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Performance of the NOAA USCRN Weighing-bucket Precipitation Gauges during the Heavy Snow-storm Event of December 5-8, 2003

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1. *Introduction*

This technical note examines the performance of the weighing-bucket gauges at seven USCRN stations during the course of the heavy New England snow event of December 5-8, 2003. The storm presented a case study for examining the performance of the USCRN precipitation measurements not only because it was a significant snowfall event accompanied by strong winds, but also because the USCRN stations in its path had some interesting characteristics. It also provided an opportunity for other researchers to undertake some initial network intercomparisons in terms of precipitation catch efficiency.

In the early stage of this snow event, the western edge of the storm passed over Elkins, WV, where a USCRN site is equipped with independent wind and solar power systems. The storm then passed over twin sites in Rhode Island, which are less than one mile apart. Next in the path of the storm were two sites in New Hampshire. One of the New Hampshire sites was not equipped with the standard wind shield configuration that marks the rest of the USCRN network. As the storm intensified on its northeasterly route, it brought heavy snowfall to Old Town, ME, but a much lesser amount to the Limestone, ME, USCRN station, which is further from the ocean. See Table 1 for a listing of the USCRN stations and relevant information.

Station Name	Elev	Lat	Long	Alias
Durham 2 N, NH	163'	43.17	70.93	Kingman
Durham 2 SSW, NH	105'	43.11	70.95	Thompson
Elkins 21 ENE, WV	3410'	39.01	79.47	Canaan Valley
Kingston 1 NW, RI	140'	41.49	71.54	Plains Road
Kingston 1 W, RI	124'	41.48	71.54	Peckham Farm
Limestone 4 NNW, ME	775'	46.96	67.88	Aroostook
Old Town 2 W, ME	167'	44.93	68.70	Rogers Farm

Table 1 USCRN Station locations included in this study listed by name (location and local alias name).

2. *Storm Summary*

The first major snowstorm of the 2003-2004 winter season moved into West Virginia on Friday, December 5th. The storm hit much of New England late Saturday with heavy snow, strong coastal winds and blizzard conditions. For many areas south of the Massachusetts Turnpike, this was a 40 to 48-hour snowstorm, while in Southern New Hampshire the duration was 30 to 38 hours. Wind gusts over 40 mph were quite common. By 0800 EST Monday December 8, 2003, the storm had moved offshore, as the Surface Weather Maps of 0700 EST December 5-8 in Figure 1 show.[1]

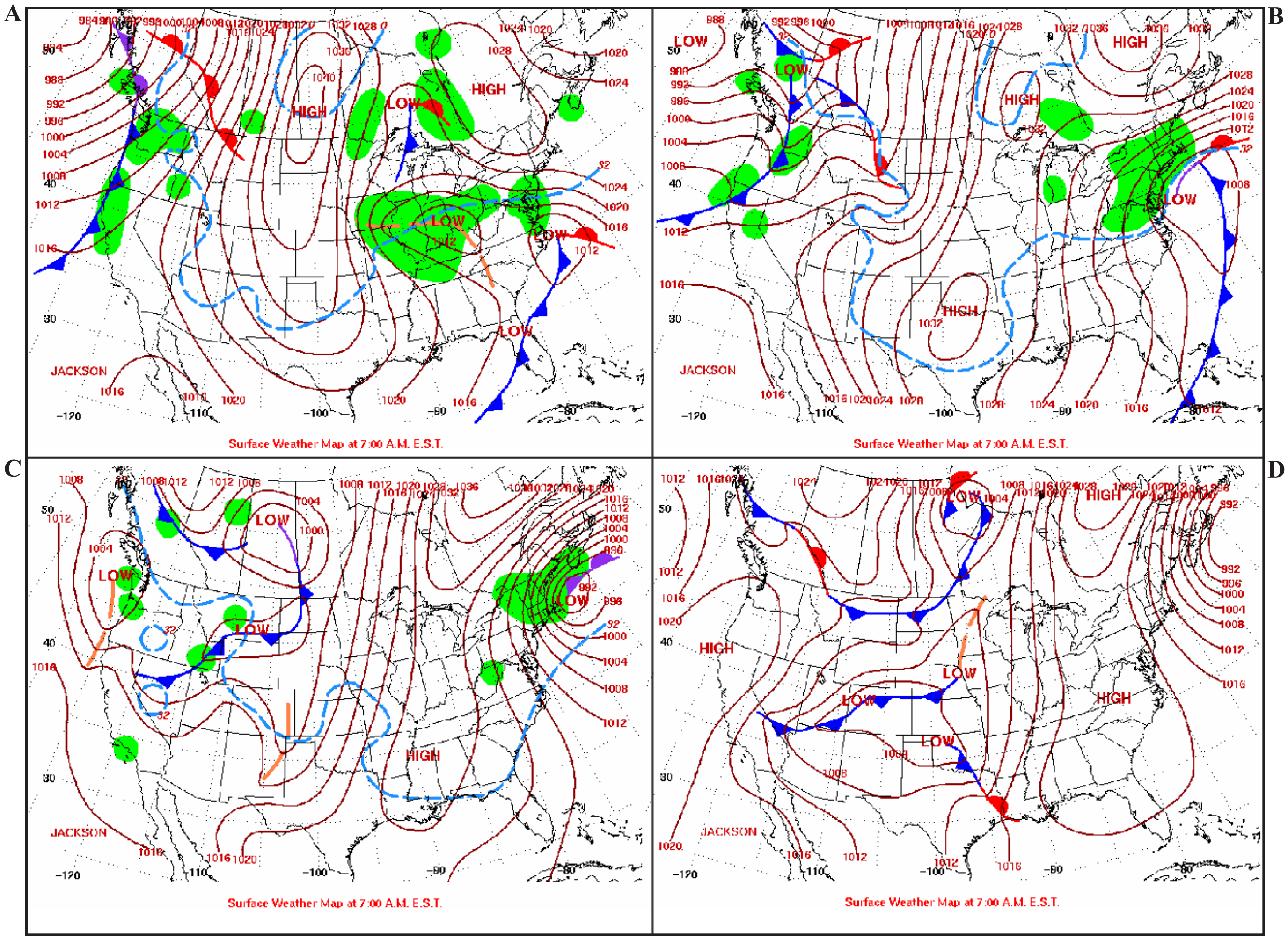

Figure 1 Surface Weather Maps valid 7 am EST on Dec. 5 (A), Dec. 6 (B), Dec. 7 (C), and Dec. 8 (D), 2003.

The National Weather Service (NWS) North East River Forecast Center (NERFC) provided contour

[1] Public information Statement, National Weather Service, Taunton MA and Gray ME accessed from website http://www.erh.noaa.gov/er/box/fcsts

plots of snowfall and precipitation for the storm event, 0800 December 5 through 0800 December 8 LST. These contour plots were produced from NWS cooperative weather stations' reports and data from other reporting networks available to the NWS.

