"Remote Identification of Precipitation Type," by Ferguson and Breyfogle. Presented at the 1994 International Snow Science Workshop, Snowbird, Utah, October 31 to November 4, 1994.

REMOTE IDENTIFICATION OF PRECIPITATION TYPE

by

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ABSTRACT

The results of a 2-year project to investigate the feasibility of automatically detecting precipitation type for highway hazard-reduction programs in the Cascade Mountains of Washington State are reported. The project investigated available technology for remote identification of precipitation type, selected a suitable sensor for testing, and compared field and laboratory tests with visual observations. Modifications of the hardware and software were conducted to optimize the use of precipitation identification (PID) sensors in operational hazard-reduction programs.

A survey of available PID sensors showed that a variety of techniques to determine the phase of precipitation are being developed. Only a few of the PID sensors that are available commercially, however, were found capable of operating reliably in remote mountain locations. Of these, only one, called HYDROS, was sufficiently cost effective for hazard-reduction programs.

A HYDROS sensor was installed at the Washington State Department of Transportation (WSDOT) observation station at Snoqualmie Pass, and was connected to automatic data-logging equipment. Another HYDROS was equipped for mobile use and tested at mountain sites in Alaska, other areas of Washington, and in Japan.

Data from each sensor were compared against visual observations. The results of this analysis showed adequate performance from the HYDROS. The analysis also showed that the HYDROS data can be a valuable asset to the hazard mitigation programs along mountain highways, particularly when combined with data-loggers, totaling precipitation gages, and computer graphics.

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1. INTRODUCTION

Many hazard-reduction programs in the mountains rely on a significant amount of quality weather data. Traditionally, these data have been acquired by visual observation. However, because of increasing population, development in the mountains, and level or reduced staffing, these programs must constantly improve their response efficiency. To do so, automated weather stations that can operate continuously in remote locations are being employed.

Reliable, automated weather data has been available for nearly 20 years. There are several weather parameters, however, that are difficult to measure. One of these critical parameters is type of precipitating particles. There are a number of reasons why hazard-reduction programs need to know whether precipitation is solid or liquid. The following describe two critical functions that have been identified in the Cascade Mountains of Washington State.

1.1 Avalanche Control Response Procedures

Being able to remotely determine whether precipitation is solid or liquid could offer a vast improvement to avalanche control programs in the Washington Cascades because of a unique aspect of weather that exists there. Mid-winter rain storms are frequent in the coastal mountain ranges and often snowfall can change to rain almost instantaneously in the Washington Cascade passes. This occurs when persistent temperature inversions from easterly pass winds are quickly eroded by dynamic storm fronts. Under such conditions, numerous large and dangerous avalanches can begin within minutes after the precipitation type change.

Methods to forecast these kinds of rapid changes in precipitation type have improved dramatically over the past few years. Unfortunately, these predictions are only approximations because the depth and strength of inversions, and the slope and strength of approaching fronts, cannot be known exactly with today's technology. Forecasts are accurate only to within 1/2 to 1 hour, 6 to 24 hours in advance (Ferguson and others, 1990). This uncertainty does not always allow enough time to close roads or deploy avalanche control personnel in the most efficient manner, especially for the large number of avalanches that may release spontaneously with a precipitation type change.

Currently, precipitation type changes are monitored by visual observation. Making visual observations is a difficult task because the inversion and frontal characteristics common in the Cascade passes cause precipitation types to change in complex patterns. Figure 1 shows a schematic, cross-sectional diagram of typical precipitation patterns that may occur in the Cascade passes. Figure 1a shows the large horizontal and vertical variation in precipitation types that is possible during a moderate, easterly pass-wind inversion. Moments later, that pattern can change dramatically, as illustrated in Figure 1b. Observers are unable to notice changes in precipitation type at all of the widely spaced avalanche paths in time for even the most efficient deployment of avalanche control measures during major storm cycles. A method of remotely monitoring precipitation changes would help solve this problem. In addition, historical records of precipitation type and amount can be compared with avalanche occurrence records to develop a better understanding of these large and dangerous avalanche cycles.

