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WATER EQUIVALENT VS RAIN GAUGE MEASUREMENTS FROM THE MARCH 1993 BLIZZARD

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INTRODUCTION

On March 12-14, 1993, the eastern seaboard of the U. S. was struck by what is now referred to as: 1) The Storm of the Century, 2) The Blizzard of 93, or 3) The Big One! One of the interesting and more overlooked aspects of the storm was the discrepancy between liquid water measurements by the rain gauge and water equivalent 'core samples' of the snow/ice on the ground. In examining these data, I found that many stations appeared to either have a problem with 'undercatch' of snowfall by the rain gauges, or a systematic problem with water equivalent measurements. This report will attempt to show that: 1) The most likely scenario is a problem with 'undercatch' of snowfall, and 2) the careful measurement of water equivalent is an important element for hydrological interests and the climatic records.

Water equivalent measurements are taken by extracting core samples, or slices, of the snow/ice on the ground, and then melting the sample to calculate the water equivalent of the snow/ice. The measurement can be done carefully with a rain gauge (e.g., an 8-inch sample of 16 inches on the ground melts to 1 inch of water, indicating an 8-1 ratio and 2 inches of water equivalent). It is very important that the sample be representative of the full profile of the snow/ice depth. Care must be taken not to compress or compact the snow for the sample, since the density of snow in the sample should be the same as that on the ground.

The problem with 'undercatch' of snowfall by rain gauges has been documented in previous studies (Larson and Peck, 1974; Peck, 1972). These studies have established empirical relationships between gauge measurements, water equivalent measurements of snow on the ground, and wind speeds. From these relationships and field testing of the ensuing equations, unshielded gauges were shown to 'undercatch' precipitation by 70% or more (40% or more for shielded gauges) during snowfall events with wind speeds of 20 MPH or higher. Suffice it to say that this storm presented an excellent opportunity to observe this problem.

DISCUSSION

The accompanying table presents statistics on the measurements made during the storm at 40 stations. By carefully studying the table, several aspects become readily apparent. These aspects are discussed below.

The snowfall storm totals (INCR1) were quite substantial, with totals of 1 to 2 feet being common throughout much of the eastern U.S. These totals are based on snow depth reports before, during, and after the storm, in order to better correlate them with water equivalent 'core samples' taken at about the same times. Generally, the greatest depths were observed on the 14th.

The water equivalent storm totals (INCR2) were also unusually high for a snow event in this part of the country, with amounts of 2 to 4 inches being rather common. If these totals are accurate, then the 'true' amounts of liquid deposited by the storm should be equal to or greater than those shown in the INCR2 column. In other words, the 'true' liquid total from a storm is always equal to or greater than the final water equivalent measurement. The observer's measurement of the greatest water equivalent amount (WTEQ2) does not account for melting of snow/ice near a ground surface with above freezing temperatures at the beginning of the storm. Since this storm was a late season event, most of the affected areas did have above freezing ground temperatures at storm onset, and, in some cases, several hours of snow fell before actual accumulation began. Then, as heavy snow fell and accumulated, some melting from underneath occurred throughout the storm at many locations.

This affect can be seen in looking at the synoptic-hour observations (every three hours) of snow depth, which show a decrease in snow depth for some stations during the hours immediately after the storm--with temperatures still well below freezing--an indication of melting from underneath. Also, the true amount of liquid would tend to be higher than 'INCR2' since most stations reported some additional snowfall after their report of the maximum water equivalent amount (WTEQ2).

'RATIO1' is a measure of the apparent undercatch by the gauges (rain gauge vs water equivalent), although the factors mentioned above have to be considered. For the 28 stations reporting 'SNOW' as the predominant precipitation type, 4 are within a range of .01 to .40, 15 are within .41 to .80, 8 are within .81 to 1.20, and 1 is over 1.20. In light of previous studies mentioned above ('undercatch' precipitation by 70% or more...), these figures are not surprising since wind speeds generally averaged 10-30 MPH at most stations during the heavy snowfall. Also, they show more than half (15) of the values to be within the second of these four ranges.