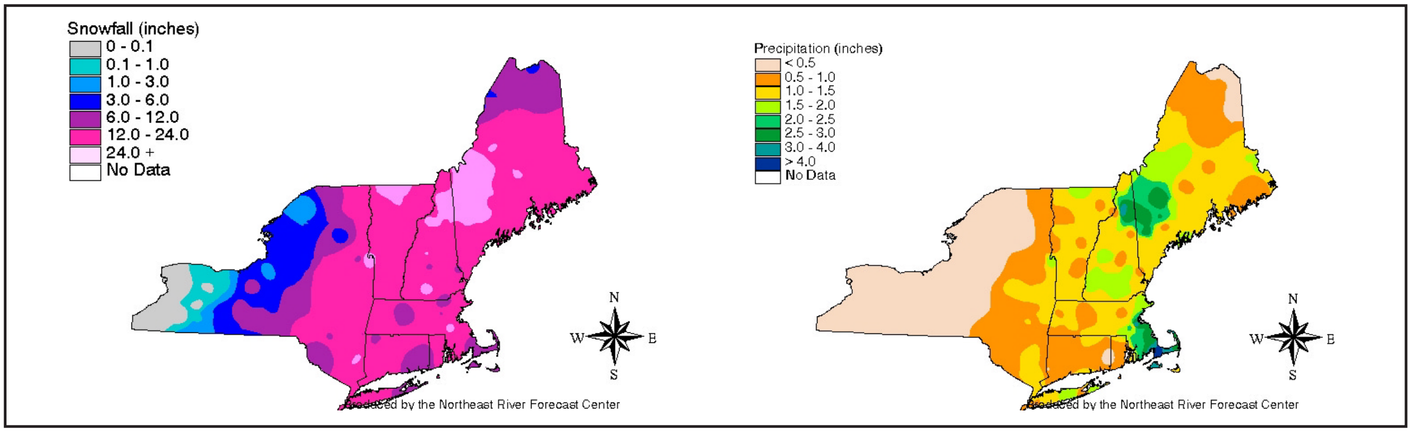

Figure 2 Snowfall and precipitation contour plots for the storm event 0800 December 5 through 0800 December 8 LST, 2003.

3. General Performance of the Seven USCRN Stations

All USCRN station sensors functioned optimally throughout the storm and reported all meteorological parameters and other diagnostic data. Data transmission also functioned flawlessly. The USCRN website's Time of Receipt Report [2] indicated that 100% of the stations reported all observations within an hour.

Figure 3 indicates schematically the precipitation periods for the seven USCRN stations beneath the cloud shield of the storm starting with Elkins, WV, and moving northeastward to Limestone, ME. The storm lasted about 41 hours at Elkins and 27 hours at Limestone. It snowed continuously at Kingston, RI, and Limestone, but there were breaks in the snowfall at the other sites.

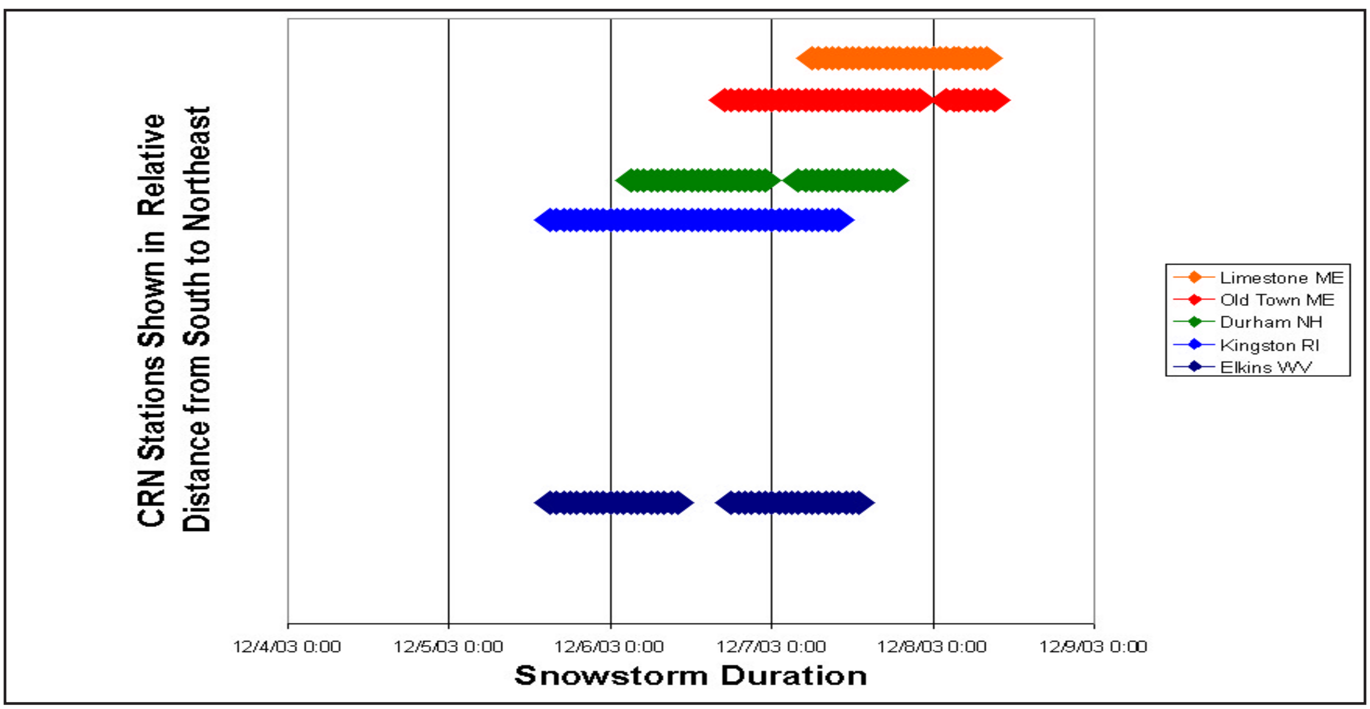

Figure 3 Relative locations of USCRN sites in path of storm with indication of beginning and end times of precipitation.

[2] Time of Receipt runs dynamically from <http://www.ncdc.noaa.gov/servlets/USCRNreport>

4. Performance of Elkins, WV, and Limestone, ME, Sites

Hourly total precipitation and cumulative precipitation amounts for both the Elkins, WV, and Limestone, ME, USCRN stations are plotted below in Figure 4 for the entire storm duration, from 0800 LST December 5 through 0800 LST December 8, 2003.

The snow at Elkins had mostly ceased by the time it began at Limestone. Interestingly, both Elkins and Limestone recorded approximately the same amount of precipitation. The nature of the snowstorm at each location was different, however, with long-duration light snowfall at Elkins and short-duration moderate snowfall at Limestone. All other figures with hourly precipitation are plotted on the same scale, unless indicated otherwise.

The station at Elkins was installed with independent wind and solar power. Though the station operated flawlessly during the storm, it failed a few days later after a long period of cloudiness prevented adequate recharging of its batteries. Incidentally it was found that the wind speed was insufficient for wind power backup at the site. Both of these deficiencies have been addressed and the knowledge gained will inform future system deployments of USCRN stations in similar severe mountain environments.

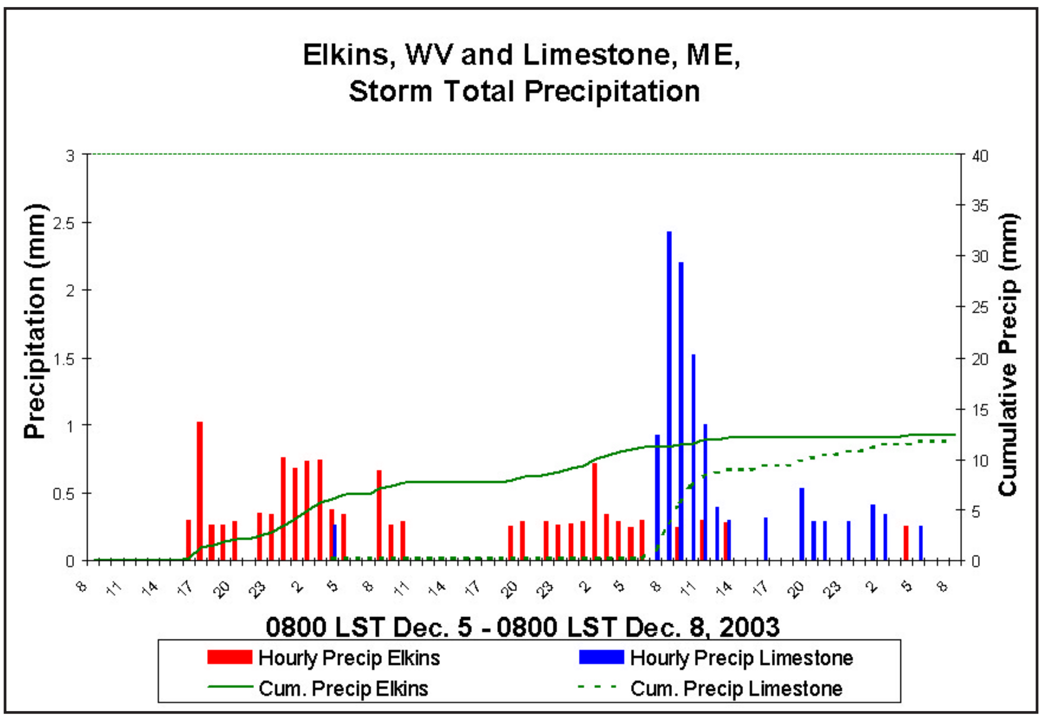

Figure 4 Hourly and cumulative precipitation for Elkins WV and Limestone ME for the snowstorm period 5-8 December, 2003.

