A scheme to produce high-resolution gridded snowfall estimates over the Conterminous United States

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I. Introduction

For the casual weather consumer served by THE WEATHER CHANNEL®, there is great interest in reports of actual snowfall amounts associated with specific storms, or integrated over longer timescales encompassing an entire winter season or an entire climatological year (see **Figure 1.1** for an example of a monthly snowfall product). Thus, it is desirable to have timely, accurate, frequent, and high-resolution estimates of snowfall for a domain that covers - at minimum - the Conterminous United States (CONUS).

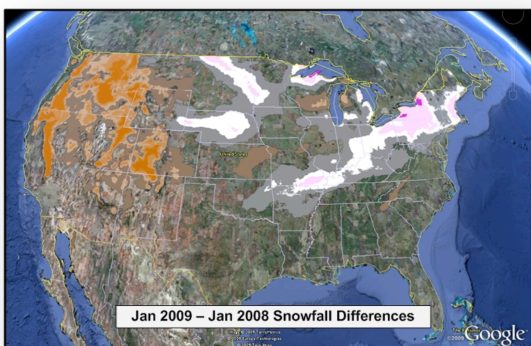

Figure 1.1 – *Monthly snowfall difference between Jan 2009 and Jan 2008. Darkest ochre color is -30" and deepest pink is +30". This gridded dataset used at The Weather Channel is 2.5 km x 2.5km and built from snowfall estimates over the CONUS.*

Unlike rainfall, there is no automated snowfall measurement gauge or instrument in widespread use within the CONUS observation network, so most surface observations of snow accumulation are provided manually by trained NWS employees, cooperative observers, or storm spotters (e.g. see Brazenac, 2005 at: http://ccc.atmos.colostate.edu/pdfs/Brazenec_Thesis_ALL.pdf for a good discussion). These manual reports are often non-standard, may cover different snowfall durations, are often significantly delayed, and may have problems with quality control or consistency. The collection, assimilation, and synthesis of a large domain of near real-time high-resolution snowfall information, based upon this loose confederation of manual snowfall reports, is a very difficult task. We've found such results are typically unsatisfactory when performed on a large scale, or performed without a great deal of human oversight and intervention.

One proposed alternative to building gridded estimates of snowfall from manual reports is to transform the much denser, higher fidelity and more automated total melted precipitation information compiled by NOAA/NWS into equivalent snowfall data. An example of these high-resolution precipitation fields is the so-called Stage IV gridded 24-hour precipitation produced by NOAA's River Forecast Centers (RFC) and mosaicked and published by the Hydrometeorological Prediction Center (HPC) – a department within NCEP. Another alternative starting point is the 1-km by 1-km gridded snowfall precipitation (in melted form) published by the National Operational Hydrologic Remote Sensing Center (NOHRSC) as part of their cryospheric analyses for the CONUS and nearby regions.

The transformation of Stage IV melted precipitation to actual snowfall estimate can be quite involved because Stage IV grids include no information about precipitation type occurring over the 24-hour measurement period. In the case of NOHRSC, precipitation type is inherent in

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the definition of the product - but the actual estimated melted precipitation amounts can be less accurate than those provided by the Stage IV analysis.

In this paper, we describe transformation methods that employ Stage IV and NOHRSC gridded melted precipitation estimates in determining daily, monthly, and seasonal snowfall estimates at high resolution across CONUS (section II). Some operational results are provided and discussed for each approach, and simple comparisons between the two resulting fields are also provided (Section III). We discuss the trade-offs involved with the two methods, and we conclude with a brief discussion of future work needed to refine this synthetic field of snowfall information (Section IV).

II. Methodology

There is research that relates visibility reduction or Runway Visual Range (RVR) to snowfall rates under differing temperature and time of day conditions (Rasmussen et. al., 1999; Seliga et. al. 2006) and there is on-going work to relate instantaneous measures of hydrometeor fall rate or density to snowfall using 1-minute data flowing from an ASOS LEDWI (Wade., 2004 or see: http://www.asr.ucar.edu/2004/RAP/snowfall-freezing.htm). However, these techniques presume collocation with an observing platform that can measure quantities like horizontal visibility or precipitation rate.