Some of the snow/water ratios (RATIO2) seem quite low (i.e., high water content). However, given that this was a very deep 'spring-type' storm which drew in large amounts of Atlantic and Gulf of Mexico moisture, it is likely that the snow had a higher liquid content than would be expected in a 'normal' winter storm. Unfortunately, I am not aware of any studies which have attempted to correlate the severity and type of storm system with the resulting liquid water content of snowfall. Such a study is not within the scope of this paper.

Although there were a wide range of temperatures among stations during the heavy snowfall, the general range was 25-34 degrees Fahrenheit at storm onset, falling to 10-25 degrees Fahrenheit when heavy snowfall ended. Dew point depressions averaged about 2 degrees Fahrenheit throughout the storm. The dew points are probably a better indicator of the liquid content of snowfall in a storm system with large amounts of moisture entrained, since they give us a 'reading' of atmospheric moisture content. Historically, dry bulb temperatures at the surface have been used as a 'rough' indicator of liquid content, with readings of around 30 degrees Fahrenheit indicative of 'wet snow.' However, a 30-degree dry bulb with a 25-degree dew point would tend to indicate less liquid content than a 30-degree dry bulb with a 28-degree dew point.

In looking at this aspect further, I chose 9 stations along the Appalachian chain where geography and the synoptic situation would be similar for this event. The table below presents each station's mean dew point temperature during the time of moderate to heavy snow (i.e., when most of the snow fell) as compared to the snow/water ratio (RATIO2).

STATION	MEAN DEW PT	RATIO2
Asheville NC	30	4.2
Hickory NC	29	6.0
Charleston WV	24	6.8
Roanoke VA	27	7.6
Huntington WV	23	7.9
Beckley WV	20	8.1
Elkins WV	18	9.5
Pittsburgh PA	20	11.9

Binghamton NY	14	14.0

One would expect that as the dew points fell, the snow/water ratios would increase. The table shows this to generally be true. To investigate this further, the correlation coefficient can be calculated which will estimate the affect of the mean dew point on the snow/water ratio. A 'perfect' correlation here would be -1.00 since a decrease in the mean dew point yields an increase in the snow/water ratio. The actual correlation coefficient for these values is -.90, and 80.3% of the variation in snow/water ratio is accounted for by a linear relationship with the mean dew point. Also, by restricting the list to Asheville, NC plus the four West Virginia stations (five stations with very similar terrain influences), the coefficient 'improves' to -.98, and 96.1% of the variation in snow/water ratio is then accounted for by the relationship with mean dew point. Although this cannot be said to validate the water equivalent measurements for these stations, it certainly adds more credibility to the values.

Other factors that may come into play in a storm such as this would be the proximity of the station to large bodies of water, and the location of the station to the leeward/windward side of mountain ranges. However, in my evaluation of the data (for all 40 stations), I did not find any direct correlations with these factors. As for the distribution of 'RATIO2' values for the 28 'SNOW' stations, 3 are within the .1 to 4.0 range, 13 are within 4.1 to 8.0, 10 are within 8.1 to 12.0, and 2 are over 12.0. Therefore, nearly half (13) have ratios of from 4.1 to 8.0. This is certainly a significant departure from the 10.0 ratio that is commonly used when an actual measurement is not taken.

The inconsistency of reports between stations is especially apparent for 'RATIO1' and 'RATIO2.' As the distributions shown above indicate, the data do show some clustering of values within certain ranges. However, there is considerable variability in the data and spatial (i.e., geographic) clustering cannot be shown. A few cases of large differences over short distances (e.g., Rochester vs Syracuse, NY) may indicate a problem in the validity of a few of the values. Some of these variations can probably be explained by geographic/terrain differences; snow melt during the storm at some locations (melting underneath mentioned above); and possibly some subtle differences in observing practices between stations.