5. Performance of the Kingston, RI, Paired Sites

Hourly precipitation values for Kingston 1NW reported from each of the three vibrating wire sensor transducers in the weighing-bucket precipitation gauge during the storm are plotted below in Figure 5. Also displayed is the cumulative hourly precipitation (mass curve) for the same period. Total precipitation measured for the storm period was about 37mm. Vibrating wires VW-1, VW-2 and VW-3 recorded storm totals of 36.6, 37.3, and 36.7 mm, respectively. This variance within the three transducers is within the acceptable range established by USCRN data quality guidelines to maintain a high-confidence official precipitation measurement.

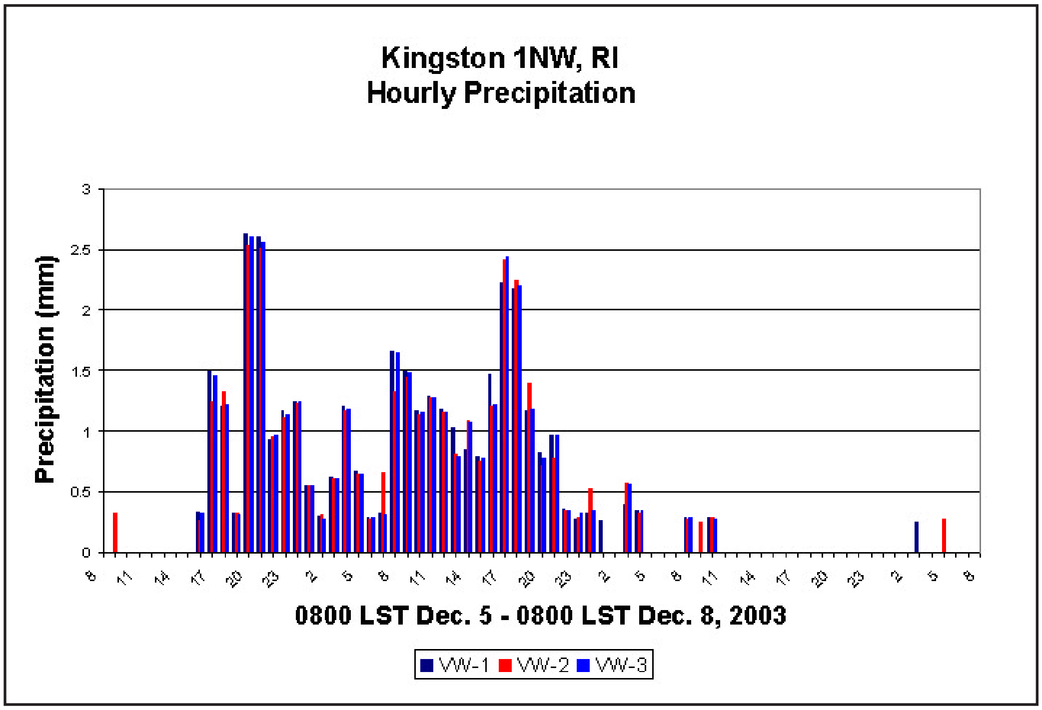

Figure 5 Kingston 1NW RI hourly precipitation during storm period.

At Kingston 1NW the maximum precipitation rate recorded was about 2.5mm per hour. Reports[3] from nearby Providence, RI, indicated heavy snowfall banding, which tends to occur in many nor'easters, attributable to the oscillation of the coastal front. It is likely that two of these bands are captured at Kingston 1NW as two surges in peak precipitation occurring between 2000 - 2200 on December 5 and 1700 - 1900 on December 6.

A plot of the cumulative precipitation during the storm, with values obtained from each of three wire sensors, shows no deviation among the wires in their reported amount or rate of precipitation. The curve shows a relatively steady increase in accumulated precipitation. The absence of any sudden changes in intensity indicates no clogging of the chute or sudden release of snow or ice into the receiving bucket. (The weighing-bucket gauges used in the USCRN network are equipped with thermostatically controlled heat tape that prevents wet snow or freezing rain from collecting on the entrance chute to the bucket.)[4] Similar agreement was evident in the values from the three wires at Kingston 1W site. The three wires were in excellent agreement at both Kingston stations.

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[3] Public Information Statement, National Weather Service, Taunton MA 8:45 PM EST December 9, 2003

[4] A description of the weighing-bucket gauge used by USCRN can be found at <http://www.ncdc.noaa.gov/servlets/crninstrdoc#SENSORS>.

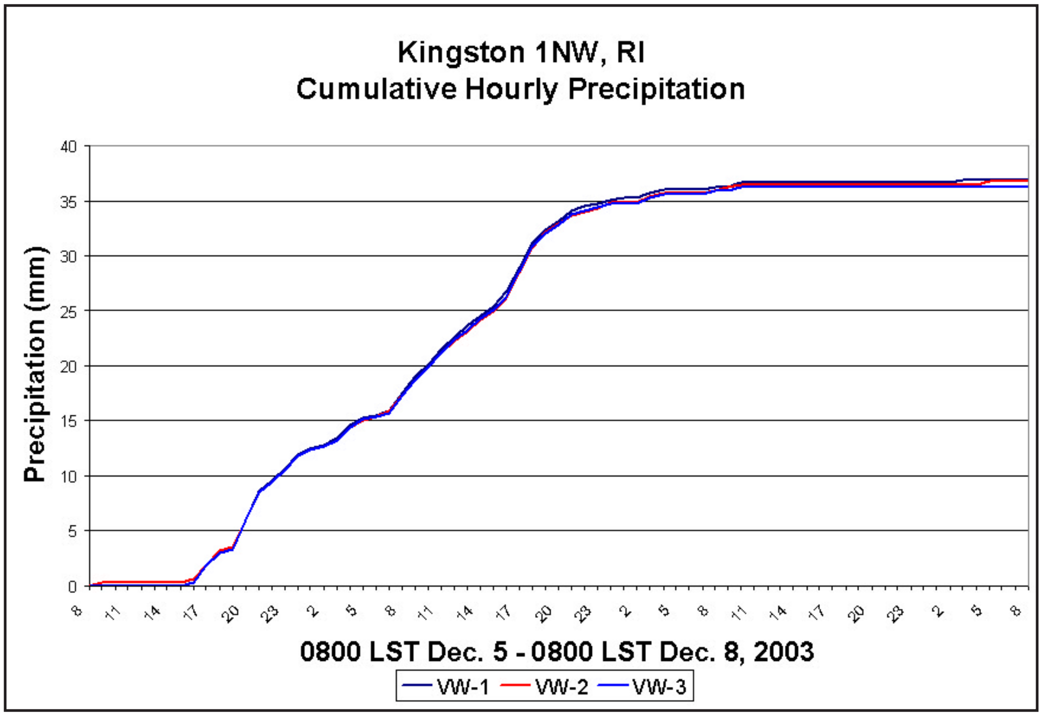

Figure 6 Cumulative hourly precipitation Kingston 1NW for storm period.

Next, the cumulative precipitation from the three wires at Kingston 1NW was compared to those of Kingston 1W. The cumulative precipitation (mass) plots show remarkably close agreement between the two stations. Both stations are equipped with Alter and Small Double Fence Intercomparison Reference (SDFIR) wind shields.