Snowfall estimation that is spatially continuous or independent of the network of surface observations is possible using the network of NWS WSR 88-D radars from Z-s relationships, but the results are not very precise or spatially consistent. Satellite imagery can be used to deduce areas of snowfall, and can be helpful in determining rough estimates of snowfall amount, especially in mountainous terrain but the results are crude and miss most light intensity snowfall events (e.g. Mejia, 2007).

IIa. NOHRSC fields

NOHRSC is an excellent source of high-resolution snow and ice data (e.g. Carroll et. al., 2001 or http://www.nohrsc.noaa.gov/technology/pdf/NOAAs_National_Snow_Analyses.pdf) and does provide a timely grid of 1-km by 1-km snowfall data. This takes the form of a quantity termed melted snowfall precipitation. That is, a 24-hour fraction of the melted precipitation that is presumed to fall as snow or ice in inches or centimeters.

For the NOHRSC melted snowfall quantity to be converted to 24-hour snowfall, a bulk snow-to-meltwater ratio (more briefly: *bulk snow ratio*) must be determined that reliably takes into account all temporal variations in snow ratio occurring over the time interval in which snowfall occurs. And to determine this bulk snow ratio, a good representative sample of instantaneous snow-to-meltwater ratios (more briefly: *snow ratios*) must be calculated over the same 24-hour period.

To compute our own snow ratios at high resolution, we employed an estimation of snow ratio using a blend of column and surface-based methods applied against the 13 km hourly RUC model output supplied by NCEP (Benjamin et. al. 2004). The column method is based on an approach proposed by Cobb and Waldstreicher (2005). The surface method is driven principally by screen temperature. The blended ratio is collapsed into a single bulk snow ratio for each point that is representative of the entire time period (24 hours). We take care to ensure that only valid snow ratio results are used in the aggregation so there is every attempt to produce an unbiased representation of the period.

The column method snow ratio, r_{col} , for each point in the model grid is calculated by estimating a ratio at each pressure level p and blending these using the upward vertical velocity, $\omega[p]$, at each level. We use a version of Cobb and Waldstreicher's spline curve to derive an empirical ratio, $r_{\lambda}(T)$, as a function of the temperature, $T[p]$, at each level. We adjust $\omega[p]$ at non-freezing or dry pressure levels, and then blend these ratios based on the relative $\omega[p]$ values. Pressure levels with larger upward motions exert greater influence on the overall magnitude of the snow ratio. Conversely, layers of small or downward motion contribute little towards the total snow-to-meltwater ratio.

Some points have total atmospheric columns that are dry or exhibit no rising motion (i.e., have few or no pressure levels capable of producing ice or dendrites). To avoid calculating misleading column ratios for these points, we calculate an alternative snow ratio based on the critical thickness or heat content of the air near the surface. Thus, if a given column lacks sufficient ice producing levels, we compute a suitable blend of surface and column-based ratios to generate a final snow ratio for that point. When the atmosphere is cold enough, the column-based method makes up most of the final answer. If conditions are marginal for producing snowfall through the depth of the atmospheric column, the final ratio will be largely a function of near-surface temperature. If the solution lies between these two regimes, the two methods are blended in a sensible manner.

The surface method snow ratio, r_{sfc} , is based on a logistic curve (here, a sigmoid) that is a function of the 2-meter temperature and tuning parameters. The idea is to create a smooth (differentiable) curve that has a relatively constant value at low temperatures and transitions to near unity around the freezing point (surface temperature in °F):

$$r_{sfc} = r_{ref}\left(1 - \frac{a}{a + e^{-x}}\right). \qquad \textbf{Eq. 2.1}$$

Here, r_{ref} is an upper threshold value of snow ratio when temperatures are very cold, a is a tuning parameter determined from experimentation and x is a function that is dependent on the surface temperature. **Figure 2.1** shows the trace of snow ratio versus surface temperature when r_{ref} is 30, a is 2, and $x = (T_{2m} - 30) / 8$.

