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A HYDROMETEOROLOGICAL ASSESSMENT OF THE OCTOBER 1996 RECORD RAINSTORM IN MAINE

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1. INTRODUCTION

On 19-22 October 1996, a cut-off extratropical cyclone with a persistent moisture feed from Hurricane Lili produced excessive precipitation. All-time rainfall records were shattered in southern Maine. Extreme flooding resulted, greatly impacting travel and commerce. Extensive damage occurred to state infrastructure and private homes.

A hydrological overview and statistical analysis of the rainfall totals will be provided to demonstrate the magnitude of this unique storm. Performance of the Gray, ME WSR-88D (KGYX) Storm Total Precipitation (STP) product will be discussed. Emphasis will be on manipulating equivalent reflectivity-precipitation rate (Z_e-R) relationships and scanning techniques within the Precipitation Processing Subsystem (PPS) to optimize radar-based precipitation estimation.

When conducting PPS tests, it is important to acknowledge sources of sampling error inherent with rain gages and to consider radar limitations. This will improve understanding of radar biases when evaluating the STP. Droplet size/distribution and bright banding are just two phenomena that greatly impact precipitation estimation. Therefore, an environmental overview will be provided.

2. DISCUSSION

a. Historical Perspective

Cut-off extratropical systems with associated slow-moving surface boundaries can entrain tropical moisture resulting in excessive rainfall and flooding in Maine. Examples include the 11-12 May 1989 and 8-13 October 1998 storms, which were characterized by persistent moisture bands converging on Maine’s southwest coast from the subtropical Atlantic. Another synoptic setting which frequently leads to flooding, landfalling tropical cyclones such as Hurricane Bob, has accounted for the top three precipitation events at Portland (PWM) (Sardinha 1998). The October 1996 storm, however, exhibited synoptic characteristics of an extratropical cutoff system with a direct tropical connection to mature Hurricane Lili. Effective precipitation production due to quasi-stationary focusing mechanisms established Maine’s all-time single rainstorm record at 488 mm (19.20 in).

b. Z_e-R Trials and Scanning Techniques

Rainfall estimates, derived by the KGYX PPS in real-time, used the "default" Z_e-R relationship (Z_e=300$R^{1.4}$) in October 1996. Significant rainfall underestimations were depicted (Fig. 1a) when compared to observational data (Fig. 1b). Operational experience and research (Klazura et al. 1997; Wilson and Brandes 1979; Burkhart 1996) suggest that this is often the case when sampling a tropical airmass. This known deficiency poses a significant threat since tropical moisture is a key ingredient to flash flooding.

In February 1999, improved coding of the WSR-88D Algorithm Testing and Display System (WATADS version 10.1) increased the reliability of PPS output (Tim O'Bannon Operational Support Facility (OSF) oral communication, 1999). In addition, the new WATADS version included a Terrain-Based Hybrid scan which could be examined. This technique has since become operational at all WSR-88D sites, however was unavailable during the October, 1996 storm. The scanning technique offers improved precipitation estimation by smoothing discontinuities due to strong vertical reflectivity gradients, which show as rings of sharply discontinuous rainfall estimates (O'Bannon 1998). Image smoothing is accomplished by removing an "optimal height" requirement in PPS adaptation data. The result is a strategy which uses reflectivity data from the lowest tilt if the bottom of the beam is not blocked by terrain. Therefore, a relatively fixed height above ground level is sampled by the radar.

Joss and Lee (1995) indicated vertical reflectivity gradients are most common across varied terrain. Therefore, this new surveillance method may be a valuable technique in Maine, where terrain is complex. Vertical reflectivity gradients also appear to be prominent during coastal orographic rain events and in "bright bands", both common phenomena in the KGYX surveillance range.

c. Methodology

After assessing hydrometeorological aspects of the record-breaking storm, components of the PPS were manipulated. Archive II data was obtained from the National Climatic Data Center (NCDC). Next, WATADS user-selectable parameters (Mckibben and Oakland 1994) permitted testing of the "default", "tropical" and "snow" Z_e-R equations (respectively; $Z_e = 300R^{1.4}$, $Z_e = 250R^{1.2}$ and $Z_e = 130S^{2.0}$) to produce Storm Total Precipitation (STP) products. The tropical relationship (Rosenfield et al. 1993) was included for investigation due to its superior rain gage to radar performance, called G/R ratio, when compared to several other Z_e-R equations during tropical rainfall events (OSF 1995). Also, the new snow Z_e-R relationship was investigated as it shows promise in recent operational tests (Super and Holroyd 1997). All three Z_e-R relationships have been approved for operational use by the OSF. Lastly, output from the Terrain-Based Hybrid scheme was compared to the Four Layer scanning technique. G/R ratios were then calculated and will be discussed both quantitatively and qualitatively.