Other important considerations are the wind speeds associated with the storm and the existence (or not) of windshields for each of the gauges. Some of the National Weather Service (NWS) stations in the Northeast are equipped with windshields, while most in the Southeast are not. Wind speeds generally averaged 10-30 MPH for most stations during the moderate to heavy snowfall, but were quite gusty. Estimating an average wind speed for the storm for each station is of questionable value due to this gustiness, and since the wind's affect on the gauges would depend on the gauge exposure. However, data for mean wind speeds and the existence of windshields are included in the data table (see WND and SHLD columns) to provide some indication of how these data correlate with the 'undercatch' of the gauges (RATIO1). Following are correlation coefficients calculated from these data by correlating 'RATIO1' with 'WND':

19 'SNOW' stations without windshields = -.39
9 'SNOW' stations with windshields = -.33

Here, a 'perfect' correlation would be -1.00 since 'RATIO1' should decrease as 'WND' increases. These poor correlations may be due not only to the factors mentioned above, but also to variations in snow density (i.e., snow weight, which is directly proportional to water content and inversely proportional to 'RATIO2'). Heavier, wetter snow would tend to be less affected by the wind than drier snow. However, I am not aware of any previous research of this effect. Correlations can be calculated using groups of stations with similar values for 'RATIO2' and/or similar geographical influences, but I found most combinations to only yield coefficients of between -.30 and -.60. It is my opinion that these low correlations are the result of the uncertainties cited above as well as possible inconsistencies in reporting practices among the various stations.

CONCLUSION

Of the 28 stations which reported 'SNOW' as the predominant precipitation type, 23 (82%) show gauge 'catch' lower than the water equivalent storm total (see RATIO1 column). However, of the 12 which reported 'SNOW, IP' or 'MIXED' as the main type, only 4 (33%) show gauge 'catch' lower than the water equivalent storm total. Therefore, those stations which received less snowfall and more ice pellets/rain showed a much lower tendency for 'undercatch.' Also, 15 of the 28 'SNOW' stations (54%) have a RATIO1 value of from .41 to .80, with a mean for all 28 stations of .68. These statistics indicate significant 'undercatch' of snowfall by the gauges.

The mean for 'RATIO2' for 'SNOW' stations is 8.2. This seems to indicate a rather wet snow as compared to the typical 10-1 ratio that we're accustomed to using. (Perhaps it's time to reevaluate this 'typical' ratio, since snowfall often has a somewhat lower or higher ratio than 10-1.) These statistics also point to a need for further study of the methods used in measuring water equivalent of snow/ice on the ground, as the variability of the data indicate possible problems with a few of the values.

However, this should not diminish the importance of water equivalent measurements/data for climatic records and for hydrological interests (river forecasting, etc.). In fact, considerable flooding occurred in parts of the eastern U.S. shortly after the storm mainly due to snow melt. In 'extreme events' of this nature, it would be wise for hydrologists and climatologists to take note of how the water equivalent reports compare with the rain gauge reports. This is especially true for a month such as March 1993 when this event contributed greatly to the month's precipitation total (based on rain gauge measurements), but where the 'official' totals for the month probably fell significantly short (20% or more in some cases) of the actual liquid amounts received. In summary--the water equivalent reports are very important for the climatic records--not only to get a true picture of the liquid amounts received, but also to provide a baseline for studying the problem of 'undercatch' by gauges.

As to what can be gained from all of this, I suggest the following:

a. Although water equivalent has not been one of the more used/studied meteorological elements, this storm is a prime example of the usefulness of these data when measured correctly. I would encourage future observing practice standards (i.e., the FMH) to emphasize the measurement of 'core samples' (even in the age of automation). The measurements are especially important to hydrological interests and climatological records, as discussed above.

b. Recent studies have indicated that the Canadian 'Nipher' shield may be the best available due to its structure allowing for better 'catch' of snowfall. The use of this shield could be implemented on a 'test' basis at several stations with frequent snowfall. Optimally, a three-way test could be conducted with the Nipher shielded gauge vs the standard NWS shield vs an unshielded gauge. Of course, the gauge type would have to be the same in each instance. These data could be compiled with follow-on recommendations for precipitation measurements.

c. Some equations have been developed (Larson and Peck, 1974) for estimating the 'true' liquid amount during snowfall events. These equations use (as input) the rain gauge measurement and estimated average wind speeds. One equation is used for shielded gauges and another equation for unshielded gauges. This storm would be an excellent case study for the application of these equations. Such a follow-up study could add to the table shown in this report by calculating:

1) Estimated 'true' liquid amounts using the equations mentioned above.
2) Comparison of these estimates to the water equivalent storm totals (INCR2).