1.2 Snow-Stability Forecasting

In addition to instantaneous avalanche initiation by rain-on-snow events, there are a variety of other conditions that cause snow to avalanche in mountain areas. One way of determining snow stability is to gather data on the vertical and horizontal structure of snow layering. Usually, this involves a cumbersome method of digging a hole in the snow to gather a number of physical and mechanical measurements on each layer. These snow pits are only representative of specific sites and times and require a significant amount of time to perform. Also, conditions under which pertinent data are obtained from required elevations and slope exposures can be difficult and often hazardous.

An alternative to digging numerous snow pits is to use computer programs that model snow-layer stratigraphy. Currently available models require hourly weather data as inputs, including accumulations of each precipitation type.

Hourly weather data are available through existing mountain-located automated weather stations. The sensors at these stations record total precipitation, temperature, relative humidity, wind, and snow depth. There are no direct measurements of precipitation type. If snow stratigraphy models are to be used for assessing snow stability in large areas, there must be a way of remotely monitoring precipitation type.

2. REVIEW OF METHODS TO IDENTIFY PRECIPITATION TYPE

To better support avalanche control programs and provide data to snow-layer stratigraphy models, measurements of precipitation type are needed. Conditions that cause precipitation to reach the ground as a solid or liquid depend on vertical gradients of temperature and dew point, particle size, and particle fall speed. A complex interaction of these parameters determines the precipitation type. Because of this complexity, only rough estimates of precipitation type are possible through indirect correlations. Direct measurement of precipitation type is difficult because different types share many of the same physical characteristics.

2.1 Indirect Correlations

There has been some effort to relate precipitation type to upper atmosphere conditions (Murray, 1952; Lamb, 1955). These relative comparisons do not consider the low-level temperature inversions that are common in the Cascades. For example, Figure 2 shows the probability that precipitation type is snow in a Cascade mountain pass (Stampede) for observed upper-air temperatures (850 mb) from the closest radiosonde observation, which is on the Pacific coast (Quillayute). When pass winds are from the east (bringing cold, Arctic air into the pass) the probability of snowfall at Stampede significantly increases, even when 850 mb temperatures are well above freezing.

In addition to poor correlations between the upper atmosphere and Cascade pass precipitation type, upper-air data are gathered only twice a day from stations (such as Quillayute and Spokane) that are quite far from mountain precipitation sites. Their designated observation times do not always coincide with precipitation periods. Therefore, accurate predictions of precipitation type from upper atmospheric conditions are not possible.

Measurements of ground-level air temperature most often have been used to determine precipitation type. Significant research to study the relation of air temperature to precipitation type has been conducted in Japan, where heavy snowfalls affect the large population and automated snow-melt systems are used to clear roadways. For example, Tamura (1990) found that near-surface air temperatures during snowfall in Nagaoka, Japan, ranged from -6 °C to 6 °C. Sugai (1992) also found that snow accumulated at ground temperatures as high as 6 °C. The average threshold temperature for the snow-to-rain transition ranged from -0.4 to 2.6 °C for 13 observation sites in Japan. This range of threshold values is too large for accurate rain-snow predictions in an operational hazard-reduction program.

Measurements of snow depth also have been used to help identify precipitation (Mark Moore, *personal communication*). When snow depth is increasing, accumulating precipitation is obviously of the solid type. On the other hand, solid precipitation could be accumulating when snow depth is remaining constant or actually decreasing. This would occur if the rate at which the snowpack settles is greater than the snow accumulation rate. This phenomena is common in the Cascades. Therefore, a strict reliance on snow depth as an indication of precipitation type is not feasible.