3. METEOROLOGICAL HIGHLIGHTS

a. Extratropical Features

On 18 October, a 90-kt jet entered a negatively tilted 500-mb low which intensified into a vigorous cutoff system (5400 gpm). The system became quasi-stationary over eastern Pennsylvania by 1200 UTC, 20 October, and was embedded in an omega blocking pattern (not shown). Simultaneously, a surface low pressure (1004 mb) was situated in northeast Pennsylvania with an occluded front extending into southern New England. High pressure strengthened (from 1025 mb to 1034 mb) over the Canadian Maritimes by 1500 UTC, 21 October. Low-level winds increased as a strong northeast surface gradient developed over New England. Easterly winds persisted over the Gulf of Maine, which created a confluent boundary along the coast. In this case, low level ascent was likely enhanced as maritime air funneled toward the coastline in a single band. This focusing mechanism is a common phenomena during winter weather events and is known to enhance precipitation in the Northeast (Maglarus et al. 1995).

WSR-88D reflectivity images revealed this band slowly propagating north on 21 October. The southeast-northwest oriented echoes gradually backed in an east-west fashion as the system became more negatively titled, leaving southern Maine in an axis of heavy rain. This is fairly common, as a pivoted moisture band and resultant train echoes contributed to excessive precipitation during May 1989 (Cannon 1992) and other floods.

b. Connection to Hurricane Lili

Due to the sparsity of surface-based observations over the North Atlantic, satellite products, aircraft data, buoy reports and radiosonde data were examined to determine the connection of Hurricane Lili's moisture to the complex extratropical system. Also, forecast parcel trajectories were retrieved from the Air Resources Laboratory home page (http://www.arl.noaa.gov/ready/hysplit4.html) using the HYsplit trajectory model (Draxler and Hess 1997).

Lili formed in the western Carribean, traveling northeast before stalling as a mature hurricane near 34° N, 58° W on 21 October (not shown). It is difficult to quantify the extent of moisture advected to New England's coast from Lili. However, water vapor imagery indicated mid-level moisture entrainment along and north of the surface occlusion by 0015 UTC, 20 October. Low and mid-level trajectories from the HYsplit model depicted a deep east to southeast fetch of moisture being advected toward coastal Maine throughout the precipitation event. Experimental satellite-derived estimations of precipitable water, rainfall rate, and theta-e further supported the notion of significant moisture entrainment from Lili along this axis. Radiosonde and KGYX VAD Wind Profile data depicted a deep easterly wind component with maximum winds near 60 kt above 850 mb, providing an efficient conveyor belt transport of low and mid-level moisture.

c. Airmass Characteristics

To determine airmass characteristics sampled by KGYX during the event, upper air data derived from ETA initial gridded data fields, sounding data, and surface plots were examined. An axis of warm, moist air was advected north from the Gulf Stream to southern Maine. By 1200 UTC, 21 October, the GYX sounding was saturated from the surface to 600 mb (Fig. 2). At 850 mb, the temperature and dew point reached +9 C, while a 40-kt low-level northeasterly flow created a pronounced inversion within the KGYX surveillance range. The freezing level, a suspect area for bright banding, maintained a height near 3.2 km. Precipitable water values maximized at 32.3 mm (1.27 in) on 21 October.

The possibility of elevated convection existed, but sounding data indicated the likelihood of persistent stratiform rain embedded in the deep maritime flow. Although the source region for precipitation from Hurricane Lili was of maritime-tropical origin, KGYX was sampling a significantly modified airmass due to the influx of low level polar air.