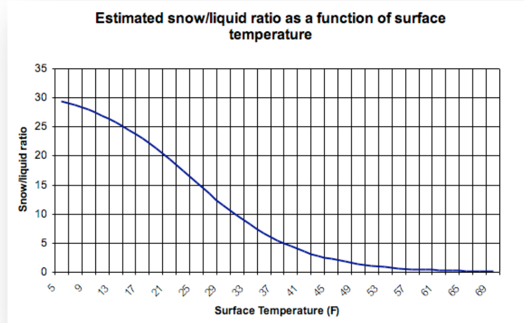

Figure 2.1 – *A sigmoid function that represents snow to meltwater ratio versus surface temperature (i.e. snow ratio versus T_{2m}).*

When the atmosphere is cold enough and r_{col} is valid (calculable from layer inputs), we want this column-based method for determining snow ratio to dominate over r_{sfc}. Otherwise, we want r_{sfc} to take on the larger weight. In either case, a smooth blending between the two regimes is desirable, so we again use sigmoid functions to generate this transition.

The final snow ratio is then a weighted average of r_{col} and r_{sfc}:

$$r_{final} = w_{col} r_{col} + (1 - w_{col}) r_{sfc}, \qquad \textbf{Eq. 2.2}$$

where w refers to weights and r refers to snow ratios. The estimated snowfall field for any particular day represents the integrated snow precipitation over some time period (typically 24 hours). However, the weighted snow ratio described above is valid for a single instantaneous point in time. There remains the task of transforming a series of instantaneous snow ratios into a single representative or bulk value that will act as a suitable proxy for the entire period in question.

To accomplish this, we sample the RUC model atmospheric column at several time steps over the 24-hour period and calculate the snow ratio grid for each step. The simplest approach would be to average all of these sampled ratios into a single result. However, this approach does not work well when the 24-hour period includes a variety of precipitation types and/or widely variable precipitation rates.

It is difficult to account for simultaneously varying precipitation rates and snow ratios, but we can at least mitigate the effect of changing precipitation type over time. In the following examples, we assume that sampling occurs every 6 hours, resulting in 4 values for each point for the 24-hour estimation period.

1. *Some snow, some mix or rain*

In this example, 2 periods have a 10:1 ratio with 0.1” precipitation each and 2 periods have rain (assume the surface method calculates a 0.1:1 ratio) with 0.1” precipitation each. This should result in 2” of snowfall and 0.4” total precipitation (0.2” snow precipitation).

a. If we average the ratios for all 4 periods, we get a ~5:1 bulk snow ratio. This would result in an estimated snowfall of 5:1 * 0.2” snow precipitation = 1” snowfall. (INCORRECT)

b. If we average the ratios only for periods that we deem to have valid ratios, we get a 10:1 bulk ratio. This would result in an estimated snowfall of 10:1 * 0.2” snow precipitation = 2” snowfall. (CORRECT) This also shows why it is necessary to use snow precipitation and not total precipitation.

2. *Varying snowfall rates and ratios*

In this example, 3 periods have a 10:1 snow ratio with 0.1” precipitation each and the last has a ratio of 25:1 with 0.2” precipitation. This should result in 8” of snowfall and 0.5” snow precipitation.

a. If we average the ratios for all 4 periods, we get a ~14:1 bulk ratio. This would result in an estimated snowfall of 14:1 * 0.5” snow precipitation = 7” snowfall. This is not exactly correct, but is relatively close and probably within the margin of error for our method.