2.2 Direct Measurement

Sensors developed to more accurately measure precipitation type consider latent heat, conductivity, impact noise, opacity, and fall speed. Latent heat devices measure the amount of thermal changes in a heated bath of water. Conductivity sensors place conductors on a heated plate so that accumulating snow will bridge the circuit and cause a small current. Tests on acoustic signals of falling precipitation, using a sensitive microphone attached to a heated plate, are just beginning. Opacity of falling snow has been detected by using simple video cameras, and recent work is being conducted to digitize the images for remote monitoring and data storage. Light beams also have been used to determine the reflectance of falling particles. Many of these sensors are summarized in a recent paper by Tamura (1992) for Japan's automated, road snow-melt program.

Fall speed can be determined by using vertically oriented radar. Also, falling particles through a horizontal light beam disrupt the beam in characteristic frequencies that depend on its terminal velocity. Terminal velocities for snow range from about 0.5 to 1.5 m/s, and graupel fall speeds are about 1.0 to 2.5 m/s (Hobbs, 1974). Rain falls at speeds centered around 7 m/s (Wallace and Hobbs, 1977). Solid and liquid precipitation also can have distinctly different sizes. Rain drops usually are a few hundred microns in diameter (Wallace and Hobbs, 1977), whereas snow particles can range in size from several hundred microns to several thousand microns (Hobbs, 1974). Snowflakes (aggregates of snow crystals) can be several millimeters in diameter. Therefore, a sensor that can measure both size and fall speed is more accurate than one which measures just one or the other.

The new weather radars, NEXRAD, that are being installed around the country by the National Oceanic and Atmospheric Administration (NOAA) can locate bands in the atmosphere where precipitation type is changing. Unfortunately, the only existing NEXRAD for Washington State is located on Camano Island. The signal from this radar is blocked by the high terrain that surrounds the Cascade passes and probably cannot see reflective patterns within the pass. A second radar is planned for installation in Spokane, which will help but not solve the Cascade viewing problem.

Only two, on-site, precipitation identification sensors were found to be available commercially in the United States. Both use an infrared laser beam to determine fall speed and particle size. The two sensors have been tested at length in laboratories and at field stations of low elevation. One, the LEDWI sensor (Scientific Technology, Inc.), is being installed at all newly automated observation stations (ASOS) by the National Weather Service (NWS), a division of NOAA. The sensor costs about $15,000 and requires a concrete mounting base. The HYDROS (Contracting Technologies, Inc.) costs about $3,000 and can be mounted on any existing tower or pole. HYDROS was chosen for this project's testing because it is significantly less expensive than the LEDWI, has more versatile installation options, and seemed to perform equally in manufacturer's tests.

3. PROCEDURES

The dimensions and components of a HYDROS precipitation identification sensor are illustrated in Figure 3. HYDROS is designed to operate in a local or remote mode. In local mode, it can be linked directly to a computer. Parameters that determine its discrimination algorithm can be changed, and a history of particles that have passed through the beam can be reviewed. In remote mode, HYDROS outputs precipitation type and intensity after temperature and relative humidity are given as inputs. HYDROS discriminates precipitation type into six categories, as shown in Table 1.

Table 1. HYDROS precipitation categories.

1 = none (no precipitation)
2 = yes (precipitation unidentified)
3 = rain
4 = snow
5 = mist
6 = snow flurry

3.1 Remote Mode

One HYDROS was installed at the WSDOT Snoqualmie Pass observation station. It was connected to a CR10 programmable data-logger (Campbell Scientific, Inc.) to test its ability to operate remotely. Relative humidity and temperature sensors were connected to the CR10 so that it could be programmed to initiate a response from HYDROS by automatically sending current air temperature and relative humidity every 20 seconds. A totaling precipitation gage also was connected to the CR10 to determine water equivalent values of precipitation particles.