4. THE HYDROLOGICAL EVENT

a. Statistical Evaluation of the Rainfall Intensity

At PWM, the 2-day storm total reached 14.49 in (Fig. 3), with a 1-day rainfall of 11.73 in on 21 October (Fig. 4) and 12.40 in falling in a 24-h window on 20-21 October, all new records (Keim 1998). An all-time state rainfall record was set for a single storm as 19.21 in was measured in the Saco community of Camp Ellis. This amount is just shy of the New England record of 19.76 in which was produced by Hurricane Diane in Westfield, Massachusetts in August 1955.

Keim estimated the statistical significance of the October 1996 event using recurrence intervals (Table 1). The availability of accurate and extended rainfall records and hourly rainfall information near the area of maximum rainfall made PWM the best candidate for examination. Using quantile approximations described by Wilks and Cember (1993), Keim yielded 1 day/100-yr precipitation estimates for PWM of 7.09 in and 9.05 in respectively, well under actual measured storm totals. The Hershfield (1961) quantile estimation technique, which allows for 24-h moving windows of observational data, yielded maximum 24-h/100-yr rainfall estimations of 6.24 in, less than half of the actual rain totals. 24-h rainfall totals may have been even more impressive in locations such as Camp Ellis, however hourly data was unavailable. Finally, multiple quantile methods were used to derive a storm return period of 474 yrs at PWM. Considering higher rainfall totals existed south of Portland, this storm was perhaps a 500-yr event at several locations

b. Antecedent Conditions and Hydrological Response

Climatological records indicate the 5.24 in of rain which fell at PWM during the 1 September through 19 October period was very close to the normal value of 5.31 in (Local Climatological Data 1996). In addition, the Royal River (Fig. 1b) represents the closest active long-term gaged site available within the severely flooded region. Before the flood occurred, the Royal River mean flow was close to normal at 1.5 m^3s^{-1}. Its typical mean flow for the entire month of October is 1.7 m^3s^{-1}.

The United States Geological Survey (USGS) used basin discharge data to compute record-breaking streamflows and extreme recurrence intervals (Hodgkins and Gregory 1997). The Presumpscot river in Westbrook, Maine (Fig. 1b) crested at a record flow of 652 m^3s^{-1}, well above the previous flood flow of 389 m^3s^{-1} from Hurricane Bob in August 1991. Several small rivers, brooks and streams in the PWM vicinity measured peak flows >500-yr recurrence levels when compared to historical data. Ocean salinity levels fell sharply near river deltas, where large volumes of fresh water emptied into area bays. Along the Fore River (Fig. 1b), a severe oil spill was flushed and diluted by the storm.

c. Damage Assessment

The Federal Emergency Management Agency (FEMA) provided a hazard mitigation report on the October 1996 storm. Damage to infrastructure in southern Maine was estimated at 6.45 million dollars (FEMA 1996). A major disaster declaration was issued for York and Cumberland counties (Fig. 1b).

The entire city of PWM was without water for several hours during a large scale search to locate ruptured water mains. Businesses and schools were closed due to the threat of contaminated drinking water. Surgeries were delayed at area hospitals. Flooded and washed out roads caused one motorist death. The primary interstate highway, the Maine turnpike, was closed for many hours.

Motorists trapped in large traffic jams at tollbooths shared their disgust with tollkeepers. Bridges and dams were destroyed from high water on area lakes and rivers. Communities such as Ocean Park, Old Orchard Beach and Westbrook (Fig. 1b) were severely flooded and resulted in rescue operations by boats. An estimated 1,000 structures were inundated with flood water, prompting the American Red Cross and Salvation Army to feed and shelter hundreds (Greenlee and Robitaille 1996).

5. DOPPLER ESTIMATES

a. The Data Set and Potential Sources of Error

Rain gage data was chosen for examination by selecting sites which spatially surrounded the region of maximum rainfall. The Mount Washington observation (MWN) was also chosen for study in order to include an example of a site which is greatly affected by beam blockage. Latitude-longitude positions from cooperative observer rain gages were determined to the nearest hundredth of a second using United States Terrain Series, Maine-New Hampshire topographic maps. These positions were converted to azimuth-range (AZRAN) locations from KGYX using the cursor home feature at the WSR-88D Principal User Processor. Finally, the WATADS Raw Data feature allowed extraction of STP values for individual pixels at given AZRANs.