A good approach, therefore, appears to be averaging only those snow ratios where snowfall or solid precipitation is indicated (a precipitation typing scheme not discussed herein, ultimately determines time steps that include snowfall). A hard cutoff for snow ratios versus non-snow ratios is not used (e.g., only ratios greater than some threshold value are valid) since this can produce sharp discontinuities in the two-dimensional field. Instead, we employ a continuous blending function to calculate weights for each ratio and create a weighted average for the final bulk snow ratio.

IIb. NCEP Stage IV fields

Another source of very high-resolution precipitation data is NWS/NCEP Stage IV or the Multi-sensor 24-hour quantitative precipitation estimate (QPE) mosaic that is jointly produced by the National Weather Services’s WFOs, River Forecast Centers, and NCEP (Fulton, 2002 at: http://www.nws.noaa.gov/oh/hrl/presentations/amsshortcourse/qpe_nws_overview.pdf is a good overview). The data itself is derived from radar, surface gauge, satellite, and human-based sources and is closely monitored and quality-controlled. However, for the purposes of snowfall estimation there is no information about precipitation state or type. Thus, it is not possible to directly partition the QPE of Stage IV into frozen and unfrozen parts.

As a result we developed a method to use the high resolution Stage IV analysis as the basis or main input in an estimation of snowfall for the CONUS. To accomplish this it is necessary:

1. at some arbitrary point or grid intersection, to determine the portion of the Stage IV liquid equivalent precipitation that fell as snow, and

2. determine a suitable bulk snow-to-meltwater ratio of that fraction of the total precipitation that fell as snow.

Since Stage IV contains no information related to precipitation type, it is crucial to find an independent source of data that exhibits some fidelity with Stage IV liquid precipitation and also contains information about that part of the total precipitation that fell as snow. This data source should provide information about precipitation type at regular intervals (i.e. 1 km by 1 km spatial resolution and hourly temporal resolution) throughout the Stage IV integration period, and more importantly it should provide precipitation amount information at this same spatial and hourly resolution. Armed with information about the evolution of the precipitation type and precipitation amount for the period, we can then calculate a proxy for the fraction or ratio of snow precipitation to total (snow and non-snow) precipitation that makes up the Stage IV amount.

We used the 13-km RUC model as the proxy for precipitation type and rate during the Stage IV measurement period. The novel part of this method (and also the most crucial assumption) is the process of directly relating the fraction of melted snow precipitation to total precipitation from the independent method (RUC) to the Stage IV analysis.

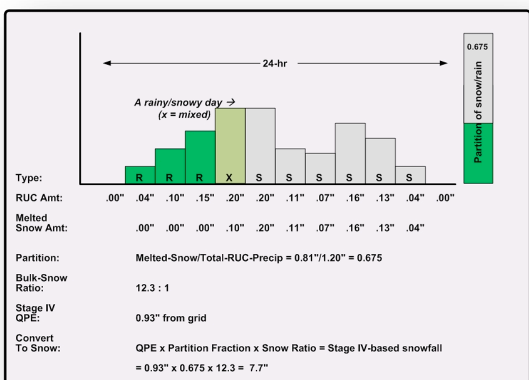

Figure 2.2 – *A schematic representation of the Stage-IV based estimation of snowfall using knowledge of RUC +1 hour forecast QPF and RUC-based derived precipitation types as they might evolve in a complex weather scenario. The bookkeeping shown here is explained in section IIb.*

To provide an example of this approach we refer to **Figure 2.2**. In **Figure 2.2**, we determined that 12 of the 24 hours during the example period had a precipitation type of snow. Two had a type of mix, and the remaining hours had rain or an undetermined precipitation type.

The total liquid equivalent precipitation, according to RUC 1 hour forecasts for the 24-hour period was 1.20”. This was calculated by summing each of the twelve two hour liquid equivalent amounts:

.00 + .04 + .10 + .15 + .20 + .20 + .11 + .07 + .16 + .13 + .04 + 0 = 1.20”

We then calculate the snowfall liquid equivalent by summing the two hour liquid equivalent amounts during which the calculated precipitation type is snow:

.10 + .20 + .11 + .07 + .16 + .13 + .05 + 0 = .81”

Next we calculate the fraction of liquid equivalent precipitation that fell as snow:

Melted snow/Total RUC liquid equivalent = 0.81”/1.2” = .675

Using the methods described section IIa, we also calculate a bulk snow ratio, determined to be 12.3:1 for this time period (not depicted in **Figure 2.1**).