For every increment of accumulation[3] that was recorded from the totaling precipitation gage, a histogram of precipitation type was stored. Every hour, current precipitation type and the incremental histograms were summed to show the last hour's water-equivalent accumulation of snow and rain. The data were downloaded several times a day into a WSDOT computer-archive file by way of a telephone modem. A sample of the output format from the CR10 is shown in Table 2. Output was compared with visual observation from WSDOT avalanche crew at least once day.

[3] The WSDOT avalanche programs use 0.01" as an increment standard for their totaling-precipitation gages.

Table 2. Sample of raw data from CR10 data-logger with HYDROS in remote-mode operation. The order of data are site identification number, Julian date, local time, battery voltage, air temperature (°C), relative humidity, hourly precipitation accumulation (inches water equivalent), current precipitation type (see Table 1), hourly water equivalent of snow, and hourly water equivalent of rain.

```
7,69,1200,12.04,4.611,93.5,.02,5,0,.02
7,69,1300,12.05,4.322,89.8,.05,5,.001,.049
7,69,1400,12.04,3.99,92.9,.03,1,.001,.029
7,69,1500,12.04,4.12,89.7,0,2,0,0
7,69,1600,12.04,2.65,91.6,.01,5,.005,.005
7,69,1700,12.04,2.958,95.1,0,1,0,0
7,69,1800,12.04,1.857,94.9,0,1,0,0
```

3.2 Local Mode

A second HYDROS was configured in local mode for transport to different observation stations. Data from this mobile HYDROS were logged directly into a portable computer. Table 3 shows the format of local-mode output data from HYDROS. Note that particle size is reported in hexadecimal numbers. Data from the mobile HYDROS were acquired during laboratory tests and from field studies in Alaska, various Washington locations, and Japan.

Table 3. Sample output of HYDROS local-mode data.

```
Time 13:27
Date 01/14/92

Precipitation type      Snow
Particle size           001A

Average size            006E
Storm intensity          99
Air temperature         0032
Relative humidity       0098
```

3.3 Configuration Parameters

The HYDROS PID sensor identifies the type of particles passing through its infrared laser by using discriminant algorithms, which are based on adjustable set points for particle-per-second, particle size, and rain-snow threshold temperature. To determine how to adjust these set points for optimal use in the Cascades, a survey of the precipitation regime at Snoqualmie Pass was conducted. This helped to determine the range and frequency of precipitation types. The survey analyzed 10 years of daily observation records from the WSDOT Snoqualmie Pass observation station between the winter seasons 1981-82 and 1991-92. Within this period, there were over 1,500 daily observations. Precipitation occurred at the time of observation (0700 PST) on 498 of those days.

Results of precipitation survey for Snoqualmie Pass are shown in Figure 4. The graph of precipitation type versus temperature includes a mixed category of sleet (both rain and snow observed simultaneously) and freezing rain. From Figure 4, it is clear there is a broad threshold temperature for precipitation type, from -8 °C to +5 °C. Below -8 °C, 100 percent of precipitation fell as snow. Above +5 °C, 100 percent of precipitation fell as rain. The mean threshold temperature, where there is a 50-percent chance of either rain or snow falling, occurs at +1 °C.

Precipitation data from Snoqualmie Pass were compared with those accumulated in Japan by Tamura (1990) and Sugai (1992). At Snoqualmie Pass, snowfall occurs at temperatures up to 5 °C. Data acquired in Japan also shows snowfall at temperatures up to 5 °C, with some stations seeing snowfall up to 6 °C.

In Japan, there were only a few stations where rain accumulated at temperatures below 0 °C. At these locations, when air temperatures were below 0 °C, less than 10 percent of the precipitation accumulated as rain. In addition, there was no rain observed at temperatures below -1 °C. In contrast, at Snoqualmie Pass, up to 20 percent of the precipitation can accumulate as rain at temperatures below 0 °C, and rain is observed when temperatures are as low as -5 °C.