This report has shown that the March 1993 "Storm of the Century" presented an excellent opportunity to study the problem of 'undercatch' of snowfall by rain gauges. Also, it has shown that the accurate measurement of water equivalent is important for both hydrological interests and for the climatic records. In fact, these measurements provide one of the bases for studying the afformentioned 'undercatch' problem. For further information about this storm, you may contact the National Climatic Data Center (phone 704-271-4800, fax 704-271-4876, internet orders@ncdc.noaa.gov) in Asheville, NC. We have a complete report about the storm, along with several digital datasets of observations taken during the "Storm of the Century."

REFERENCES

L. Larson and Peck, E.L., 1974: Accuracy of Precipitation Measurements for Hydrologic Modeling. "Water Resources Research," 857-862.

Peck, E.L., 1972: Snow Measurement Predicament. "Water Resources Research," 244-248.

DATA TABLE

MARCH 12-14, 1993 "STORM OF THE CENTURY"

All stations which reported at least 1 inch of water equivalent of snow/ice on ground at some point during storm:

STATION	DPTH1	DPTH2	INCR1	WTEQ1	WTEQ2	INCR2	DPTH3	GAUGE	PRECIP	RATIO1	RATIO2	WND	SHLD
Albany NY	4	28	24	1.2	3.2	2.0	28	1.83	SNOW	.91	12.0	20	YES
Allentown PA	0	18	18	0	1.7	1.7	16	2.01	SNOW	1.18	9.4	23	YES
Asheville NC	0	18	18	0	3.8	3.8	16	1.85	SNOW	.49	4.2	15	NO
Beckley WV	0	30	30	0	3.7	3.7	30	2.00	SNOW	.54	8.1	18	YES
Binghamton NY	13	35	22	3.2	4.7	1.5	34	1.00	SNOW	.67	14.0	23	YES
Bristol TN	0	13	13	0	1.1	1.1	12	1.35	SNOW	1.23	10.9	15	NO
Buffalo NY	4	16	12	.3	2.0	1.7	15	.82	SNOW	.48	6.5	26	NO
Burlington VT	13	31	18	2.6	3.7	1.1	25	.59	SNOW	.54	10.9	18	NO
Caribou ME	20	36	16	6.5	11.8	5.3	36	1.05	SNOW	.20	3.0	21	YES
Charleston WV	0	19	19	0	1.9	1.9	13	1.16	SNOW	.61	6.8	13	NO
Chattanooga TN	0	20	20	0	1.8	1.8	18	1.44	SNOW	.80	10.0	18	NO
Cleveland OH	3	11	8	.7	1.7	1.0	7	.55	SNOW	.55	4.0	25	NO
Concord NH	6	23	17	2.2	4.5	2.3	17	.75	SNOW	.33	4.8	17	NO
Elkins WV	1	19	18	0	1.9	1.9	19	1.22	SNOW	.64	9.5	13	NO
Erie PA	4	17	13	.3	1.3	1.0	16	.70	SNOW	.70	12.0	31	NO
Hickory NC	0	10	10	0	1.5	1.5	9	1.76	SNOW	1.17	6.0	17	NO
Huntington WV	0	22	22	0	1.9	1.9	15	1.08	SNOW	.57	7.9	16	YES
Jackson KY	0	20	20	0	3.1	3.1	20	.47	SNOW	.15	6.5	16	YES
Knoxville TN	0	15	15	0	1.6	1.6	12	1.49	SNOW	.93	7.5	12	NO
Mansfield OH	2	9	7	.3	1.3	1.0	9	.51	SNOW	.51	7.0	25	NO
Pittsburgh PA	0	25	25	0	2.1	2.1	25	1.12	SNOW	.53	11.9	22	NO
Portland ME	17	34	17	4.4	6.1	1.7	34	1.58	SNOW	.93	10.0	24	NO
Roanoke VA	0	16	16	0	1.7	1.7	13	1.97	SNOW	1.16	7.6	18	NO
Rochester NY	7	25	18	1.7	8.1	6.4	25	1.09	SNOW	.17	2.8	32	NO
Syracuse NY	5	37	32	1.6	3.5	1.9	34	2.03	SNOW	1.07	15.3	20	YES
Wilkes-Barre PA	1	21	20	0	1.4	1.4	12	1.24	SNOW	.89	7.9	18	NO
Williamsport PA	1	15	14	0	1.8	1.8	13	1.10	SNOW	.61	6.7	15	NO
Worcester MA	9	26	17	3.2	6.1	2.9	26	1.23	SNOW	.42	5.9	24	YES
Baltimore MD	0	9	9	0	2.3	2.3	9	2.48	SNOW, IP	1.08	3.9	25	NO
Hartford CT	0	16	16	0	2.0	2.0	16	2.05	SNOW, IP	1.03	8.0	18	NO
Philadelphia PA	0	12	12	0	1.5	1.5	11	1.80	SNOW, IP	1.20	7.3	31	NO
Washington-Dulles	0	13	13	0	1.8	1.8	13	1.55	SNOW, IP	.86	7.2	19	NO
Boston MA	1	12	11	0	5.0	5.0	9	1.95	MIXED	.39	1.6	44	NO
Bridgeport CT	0	10	10	0	2.2	2.2	9	2.64	MIXED	1.20	4.1	34	NO
JFK Apt NY	0	9	9	0	2.1	2.1	8	2.39	MIXED	1.14	3.8	28	NO
LaGuardia Apt NY	0	9	9	0	3.7	3.7	8	2.49	MIXED	.67	2.2	35	NO
Newark NJ	0	13	13	0	2.7	2.7	13	2.81	MIXED	1.04	4.8	23	YES
Providence RI	0	6	6	0	2.0	2.0	4	2.58	MIXED	1.29	2.0	23	NO
Washington-Natl.	0	6	6	0	1.3	1.3	5	2.31	MIXED	1.78	3.8	20	YES
Wilmington DE	0	10	10	0	2.4	2.4	9	2.33	MIXED	.97	3.7	21	NO