The Stage IV precipitation for the point in question is extracted from the high-resolution grid using standard methods and is found to be 0.93”.

Given the Stage IV precipitation estimate, the fraction of snow to rain derived from the RUC model solutions, and the RUC-based bulk snow ratio - we can now calculate a total snowfall estimate based on the Stage IV data:

.93” * .675 * 12.3 = 7.7” of snowfall in the 24-hour period.

There will certainly be many cases where the RUC’s total precipitation disagrees with the Stage IV total precipitation, but this is of minor importance as long as the fraction or ratio of snow precipitation to liquid precipitation from the RUC for the Stage IV measurement period exhibit agreement. We have found that, in fact, this is often the case and the method appears to perform well. One reason is that only very short-term "slices" of the RUC forecast are used and these +1 hour forecasts tend to track well against ground truth - especially in wintertime scenarios where synoptic scale forcing dominates the flow, and stratiform precipitation systems contribute much of the total snowfall experienced in the CONUS.

III. Discussion of results

We collected estimated monthly snowfall totals for the winters of 2007-2008 and 2008-2009. For our purposes, we defined winter as the five months spanning November through March. Section IIIa presents two analyses of winter season monthly snowfall estimates at 25 first-order reporting stations where manual or hand-measured snowfall reports take place (see ICAO list in **figures 3.1** and **3.2**). We excluded all cases where observed snowfall is missing to avoid any dry bias in the analysis.

Snowfall estimates in these analyses are derived from the NOHRSC and Stage IV-based methods described in section II and then compared to the monthly observations. For the NOHRSC-based method, we recorded data that spans two winter seasons. The Stage IV-based method was created and tested in the second half of the winter 2008-2009 season, so there is a much shorter track record for this approach. In both cases, we employ a unitless bias statistic to indicate the fidelity of the estimation:

(Estimated snowfall) / (Observed Snowfall) - 1.0 .

If the bias has a value of 0.0 it is unbiased; positive values represent an overestimate of snowfall, and negative values an underestimate.

The appendix includes four tables of data used in the analyses. These include:

1. Daily Climo or F-6 observations labeled as "F-6 Observations" - The observations of monthly snowfall for winter 2007-2008 and winter 2008-2009 for the 25 stations.

2. Table labeled "NOHRSC" - the NOHRSC method monthly snowfall for winter 2007-2008 and winter 2008-2009 for each station.

3. Table labeled "DIFFERENCE" - the NOHRSC error, that is, (NOHRSC – F-6 observation).

4. Table labeled "NOHRSC/F-6" – the ratio of NOHRSC data to F-6 data -This is the bias of the NOHRSC data.

IIIa. NOHRSC method results

Figure 3.1 snows monthly snowfall bias for all stations by month for each of the past two winter seasons.

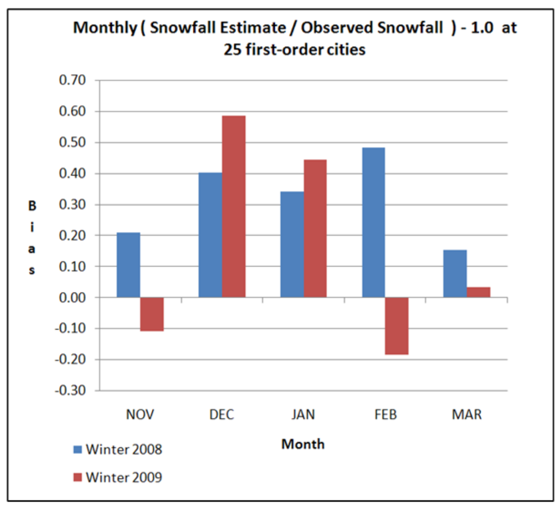

Figure 3.1 – *A calculation of NOHRSC method bias by month for both the winter of 2007-2008 and winter of 2008-2009.*