The above results confirm the uniqueness of Cascade precipitation patterns. It made clear that the rain-snow set points for the discriminant algorithms needed changing from the manufacturer's settings before HYDROS could function properly in the Cascades. The high set point required a factory change from 2.8 °C to 5 °C.

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The low set point was changed from -2.8 °C to -8 °C by the user in the HYDROS user-interface setup table.

4. PERFORMANCE EVALUATION TESTS

There is some difficulty in quantitatively testing PID sensors because precipitation characteristics can be quite variable over space and time. Also, visual observations are subjective and may include a significant amount of error in classification. Considering these difficulties, attempts were made to compare sensor data with visual observations of precipitation that included the effects of precipitation on snow and ground surfaces.

4.1 Rain, Sleet, and Snow

Figure 5 shows output data from the HYDROS and 189 coinciding visual observations of precipitation type. Sequential observations were acquired at variable increments from about 1100 hours to 1800 hours local time on January 14, 1993.

Hydros data are marked with | and visual observations are marked with o. They agree when the symbols overlap within the same category of snow, mixed, or rain. Precipitation type classifications follow those outlined in Table 4. For example, the visual category of light rain (R-) matches the HYDROS category for mist (5) and the number 2 is used on the graph to denote this precipitation type category.

Table 4. Precipitation type classification. R = rain, ZR = freezing rain, R/S = mixed rain and snow, IP = ice pellet, SG = snow grain, and S = snow (- and + mean light and heavy).

CATEGORY	OBSERVATION	HYDROS	DESCRIPTION
0	no precip	1 none	
1	R-	5 mist	
2	R	3 rain	RAIN
3	R+		
4	ZR		
5	R/S		
6	IP-		TRANSITION
7	IP		(MIXED)
8	IP+		
9	SG-		
10	SG		
11	SG+		SNOW
12	S-	6 flurry	
13	S	4 snow	
14	S+		
15	unknown	2 yes	

HYDROS never reported precipitation when none was observed. Precipitation was observed six times when HYDROS recorded none. It should be noted, however, that HYDROS requires about 1.5 minutes to establish valid precipitation and these visual observations may have occurred within that 1.5 minutes before HYDROS could respond. When the observer noted snowfall, HYDROS classified correctly 65 percent of the time. This was wet snow, though, and there may have been some unseen liquid water that only the sensor could detect. When it was sleeting, HYDROS classified 73 percent as rain, 16 percent as snow, and 7 percent as unknown.

During the test shown in Figure 5, the PID sensor was located at the Nagaoka Institute for Snow and Ice Studies in Nagaoka, Japan. Therefore, in addition to visual observations, HYDROS's data could be compared with a wide array of the Institute's automatic weather sensing devices that operate there.

Comparison with other available weather data showed that during the period when sleet was observed (about the first 100 observations), 45 mm of precipitation fell, but no snow accumulated on the ground. During this time, HYDROS reported mostly rain. It is assumed that HYDROS classified mixed precipitation as rain during the period when there was a high ratio of water to ice in the sleet mixture and no snow accumulated on the ground.

The next period of observations (from about 100 to 140) was mostly snow. HYDROS continued reporting some periods of rain. The density of snow accumulating during this time was about 250 kg/m^3, rather high for newly fallen snow, but indicative of warm, wet snow. After this (from about observation 140 to 189) HYDROS misclassified less often and accumulating snow density during this time was 100 to 150 kg/m^3, which is more typical of dry snow. It appeared that HYDROS correctly identified snow when there was a low water-ice ratio in the precipitation and ground accumulations did occur.

Another perspective of HYDROS's identification accuracy was possible from data gathered at Snoqualmie Pass (February 9 - April 12, 1994). This late in the season, there are not as many sharp changes in precipitation type. Also, air temperatures usually are warmer and less fluctuating than during early- or mid-winter conditions. There were, however, about 200 observations of snowfall, and 40 observations each of rainfall and sleet during this period.

