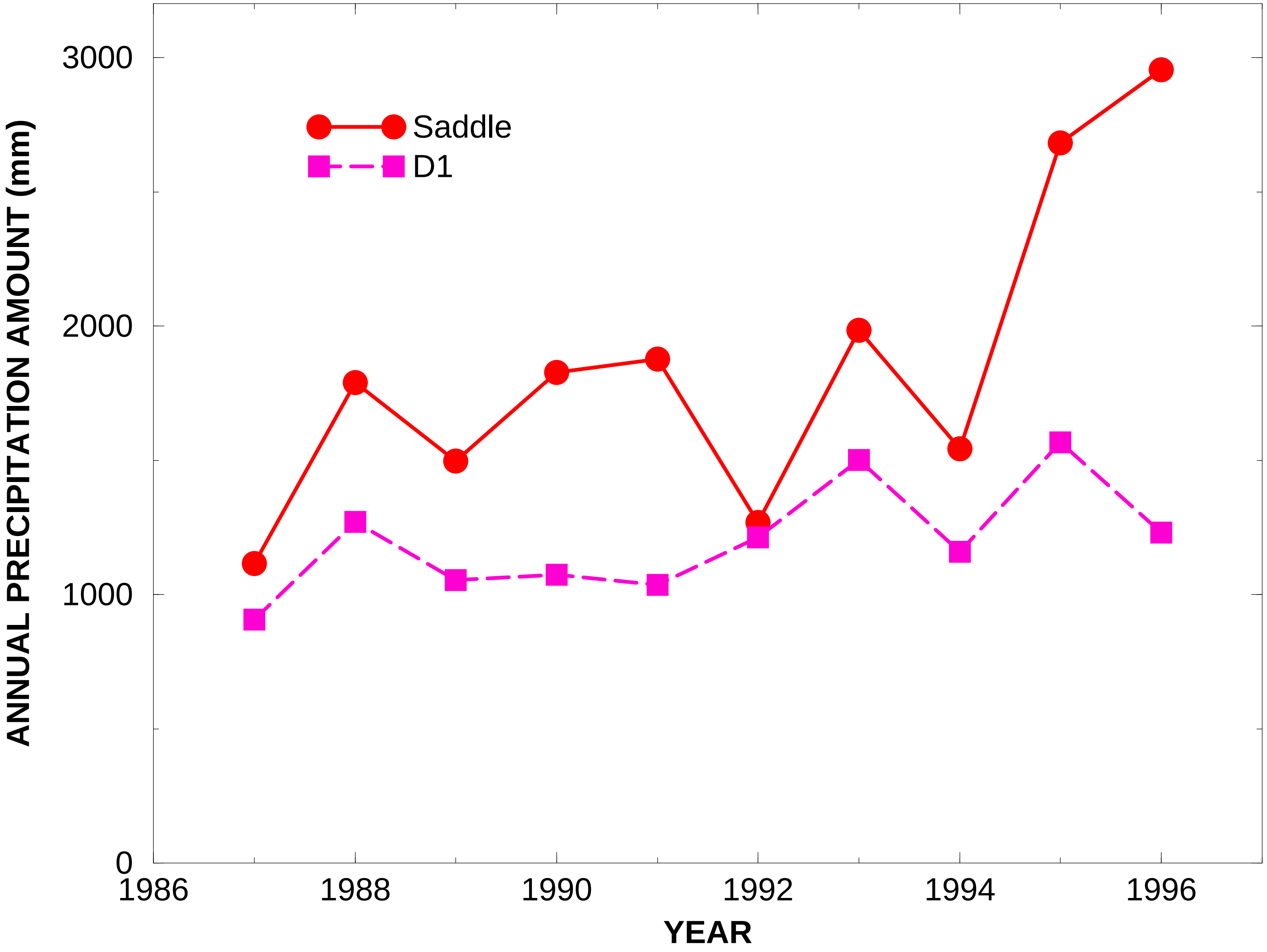
Figure 4. A comparison of annual precipitation totals from 1987 through 1996 show that the average precipitation amount of 1854 mm measured at the Saddle site was 54% greater than the 1200 mm measured at D1.


Niwot Ridge
LTER Site
COLORADO
D1
Saddle Site


800
600
400
200
0
PRECIPITATION AMOUNT (mm)
SDL
SDL-ADJUSTED
D1



80
60
40
20
0
PRECIPITATION OVERCATCH (%)
1986
1988
1990
1992
1994
1996
YEAR



Saddle
D1
ANNUAL PRECIPITATION AMOUNT (mm)
3000
2000
1000
0
1986
1988
1990
1992
1994
1996
YEAR