Positioning error was inherent when converting gage sites to AZRAN locations. Beam blockage, bright banding, clutter suppression, terrain-based occultation files, physical radar limitations and drop size/distribution are other complications in precipitation detection (Hunter 1996).

Unlike Fulton's (1999) study, user input into the PPS, such as precipitation detection thresholds, were likely not significant factors affecting the precipitation accumulation algorithm during the October 1996 case considering the relatively low reflectivity values. However, the additive dBZ component employed by the KGYX occultation file (Fig. 5) may have produced inaccurate estimations when sampling beam blockage areas of the White Mountains in northern New Hampshire. Also, the Four Layer Hybrid Scan STP products would suggest additional errors due to vertical reflectivity gradients. This source of error is magnified within 50 km of the radar where multiple elevation angles are processed. Unfortunately, this encompasses the region of maximum storm totals. Lastly, the volume coverage pattern was set at 21 and not 11, which would have provided the best spatial and temporal sampling of the rapidly moving echoes.

b. Comparitive Assessment Between Scanning Techniques and the Z-R Equations

One method of measuring a rain gage to radar correlation, called G/R ratio, is computed by totaling a network of gage readings and dividing that figure by the sum of radar totals at each gage location. Z-R relationships perform best when the G/R ratio is nearest 1.0. As an example, a G/R factor of 2.0 means that the radar estimated rainfall would require doubling in order to provide the user with the actual gage measured rainfall.

Although both scanning techniques underestimated rainfall totals, the Four Layer scheme produced an average multiplicative factor of 1.64, outperforming the Terrain-Based scanning technique with an average G/R of 2.40 (Tables 2a and 2b). In addition, the tropical Z/R relationship significantly outperformed the default and snow equations by computing superior G/R multiplicative factors. In this case, the Four Layer Hybrid tropical scan scored an impressive G/R factor of 0.97, while the Terrain-Based tropical scheme underestimated precipitation totals, yielding a multiplicative factor of 1.41.

However, the STP product and G/R ratios indicated the high terrain of the White Mountains appeared to cause significant localized error when using the Four Layer Hybrid scanning technique. This was likely due to the fact that at this range, this scanning technique employs the 0.5 deg elevation angle (center beam height 1,048 m) in the PPS. This low elevation angle would be significantly blocked by the mountains. To compensate for beam blockage, an occultation file is used to accumulate precipitation with each volume scan into the STP product. This approximation creates an increased source of rainfall estimation error.

The Terrain-Based technique showed improved performance across high terrain. This scheme most likely utilized the 1.5 deg elevation angle (center beam height 2,800 m), in an attempt to overshoot the White Mountains, thereby minimizing additive input from the occultation file.

Lastly, "bright banding" signatures were evident on STP products during the event, and likely contributed to radar overestimation over central New Hampshire. At this location, both scanning techniques would employ the 0.5 deg elevation angle. Over this terrain, the center beam lies at approximately 3000 m above mean sea level, which was near the altitude of the freezing level throughout the event.

6. CONCLUSIONS AND RECOMMENDATIONS

All-time precipitation records for Maine were established as an extratropical system connected with tropical moisture from Hurricane Lili to produce train echoes and severe flooding. Statistically, quantile methods suggested rainfall totals on the order of a 500-yr event, while USGS data indicated the resultant streamflow conditions exceeded a 500-yr event. The extreme flooding caused one death and severe damage to property and commerce.

The Rosenfield equation outperformed the "default" and "snow" Z_e-R relationships when G/R ratios were compared in this event. It is important to recognize airmass characteristics and coordinate efforts to switch default to tropical Z-R equations at early stages of an event. However if the PPS is modified too far in advance of tropical moisture, the radar may overestimate rainfall totals.

The Four Layer Hybrid scanning technique showed overall improvements and outperformed the Terrain-Based scheme. However, the Terrain-Based hybrid scheme offered visual improvements in the STP product by maintaining beam height above varied terrain.

Hopefully, highlighting this event will improve forecaster performance through pattern recognition. Accurate precipitation estimates and forecaster confidence can also be enhanced when WSR–88D precipitation algorithms are calibrated with real-time surface rainfall observations (Cannon 1995). Incorporation of rain gage data into WSR-88D algorithms within stage II of the PPS will further enhance accuracy of precipitation estimates.