At the Snoqualmie Pass site, a total-precipitation gage was used to determine water equivalent of HYDROS's observed snow and HYDROS's observed rain. Hourly output from a histogram of HYDROS's data were compared with time-specific visual observations. This meant that some misclassification is possible if a different precipitation type occurred during the hour than was observed at a moment in time by visual identification. With that caveat in mind, it is interesting to note that the average percent of HYDROS-identified rain, during the hour near visual observations of rain, was 96. Conversely, the average percent of rain was 44 when there were visual observations of sleet and rain was identified an average of 1% of the time when there were visual observations of snow. The HYDROS output data are shown graphically in Figures 6,7, and 8 for visual observations of rainfall, sleet, and snowfall, respectively.

A more complete picture of precipitation identification accuracy can be obtained by viewing individual storm cycles with visual observations that are coincident with HYDROS data. Figure 9 shows several precipitation events that occurred March 16-18, 1994. The following summarize the output:

2400-0200, 3/16	Rain observed and rain recorded.
0800-1100, 3/16	Some sleet, but mostly snow was observed. HYDROS recorded 30-percent, 3-percent, and 8-8-percent rain during each hour.
1400-1800, 3/16	Snow observed and snow recorded.
2100-0300, 3/16-17	Snow sliding off roofs was heard. HYDROS recorded about 2-percent rain during 3 hours overnight, which could indicate some wet snow precipitation or brief periods of rain.
0700, 3/17	Snow layering showed buried melt layers (from previous day's rain and sleet) with graupel on the surface.
1500-1800, 3/17	Sleet observed and HYDROS recorded 40-percent, 40-percent, and 60-percent rain during each hour.
about 2200, 3/17	Observed that previously bare parking lot was covered with snow. HYDROS recorded snowfall beginning after 1800, with less than 1-percent rain in subsequent hours until 2300.
about 0300, 3/18	Observed that previously snow-covered parking lot was muddy. HYDROS recorded increasing amounts of rain after 2400, with 60-percent to 75-percent rain from 0200 to 0400.
0700, 3/18	Snow observed and snow recorded.

These crude comparisons suggest the HYDROS discrimination algorithms may be appropriate for identifying the precipitation types that affect snow or ground surfaces. The fact that the HYDROS sensor does not have a classification for mixed types of precipitation may work to the advantage of hazard mitigation programs. For example, mixed types that are identified by HYDROS as rain usually interact with the snow or road surface like a liquid; so it makes sense that it is identified as liquid precipitation. Alternatively, observed sleet that is identified by HYDROS as snow usually interacts with the existing snow or road surface like snow. Also, the computerized snow-stratigraphy models need inputs of rain or snow, and cannot interpret mixed categories.

Note that when freezing rain is precipitating, it falls like rain. It only can be identified by additional sensors on the depositional surface. These type of sensors are available and mostly used for road and runway surface applications (Kelley, 1990).

4.2 Graupel

Because the fall speed of graupel is between that of rain and snow, there was some concern about HYDROS's ability to detect graupel as a solid. Only one period of data, between midnight and 7 am on 17 March 1994, allows an analysis of graupel detection (Figure 9).

Although small amounts of rain were identified around midnight, these corresponded to audible verification of snow sliding off of roofs. The roof slides could have resulted from wet-snow accumulations that corresponded to the period when HYDROS recorded some rain.

Graupel was observed on the snow surface at the 7 am observation. The previous hour's precipiation was identified as snow and that may have been the period during which the graupel accumulated. Therefore, it appears that graupel may be correctly identified as snow, or solid precipitation particles.

4.3 Drizzle

The mobile HYDROS was tested at remote sites on the Juneau Icefield, in Alaska, for a period of about 3 weeks in late July and early August 1993. Unfortunately, this area experienced an unprecedented period of dry weather. It afforded, however, two brief tests of scattered drizzle. HYDROS can detect particles down to 100 microns in diameter and many drizzle particles are near 100 microns. Therefore, HYDROS had difficulty detecting drizzle in these brief tests.