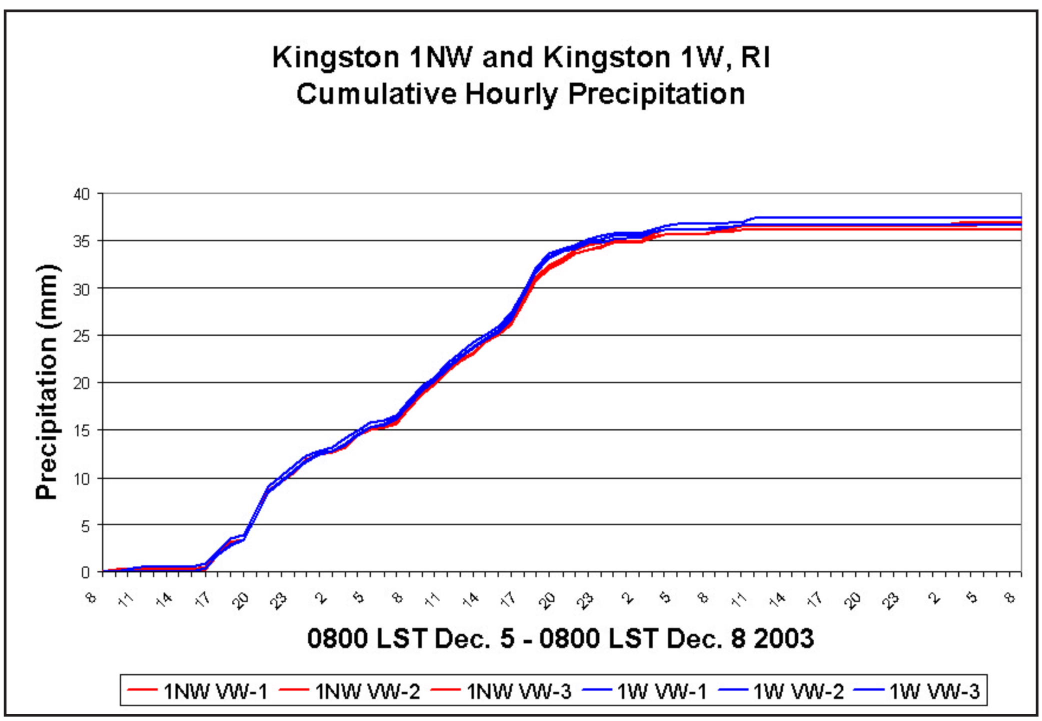

Figure 7 Comparisons of the cumulative totals and variance among the six weighing-bucket precipitation sensors (transducers) at Kingston, RI, paired sites.

Because of the excellent agreement among the three wires, we can simplify further comparison of the two Kingston sites by examining data values from a single wire at each site.

The two Kingston, RI, stations are installed within less than one mile of one another, and there is no great topographic variation either locally or regionally. *Prima facie*, the stations offer an opportunity to compare precipitation and measurement differences reported from the two weighing-bucket gauges. Given the event duration, total precipitation amount, the moderate and occasionally heavy snowfall of the December 5-8 event, and considering there was little to no noise in the wires' measurements, we can make some inferences on snowfall capture efficiency.

Hourly precipitation and cumulative hourly precipitation were plotted for both the Kingston 1W and 1NW sites for the snowfall event. Some immediate conclusions are that:

a. The storm total at both locations was 37mm.

b. The mass curves are identical.

c. The two bar graphs are nearly identical, showing that weighing-buckets at both sites effectively captured the snowfall and recorded its liquid equivalent.

d. The snow capture must have been efficient to measure the same amount and rates at both sites, each comprising three sensors, for a total of six sensors in agreement. This would indicate that the snow capture by these two stations was probably close to 100% during this high-wind event.

e. It would be highly unlikely that the two sites would independently measure the same rates and amounts if the snow capture had been inefficient.

f. Despite the close proximity of the two Kingston sites, there was a 2 meters per second difference in average wind speed during the event. Previous research[5] with unshielded gauges has shown that a wind speed difference of the same magnitude would have been sufficient to produce a differential in catch.[6]

Figure 8 below gives a detailed view of the close temporal and absolute agreement between the precipitation patterns at the two Kingston, RI, stations.

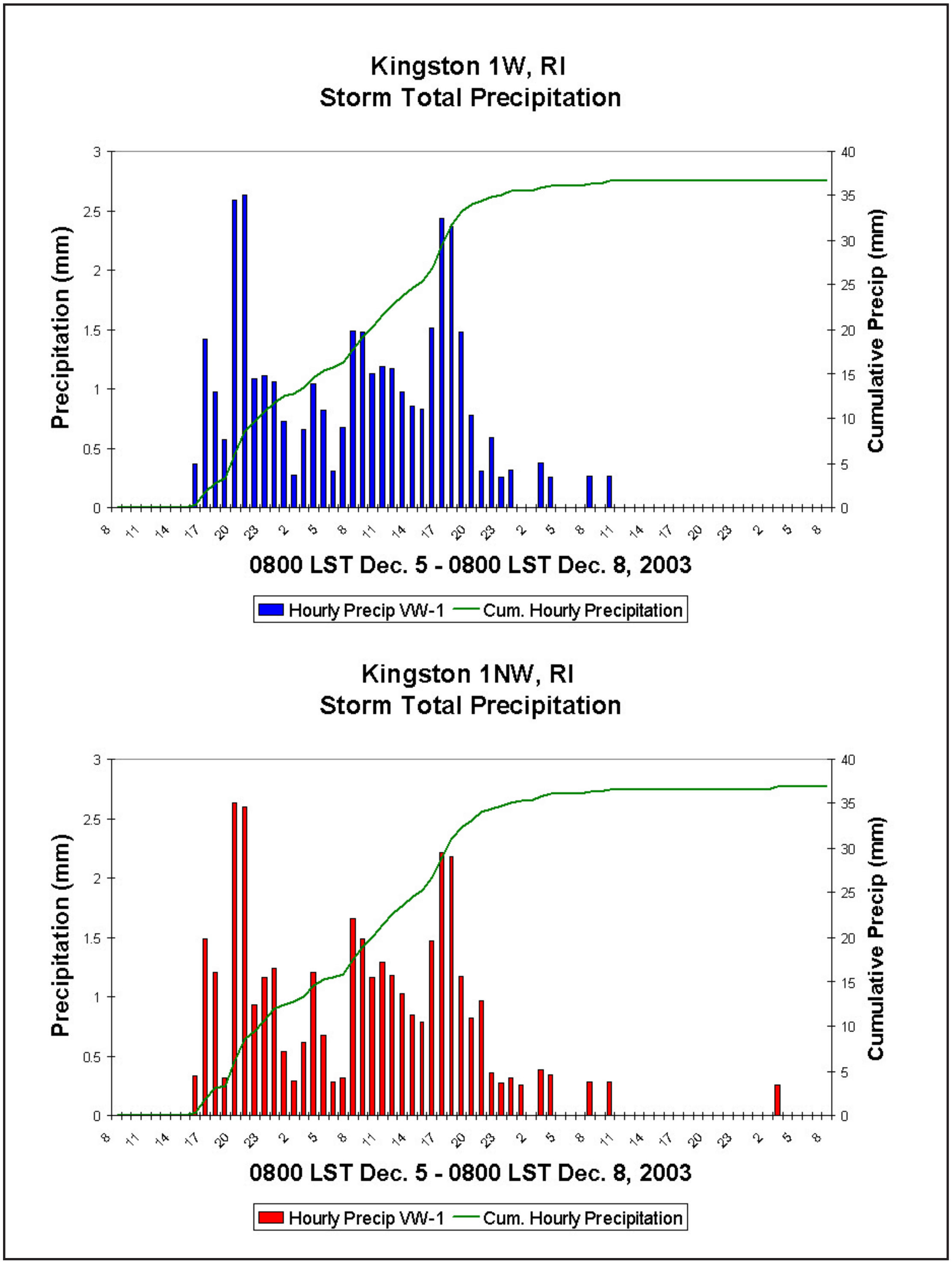

Figure 8 Kingston 1W (blue) and 1NW (red) hourly precipitation.