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FIGURES

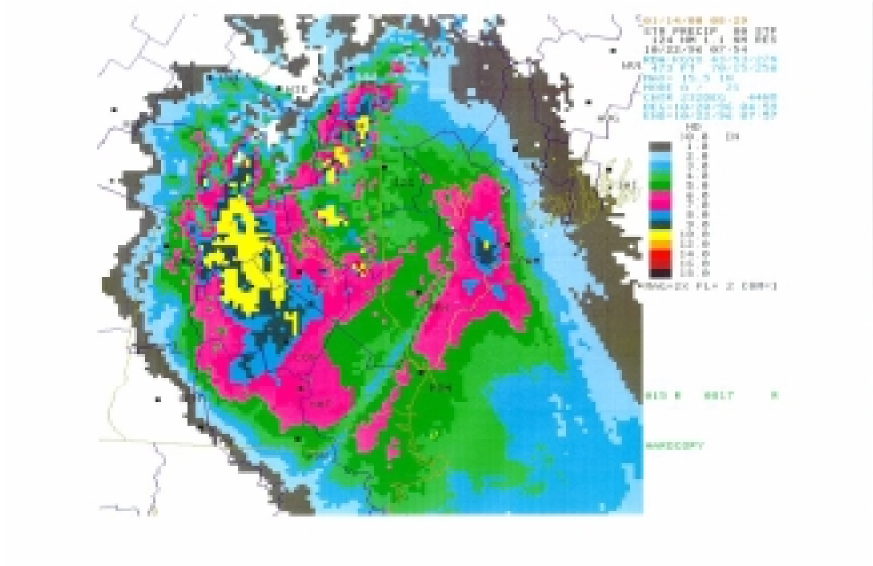

Fig. 1a. Rainfall estimations from the October, 1996 storm using the WSR-88D STP. Note yellow shading indicates 10 inches or more rainfall estimation.

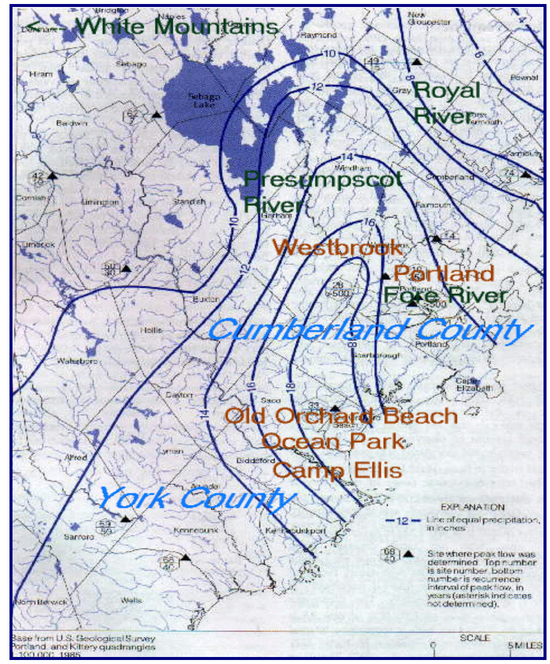

Fig. 1b. Isolines depicting storm rainfall totals in inches for the October, 1996 flood.

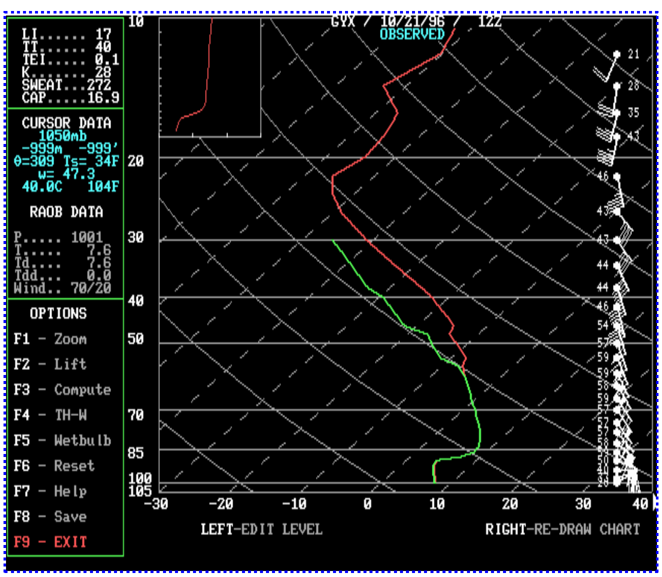

Fig. 2. 1200 UTC, 21 October, 1996 GYX sounding. Note deep southeasterly component, with inversion below 850 mb in shallow northeast flow.