KEY:

DPTH1 = Snow depth in inches before the storm (on March 11).

DPTH2 = Greatest snow depth in inches during storm.

INCR1 = Snowfall storm total in inches (DPTH2 - DPTH1) as calculated by subtracting the depth before the storm from the greatest depth reported. The actual snowfall totals may be slightly higher.

WTEQ1 = Water equivalent of snow/ice on ground before storm (on March 11) in inches and tenths.

WTEQ2 = Greatest water equivalent of snow/ice on ground during storm in inches and tenths.

INCR2 = Water equivalent storm total (WTEQ2 - WTEQ1) in inches and tenths.

DPTH3 = Snow depth in inches at time of WTEQ2 report.

GAUGE = Liquid 'catch' by rain gauge (storm total) in inches and hundredths.

PRECIP = Predominant precipitation type during storm:
IP = ice pellets
MIXED = snow, ice pellets, and rain

RATIO1 = GAUGE / INCR2. This is the amount of precipitation caught by the gauge as a proportion of the WTEQ storm total. In theory, this value should always equal or exceed 1.00 since melting from underneath the snow cover (due to above freezing ground temperature) and precipitation after the WTEQ2 report are not accounted for in the INCR2 column. In effect, this is an estimate of the gauge 'undercatch.'

RATIO2 = (DPTH3 - DPTH1) / INCR2. This is a measure of the water content of snow/ice from the storm by calculating the ratio of snow/ice accumulation to water equivalent. DPTH3 minus DPTH1 is the storm's snow/ice total at the time of the water equivalent measurement used for calculating INCR2. In effect, this is an indication of the average weight of the snow and/or ice from the storm. Over the years, stations not taking water equivalent measurements have often assumed a value of 10.0 for this calculation.

WND = The average wind speed in MPH during the storm for the period when moderate or heavy snow and/or ice pellets were reported.

SHLD = The existence (YES or NO) of a windshield for the rain gauge.