To examine more closely the storm peak period from 0800-2300 December 6, precipitation data at 15-minute intervals were plotted for the two sites. The curves are remarkably similar: they are both smooth without the step functions often seen in the records of other automated gauges not equipped with thermostatically-controlled gauge chute (neck) temperatures.[7] Step functions would indicate that the weighing-

[5] Goodison, B.E. 1978: Accuracy of Canadian snow gauge measurements. J. Applied Meteorology, 27, pp 1542-1548.

[6] The USCRN wind/snow shield configuration is described in the Geonor gauge Summary found at <http://www.ncdc.noaa.gov/servlets/crninstrdoc#SENSORS>

bucket heaters prevented the collection and delayed melting of snow or ice from the sides of the neck leading to the receiving bucket.

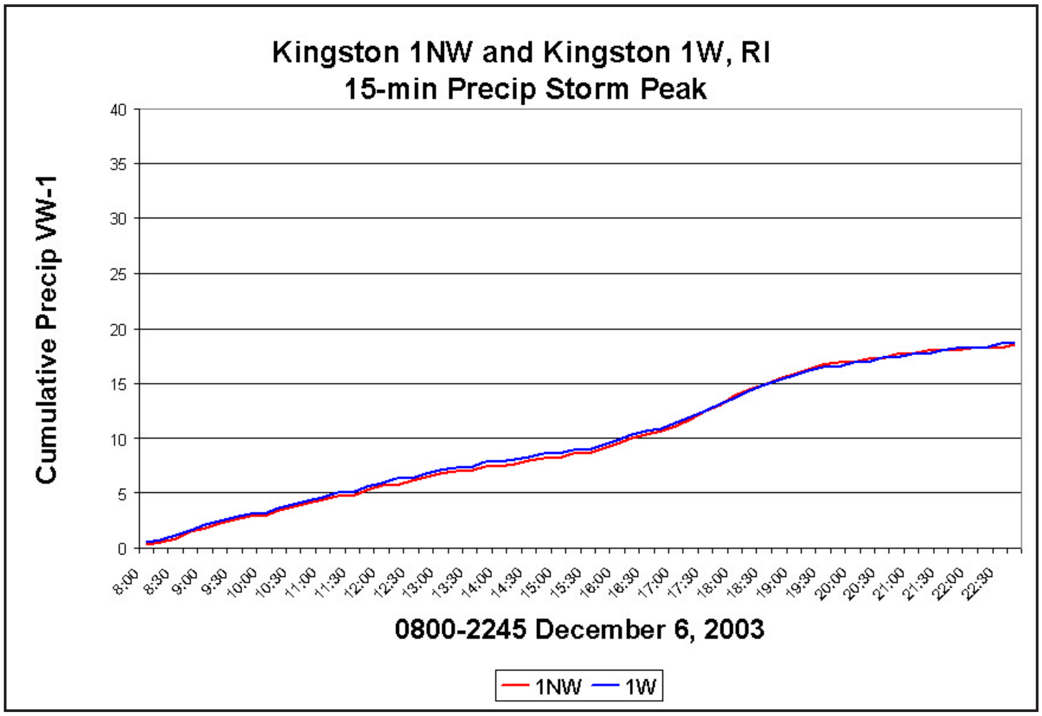

Figure 9 15-minute cumulative precipitation during storm peak.

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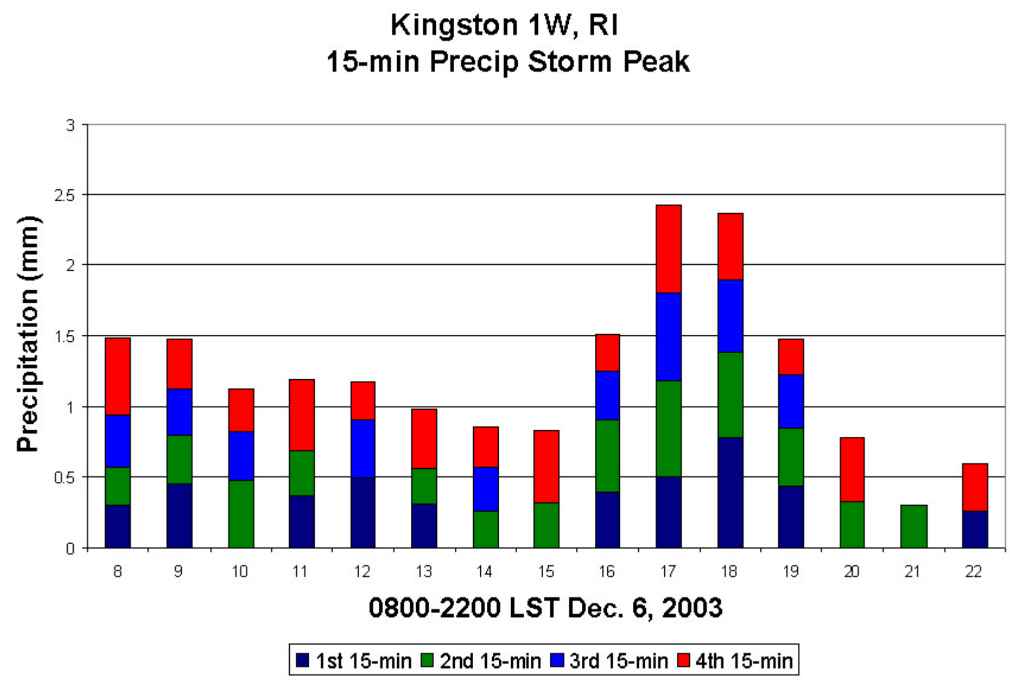
Close examination of the 15-minute interval behavior and precipitation amount between the two Rhode Island stations shows that the two weighing-bucket gauges performed flawlessly in moderate snowfall. They measured almost identical rates and total accumulations of water equivalent (WE) from snowfall. Likewise, they measured almost identical values on 15-minute time steps. The amounts had even smaller variance when the totals were clumped into hourly intervals. During the light snow conditions (the last three hours in Figure 10), the storm moved away from the Rhode Island stations. At the tail-end of storm, the temporal pattern of the snowfall apparently changed over the less than one mile distance between the two stations. Physical conditions such as semi-virga conditions and/or snow micro-bursts are not uncommon over such small distances towards the tail-end of nor'easters.

[7] Grant Goodge, cooperative observer 33 years experience with universal weighing gauges.



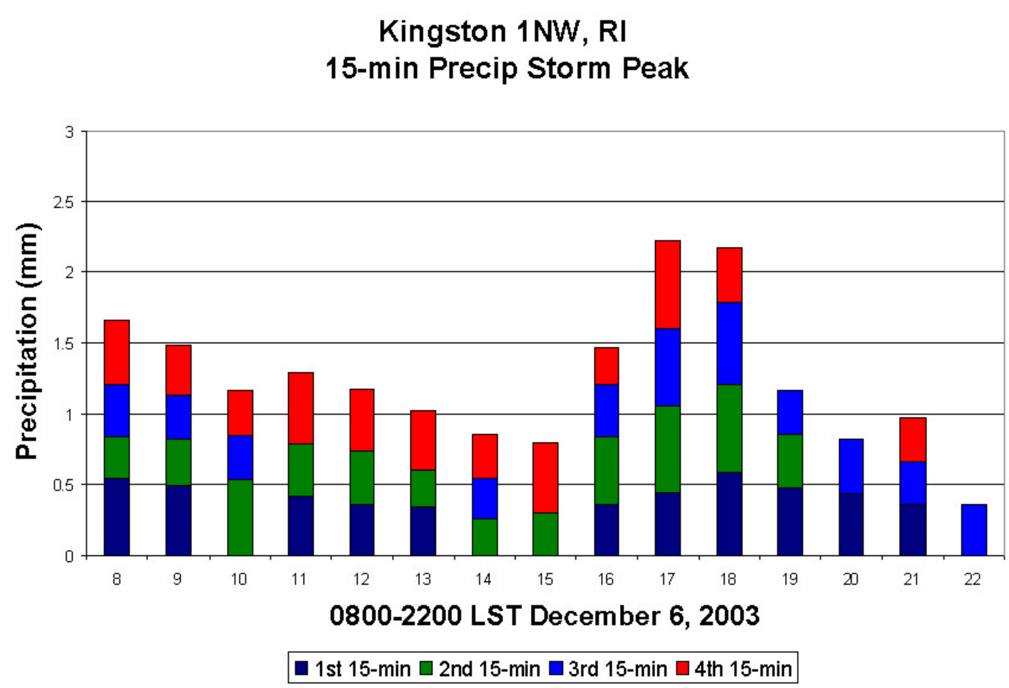


Figure 10 15-minute precipitation within hourly measurement (color-coded for 1st, 2nd, 3rd, and 4th time gate) for both Kingston 1NW and Kingston 1W, RI, stations.