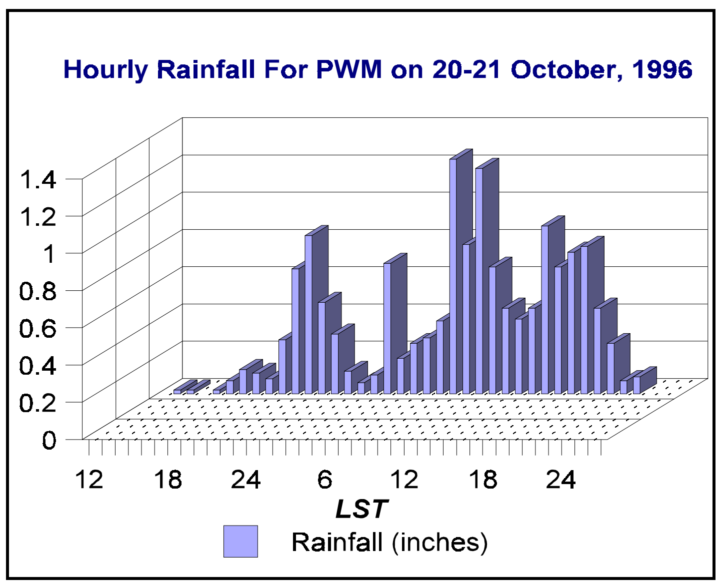

Fig. 3. Hourly accumulation of rainfall at Portland, Maine (PWM) for 20-21 October, 1996.

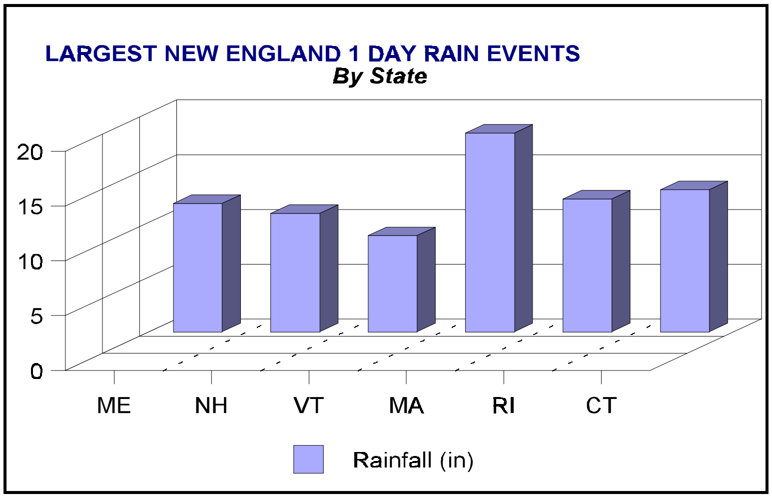

Fig. 4. All-time record 1 day rain events by state.

Rank	Rainfall amount (in)	Date	Recurrence interval (yr)
1 DAY			
1	11.73	21 Oct 1996	373
2	7.76	19 Aug1991	78
3	7.48	6 Oct 1962	69
4	7.48	11 Sep 1954	69
5	5.59	10 Oct 1998	100+
2 DAY			
1	14.49	20-21 Oct 1996	474
2	9.53	6-7 Oct 1962	102
3	8.23	9-10 Oct 1998	NA
4	8.15	19-20 Aug1991	57
5	6.77	18-19 Jun 1922	29

Tbl. 1. Top-five heaviest 1 and 2 day rainfall events at Portland, Maine, with estimated recurrence interval for each Event.