Figure 3.2 shows biases for individual stations for the two full winter seasons. The NOHRSC-based method tends to overestimate snowfall amount, when compared with observed snowfall. Overall, we found a bias of +.36 for winter 2007-2008, and a bias of +.31 for the winter 2008-2009. In other words, the NOHRSC-based method overestimated the seasonal snowfall total for the 25 study sites by about one-third.

The analysis reinforces several anecdotal characteristics of the NOHRSC data that we have observed over the course of the past two winter seasons. The overestimate or bias in the NOHRSC-based method is most pronounced during December, January and February. The overestimate is significantly less during the transitional months of November and March. For these past two seasons we've found:

1. The NOHRSC field of melted snowfall is generally overestimated. This may be a result of a general overestimate of all precipitation types, but we have not studied this part of the error. So we only conclude that the specific field of melted snowfall precipitation is overestimated.

2. This same field of NOHRSC melted snowfall precipitation tends to miss out on events with marginal surface temperatures. Significant snowfalls with surface temperatures at or above freezing are underrepresented in the NOHRSC grids.

3. Complex precipitation events with large portions of sleet or freezing rain tend to get counted as snowfall precipitation. This works well for the purposes of tracking water content of the snow and ice field, but is troublesome for estimating snowfall since discriminating ice events from snow events is critical for such consumer-based applications.

The NOHRSC method shows good skill and lower bias in some cases. For example, the NOHRSC method performed well at KCLE during winter 2008-2009 and in both years at KDSM. However, the NOHRSC-based method is very much inflated at KHTL, KOMA, and KPHL in both years, and this is attributable to a systematic bias or overestimation of snowfall in almost all individual events – especially those occurring in the coldest part of the season.

IIIb. NOHRSC vs. Stage IV method case study

It is quite possible that some of the tendency for the NOHRSC-based method to overestimate snowfall is attributed to the bulk snow ratio calculation. However, the bulk snow ratio calculation is unchanged in the newer Stage IV-based method and

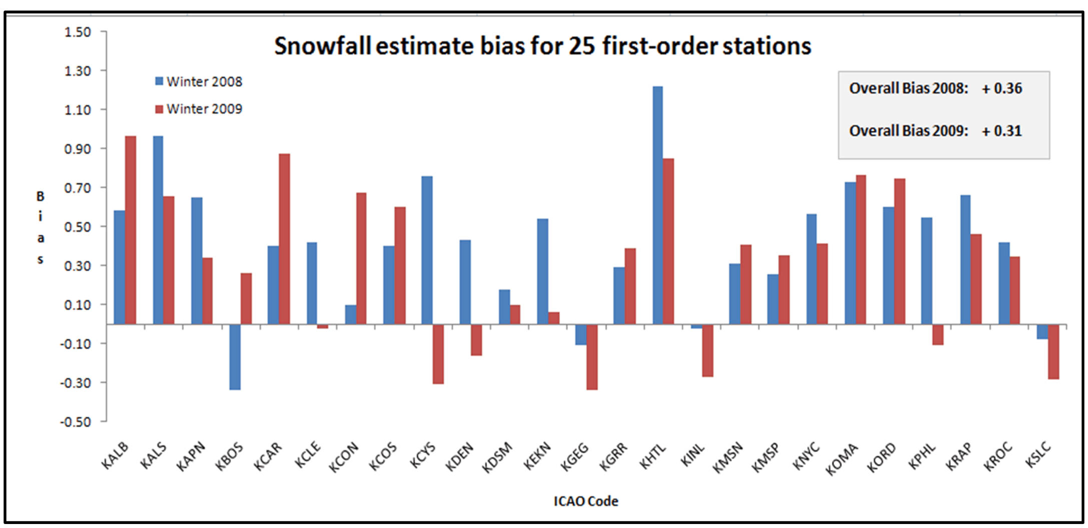

Figure 3.2 *–A calculation of NOHRSC method bias by METAR station for both the winter of 2007-2008 and winter of 2008-2009.*

we've yet to observe any notable bias in these results.