6. Performance of the Durham, NH, Paired Sites

The two New Hampshire sites, Durham 2N and 2SSW are about three miles apart. Unlike the two Kingston sites, they are not identically configured. The installation at Durham 2N lacks an SDFIR wind shield. An SDFIR is not scheduled for installation until the host agency removes a massive boulder in the glacial-till substrate of the drumlin underlying this station later in 2004.

Mass curves of the three wires from Durham 2N show a number of things. First, noting that the scale is identical to the mass plots from Kingston, RI, the total precipitation is less than at Kingston. Storm totals of about 20 mm at Durham 2N and 25 mm at Durham 2SSW were captured by the respective gauges. The water equivalent measured at Durham 2N was less than that at 2SSW. The mass curves show there was undercatch at Durham 2N.

The probable cause of the snow undercatchment at Durham 2N when it is compared to Durham 2SSW is that 2N is not equipped with an SDFIR shield. Also, the three wires at each site show more variability than what was seen at Kingston. Smaller precipitation reports were accompanied by characteristically noisier signals than larger precipitation reports.

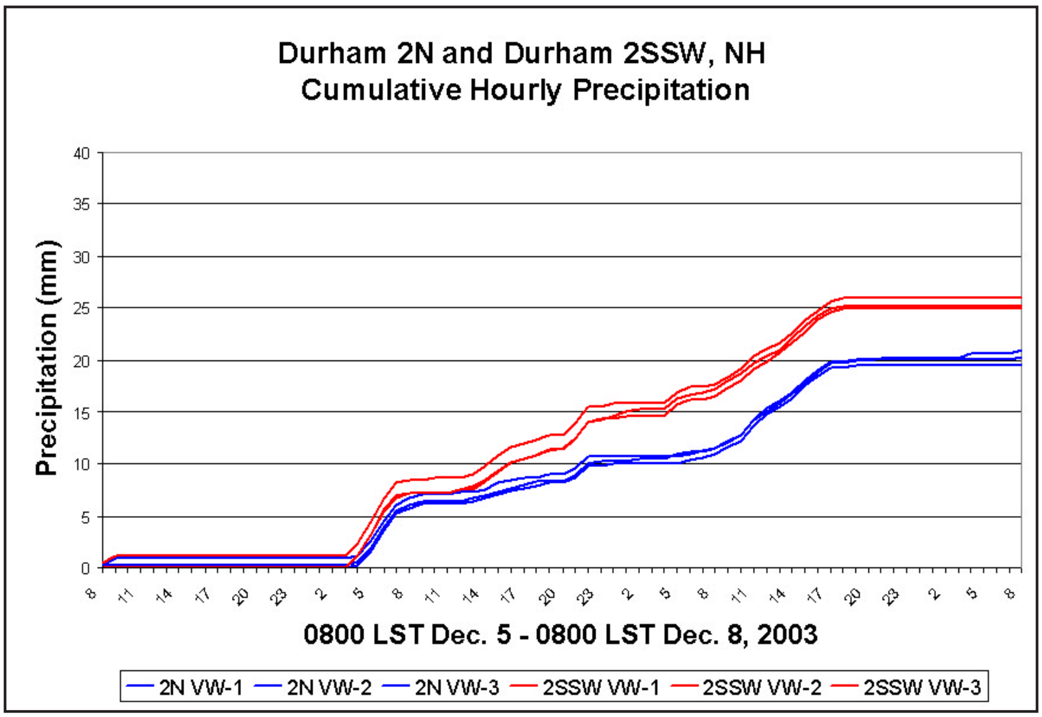


Figure 11 Comparison of cumulative precipitation at New Hampshire USCRN sites for the storm period.

Snowfall, although small in absolute terms, was captured at the same rate and with the same temporal pulses at Durham 2N and Durham 2SSW, as shown by the mass curves. Detailed snow event behavior at the two USCRN sites in New Hampshire are plotted for both the Durham 2N and 2SSW as precipitation and cumulative hourly precipitation for the snowfall event. These plots are shown for vibrating wire VW-1 in Figure 12 below. These two bar graphs indicate precipitation accumulated in about the same timeframe at both sites.

Although there are differences in magnitude between the two stations (the SDFIR question), catch behavior is closely parrotted at both sites. Snowfall, although small in absolute terms, was captured at the same rate at both stations, as shown by the mass curves.

When we consider how closely the two Kingston profiles match, with practically parallel curves, it is postulated that the difference in the water equivalents measured at the two Durham stations is due solely to undercatchment of snow at 2N. If so, this is certainly an argument for the necessity and veracity of wind shields as a standard adjunct to precipitation gauges where accuracy for climate monitoring and assessment is a primary goal.