4 - LAYER HYBRID SCAN G/R NUMBERS

VCP: 21 Date/Time:
(0525 UTC 10/19/96 - 2151 UTC 10/22/96)

Station	Height of .5 deg beam	$Ze=300R^{1.4}$ "Default"	$Ze=250R^{1.2}$ "Tropical"	$Ze=130S^{2.0}$ "Snow"	Actual Total Rainfall	G/R Nos. Default/Trop/Snow
Mt. Wash.	1048 m	5.0 inches	25.5 inches	4.1 inches	12.60 inches	2.52/0.49/3.07
Camp Ellis	555	7.9	13.9	7.2	19.20	2.43/1.38/2.67
K. Port	740	8.1	14.4	6.5	13.03	1.61/0.90/2.00
Sanford	802	8.3	14.5	6.5	11.22	1.35/0.77/1.73
Elliot	1419	8.9	15.4	6.7	11.84	1.33/0.77/1.77
Hollis	463	5.6	11.1	5.2	10.13	1.81/0.91/1.95
Waterboro	648	6.7	10.3	5.1	9.90	1.48/0.96/1.94
Limington	370	5.9	9.8	5.2	9.39	1.59/0.96/1.81
E. Hiram	432	5.8	9.7	5.0	9.20	1.59/0.95/1.84
Cornish	463	6.0	10.0	5.1	8.40	1.40/0.84/1.65
Scarb.	339	7.5	13.3	6.2	15.52	2.07/1.17/2.50
Gorham	278	8.5	15.1	6.7	19.00	2.24/1.26/2.84
Portland	278	8.6	14.7	6.4	14.68	1.71/1.00/2.29
S. Windham	185	8.4	14.7	6.5	16.00	1.90/1.09/2.46
Poland	123	5.6	7.8	4.1	8.98	1.60/1.15/2.19

Multiplicative Adjustment Factor **$F = \sum G / \sum R$ = | 1.78 | *0.97 | 2.18**

***BEST RATIO: TROPICAL**

Tbl. 2a. Rain gauge/radar ratios (F) using the Four-Layer Hybrid scanning technique. Note tropical Z/R equations outperformed other relationships.

Terrain-Based SCAN G/R NUMBERS

VCP: 21   Date/Time:

(0525 UTC 10/19/96 - 2151 UTC 10/22/96)

Station	Height of .5 deg beam	$Ze=300R^{1.4}$ "Default"	$Ze=250R^{1.2}$ "Tropical"	$Ze=130S^{2.0}$ "Snow"	Actual Total Rainfall	G/R Nos. Default/Trop/Snow
Mt. Wash.	1048 m	3.0 inches	9.9 inches	2.6 inches	12.60 inches	4.20/1.27/4.85
Camp Ellis	555	6.7	11.7	5.4	19.20	2.87/1.64/3.56
K. Port	740	7.1	12.2	5.7	13.03	1.84/1.07/2.29
Sanford	802	7.0	11.5	5.7	11.22	1.60/0.98/1.97
Elliot	1419	7.9	13.8	6.5	11.84	1.50/0.86/1.82
Hollis	463	4.9	8.8	4.3	10.13	2.07/1.15/2.36
Waterboro	648	5.4	9.3	4.7	9.90	1.83/1.06/2.11
Limington	370	4.6	7.9	4.0	9.39	2.04/1.19/2.35
E. Hiram	432	4.1	6.7	3.5	9.20	2.24/1.37/2.63
Cornish	463	4.4	7.3	3.8	8.40	1.91/1.15/2.21
Scarb.	339	5.4	9.8	4.3	15.52	2.87/1.58/3.61
Gorham	278	6.0	10.6	4.6	19.00	3.17/1.79/4.13
Portland	278	5.5	9.6	4.4	14.68	2.67/1.53/3.34
S. Windham	185	5.4	9.4	4.1	16.00	2.96/1.70/3.90
Poland	123	1.8	3.2	1.6	8.98	4.99/2.81/5.61

Multiplicative Adjustment Factor **$F = \sum G/ \sum R$ = | 2.58 | *1.41 | 3.12**

*** BEST RATIO: TROPICAL**

(visual smoothing: improvement in regions of high terrain)

Tbl. 2b. Rain gauge/radar ratios (F) using the Terrain-Based scanning technique. Note tropical Z/R equations outperformed other relationships.