Below we present an individual event that compares the NOHRSC-based method to the newer Stage IV-based method (**Table 3.1**). In this case study, we used both methods to estimate snowfall amounts during a winter storm that affected the Great Lakes and Northeastern areas of the United States from January 9, 2009 through January 11, 2000. The event was mainly a snow producer north of about 42^0N latitude. Most locations in the study received all snow from the event. More southerly locations such as KIPT, KABE, KRDG and KSEG did experience considerable mixing with sleet and/or freezing rain. As in the previous study, we used the National Weather Service F-6 data for ground truth.

The NOHRSC-based method again shows a distinct tendency to overestimate snowfall amounts at most locations, while the Stage IV-based method shows more fidelity. The NOHRSC and Stage IV-based methods use identical bulk snow ratio values for this study, but the NOHRSC-based method produces substantial overestimate exceeding 65%. The Stage IV method bias is much lower, averaging only about 10%.

IV. Summary

The results of the new Stage IV-based method are promising. In general, we believe that the very high-resolution NOHRSC gridded data (at http://www.nohrsc.noaa.gov/) is of high quality, but the strength of this dataset lies in hydrologic analysis and prediction of the water content of the snow and ice pack that evolves over a winter season and is less so for instantaneous measures of snowfall for individual events. Our new method, employing the Stage IV data, exhibits low biases and low absolute errors for a limited number of cases in the latter half of the 2008-2009 winter. We will use the new Stage IV method in operations in the coming winter season, and we hope to see good results that ultimately withstand the test of time.

ICAO Code	Stage IV Method	NOHRSC method	Ground Truth (F-6)	Stage IV Difference	Stage IV Bias	NOHRSC Difference	NOHRSC Bias
KALB	8.6”	6.7”	6.7”	1.9”	0.3	0.0”	0.0
KUNV	5.5	6.6	4.7	0.8	0.2	1.9	0.4
KIPT	6.5	9.4	5.1	1.4	0.3	4.3	0.8
KABE	3.0	3.5	2.6	0.4	0.2	0.9	0.3
KRDG	1.7	5.2	1.0	0.7	0.7	4.2	4.2
KMPO	3.4	8.0	4.0	-0.6	-0.2	4.0	1.0
KSEG	3.8	6.7	3.2	0.6	0.2	3.5	1.1
KBGM	6.0	7.2	6.1	-0.1	0.0	1.1	0.2
KELM	4.4	8.4	5.5	-1.1	-0.2	2.9	0.5
KBUF	4.4	9.0	4.9	-0.5	-0.1	4.1	0.8
KART	3.8	8.6	3.0	0.8	0.3	5.6	1.9
KROC	8.0	10.1	8.0	0.0	0.0	2.1	0.3
KCAK	10.0	8.0	6.7	3.3	0.5	1.3	0.2
KCLE	9.6	8.9	10.8	-1.2	-0.1	-1.9	-0.2
KTOL	8.9	11.6	11.9	-3.0	-0.3	-0.3	0.0
KMFD	10.2	6.6	9.9	0.3	0.0	-3.3	-0.3
KERI	4.8	10.1	6.2	-1.4	-0.2	3.9	0.6
KYNG	13.5	10.0	12.8	0.7	0.1	-2.8	-0.2
				Average:	**0.1**	**Average:**	**0.6**

Table 3.1 – *A case study examining NOHRSC and Stage IV method bias by station for a snowfall event in the Northeastern United States during the period January 9, 2009 to January 11, 2009. Units are in inches of snowfall.*

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