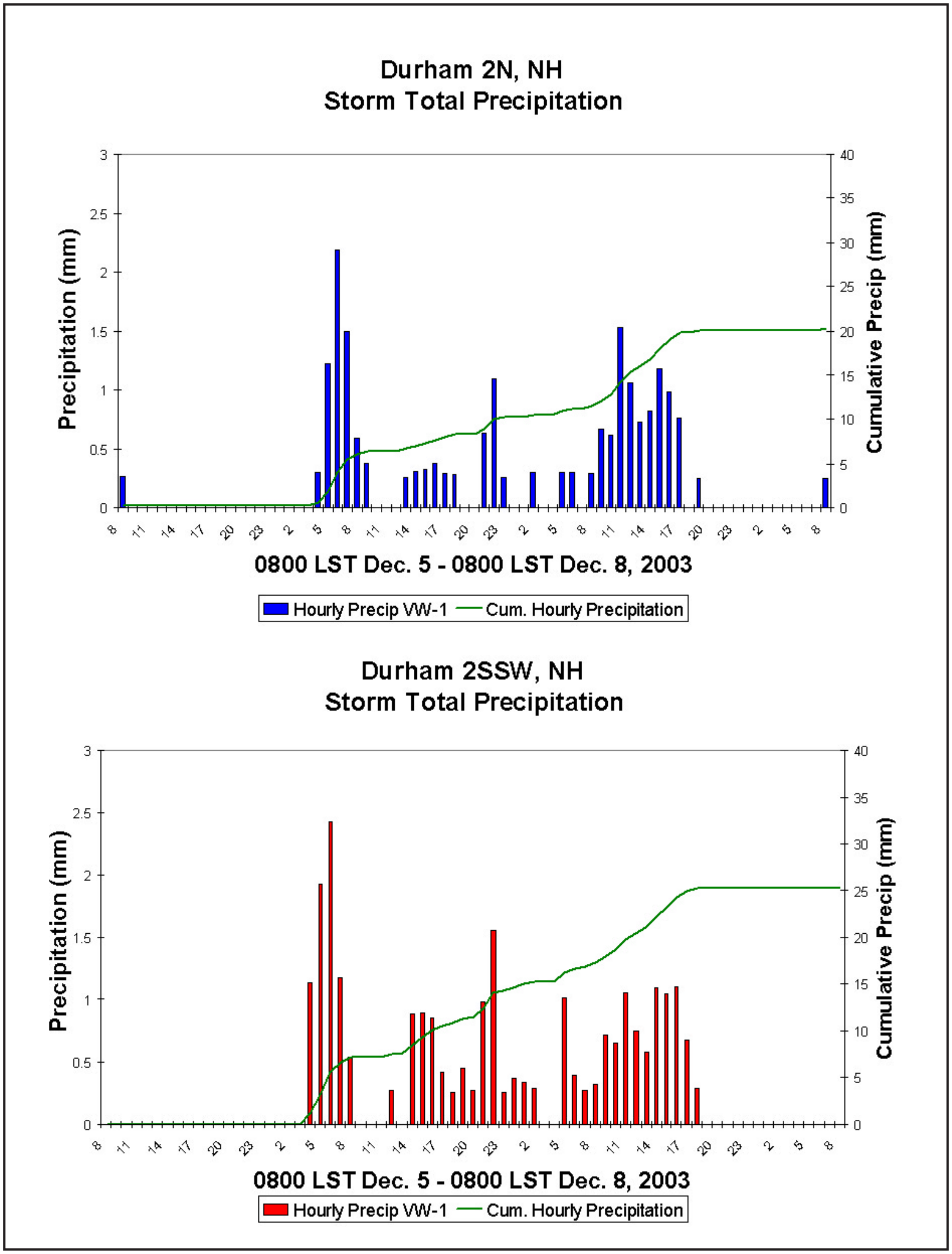


Figure 12 Hourly and cumulative precipitation for the two Durham, NH, sites for the storm event. Hourly precipitation and cumulative hourly precipitation are plotted for both Durham 2N and 2SSW for the snowfall event. These plots are shown for vibrating wire VW-1. The two bar graphs indicate precipitation accumulated in about the same timeframe at both sites.

The performance of the USCRN weighing-bucket gauges at the two Durham sites indicates that both sites functioned continuously throughout the event and both recorded nearly identical timing patterns and rates of precipitation. Additionally, there was an undercatchment of snow at the 2N site, which does not have an SDFIR shield.

7. Performance of the Old Town, ME, Site

Of all the USCRN sites in the path of the storm, by far the greatest amount of water equivalent precipitation was measured at Old Town, Maine. Shown below is the mass plot with hourly precipitation values from wire VW-1. Note that the vertical scale is twice what the other similar plots were. The storm total precipitation (WE) measured 38 mm. The greatest rate of precipitation was from 2300 December 6 through 0800 on the 7th. For this period, mass curves for the 15-minute accumulations were examined.

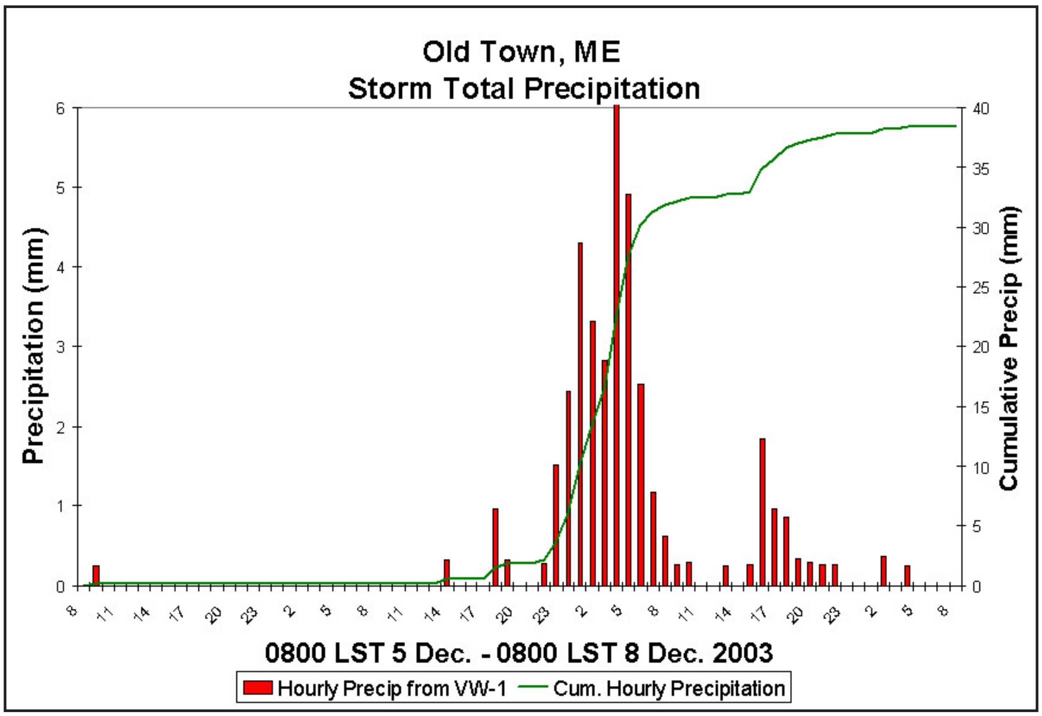


Figure 13 Old Town, ME, hourly precipitation for storm duration.

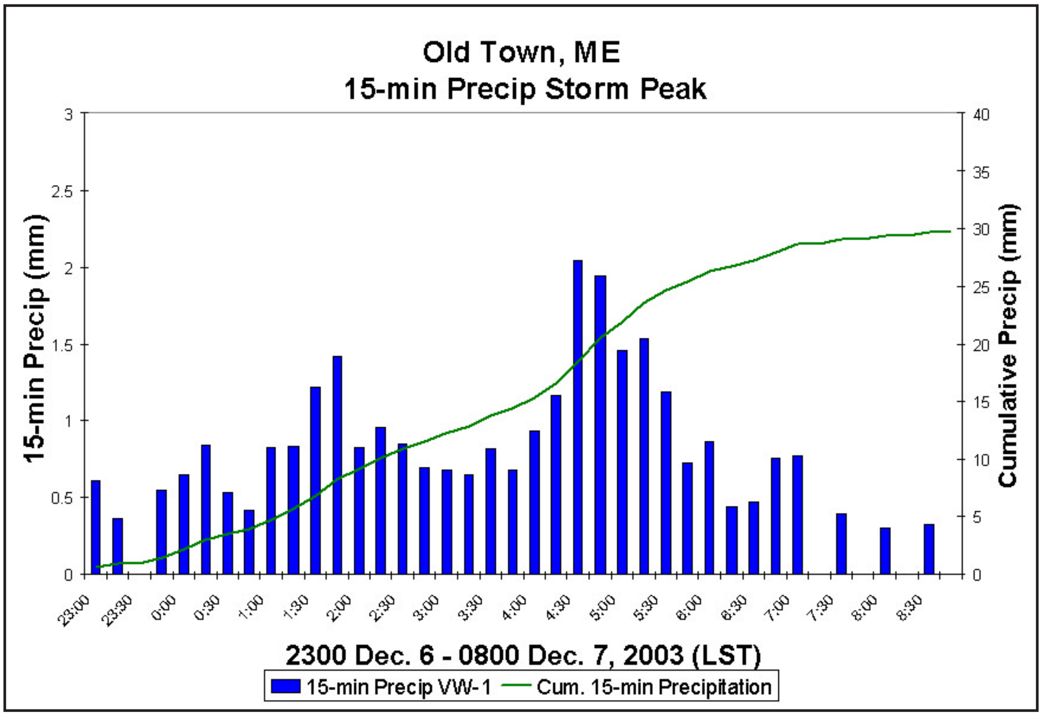


Figure 14 Old Town, ME, 15-minute precipitation during storm peak .

The mass curve of 15-min precipitation show a smooth line with no step-like increments. This would indicate that the weighing-bucket gauge continued operating optimally even in heavy snowfall, and that the neck heater operated well.

Measured 15-min precipitation amounts from wire VW-1 on the weighing-bucket gauge are shown. Note that the vertical scale is the same as that used for *hourly* precipitation on graphs presented for the Kingston, RI, and Durham, NH, stations.

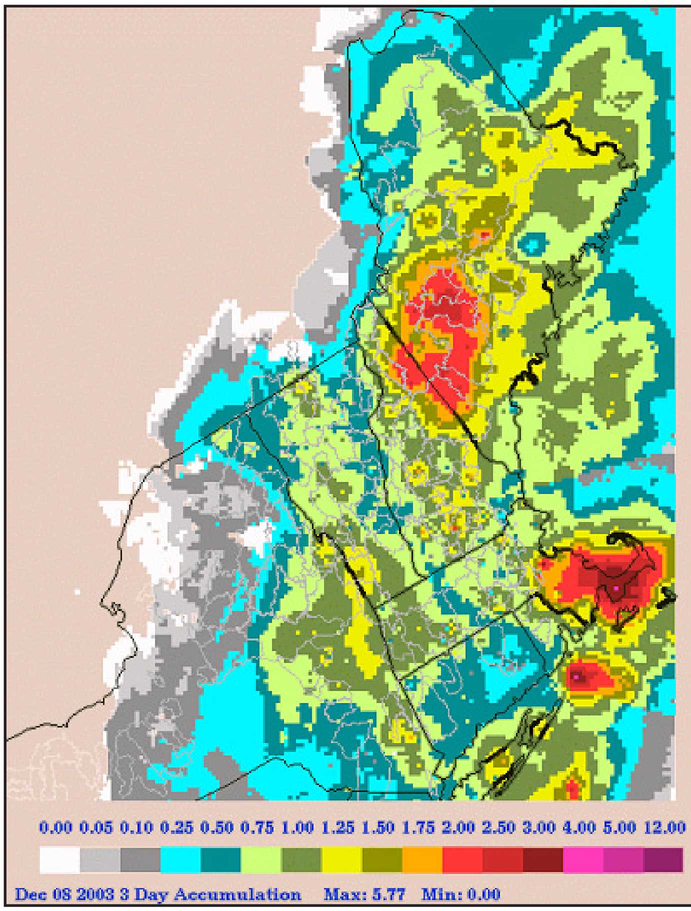
In summary, the performance of the weighing-bucket gauge at Old Town,ME, demonstrates that the gauge operated properly in a short-duration heavy snowfall.

8. *Precipitation Summary*

The weighing-bucket gauges installed at the seven USCRN sites in the path of a major snowstorm functioned normally through the entire storm event. Steady accumulations of precipitation were measured effectively both at hourly and 15-minute intervals. All sensors performed well within tolerances, and the stations' data were transmitted with no outages.

It was especially encouraging that the precipitation gauge neck heater that was desveloped and installed by the NOAA/ARL Atmospheric Turbulence and Diffusion Division in Oak Ridge, TN, performed well and continuously throughout the 48 hours of snowfall, when it was needed the most. A lack of stepwise patterns in the accumulation curves for all seven stations indicates that even during the heaviest snowfall and highest wind periods of the December 5-8 event the neck heater performed optimally. Future snow events must be measured and studied, particularly events marked by even lower temperatures, to see if there is still optimal performance in even more extreme environemts.

How did the liquid precipitation (WE) compare to amounts measured in nearby locations? A cross-network, cross-sensor quantitative assessment is beyond the scope and purpose of this quick-reaction technical note. However, a post-event qualitative comparison may be of interest to researchers who are seeking USCRN technology performance figures for future studies during a long-duration, regional event such as the December 5^{t}- 8, 2003, nor'easter. Some associative evidence gathered during this quick post-event assessment is presented below in Figure 15 in an effort to identify and preserve event evidence in a timely fashion.



0.40	Limestone ME	CRN
0.76	Caribou ME	F6
0.22	Caribou ME	ASOS

1.44	Old Town ME	CRN
1.25	Bangor ME	F6
0.29	Bangor ME	ASOS

1.47	Gray ME	F6
0.99	Portland ME	F6
1.02	Rochester NH	Coop
0.72	Durham 2N NH	CRN
0.97	Durham 2SSW	CRN
1.45	Portsmouth	ASOS
1.38	Newbury NH	Coop

0.55	Providence RI	F6
0.85	Providence RI	ASOS
1.37	Kingston 1NW RI	CRN
1.37	Kingston 1W RI	CRN

Figure 15 Composite radar imagery showing storm total precipitation plotted on Hydrologic Rainfall Analysis Project (HRAP) grid projection.

The Stage 1 composite radar imagery data with storm total precipitation (WE) for the New England area was obtained from the NWS.[8] Storm total precipitation values (in inches) from stations near the USCRN sites were also obtained. The station locations are indicated on the chart on the right of Figure 15 starting with the northernmost station.

At first glance, the figure appears to indicate variability and not much comparability between the values measured at the stations and what is estimated by radar. Usually the value at the USCRN site is higher than that at the corresponding ASOS site but this is not true for Durham. Sometimes the value from an F6 station is higher than that at the USCRN site.

Six-hourly totals of precipitation (in inches) for the USCRN sites were calculated for the December 5, 6, and 7, the heaviest part of the storm, and can be seen in Table 2 below.

December 2003	Precipitation (Inches)																Event Temp (F)		Event Wind (mph)	
STATION	DAY 5					DAY 6					DAY 7									
	0000-0600	0600-1200	1200-1800	1800-2400	**Day 5 Total**	0000-0600	0600-1200	1200-1800	1800-2400	**Day 6 Total**	0000-0600	0600-1200	1200-1800	1800-2400	**Day 7 Total**	**Event Total**	Max	Min	Max Hrly Speed	Event Mean Speed
Elkins 21 ENE	0.01	0.00	0.06	0.06	**0.13**	0.10	0.04	0.00	0.05	**0.19**	0.07	0.02	0.01	0.00	**0.10**	**0.42**	29	18	8	5
Kingston 1 W	0.00	0.00	0.10	0.35	**0.45**	0.14	0.27	0.32	0.14	**0.87**	0.03	0.02	0.00	0.00	**0.05**	**1.37**	32	24	20	11
Kingston 1 NW	0.00	0.00	0.11	0.35	**0.46**	0.13	0.26	0.33	0.14	**0.86**	0.03	0.02	0.00	0.00	**0.05**	**1.37**	32	24	22	15
Durham 2 N	0.00	0.01	0.00	0.00	**0.01**	0.14	0.09	0.06	0.06	**0.35**	0.01	0.15	0.17	0.02	**0.35**	**0.71**	29	16	16	10
Durham 2 SSW	0.00	0.00	0.00	0.00	**0.00**	0.21	0.06	0.13	0.14	**0.54**	0.07	0.14	0.17	0.00	**0.38**	**0.92**	28	17	15	11
Old Town 2 W	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.05	0.17	**0.22**	0.91	0.10	0.16	0.05	**1.22**	**1.47**	29	25	11	7
Limestone 4 NNW	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.33	0.02	0.05	**0.40**	**0.43**	23	19	14	10

Table 2 Precipitation values for the heaviest part of the storm for USCRN stations.

Although it would be desirable at some point to complete an analysis at six-hourly intervals between USCRN stations and other network stations during a major snow event such as this one, it may be impractical. Given the high variability of the snowfall pattern, the oscillation of the coastal front, and possible different methods of measuring melt water at human-augmented automated stations, it is perhaps best that the highest-confidence, highest-quality, quantitative analyses be completed at closely monitored research field sites with clustered instrumentation.

To this end, a careful multi-year study is ongoing as joint research projects at NOAA facilities in Sterling, VA, and Johnstown, PA. Results of those studies will be posted on the USCRN website when they are completely analyzed and properly reviewed.

[8] National Weather Service, North East River Forecast Center, courtesy Rob Shedd. Precipitation calculations from Z/R relationship from radar returns.