4.4 Wind

The mobile sensor also was mounted on a vehicle and tested in a laboratory to analyze the effect of wind on precipitation identification. The effective fall speed of particles may be altered under high winds. This could cause rain that is driven horizontally through the PID detecting beam to look like snow. Because the beam is 3.3 mm wide and 1.0 mm high, however, the manufacturer has minimized the effect of changing horizontal fall components. In addition, because the discriminent algorithms identify precipitation type by particle size, as well as fall speed, only unusually large, wind-driven water droplets were misclassified.

The vehicle-mounted sensor operated for several hours during 1 day of variable precipitation types. Vehicle speeds varied from 0 to 50 mph. No effect on the HYDROS output was observed. Quantitative effects were difficult, however, because the precipitation type changed frequently during the observation period. In the laboratory, water droplets were sprayed vertically (to simulate typical rainfall) and horizontally (to simulate wind-driven rainfall) through the detecting beam. In both tests, the HYDROS identified the droplet spray as rain, indicating no effect from wind.

5. APPLICATION AND IMPLEMENTATION

The results of this project indicate that precipitation identification sensors may be a useful tool for hazard mitigation programs.

To fully implement the sensor, it is useful to tie its output to a totaling precipitation gage. To do so, the data logger should be set to store a histogram of precipitation type every time the totaling gage increments. A flow chart illustrating such a program is shown in Figure 10. A sample program for the CR10 that accomplishes this task is included appendix A.

The HYDROS requires serial communication with a data-logger. Figure 11 show how to wire the sensor to a CSI, CR10 data-logger. Most other data-loggers can interface with the sensor in a similar way.

Monitoring the data-logger allows instantaneous views of precipitation type and intensity. The most practical way to view output, however, is in cumulative graphs like that shown in Figure 9. This can be accomplished by using simple graphing routines on the raw data, or through standard graphic packages.

Currently, the HYDROS requires AC or DC power, nearby data-logger or computer, and telephone, radio, or short-haul modem access. About 1 amp of power is necessary to heat the HYDROS lenses. Other power requirements to operate the data processor are small (20-250 ma). Future testing is required to determine if the lenses can operate unheated so the unit can be recharged with a simple solar panel.

6. CONCLUSIONS AND RECOMMENDATIONS

This project found that existing theoretical models cannot adequately estimate precipitation type in the Washington Cascade passes where easterly pass winds cause frequent temperature inversions. Direct measurement of precipitation type is required for many hazard-reduction programs in the mountains. Infrared sensors appear to be most economical and most capable of functioning successfully in remote winter environments.

The HYDROS PID sensor could reliably classify rain and dry snow. Wet snow and sleet were classified as rain or snow, depending upon the ratio of water to ice. Sleet interacts with road or snow surfaces like rain if its water to ice ratio is high and like snow if its water to ice ratio is low. This ratio seems to correspond with precipitation falling characteristics and HYDROS's discrimination.

In addition to sleet, ice pellets, hail, graupel, and freezing rain are not separately distinguished by the HYDROS PID sensor. HYDROS appears to correctly identify graupel as snow but may occasionally identify ice pellets and hail as rain if the falling particles are small-diameter with rapid fall velocities.

There appears to be little or no effect from wind on HYDROS's ability to accurately identify precipitation type.

Most cold-temperature rains at Snoqualmie Pass occur during an easterly pass wind and an associated low-level temperature inversion. The surface wind events that draw cold air across the passes are common in mountain areas around the world. What causes the Cascade passes to be unique is the contrast in air masses that meet there. Westerly winds, which predominate at upper levels, bring relatively warm, marine air to the mountains aloft, while surface pressure gradients cause easterly winds to drag dry, cold, Arctic air over the passes at the surface. This means that the confidence developed in a precipitation identification sensor, which can work for these extreme conditions, will easily apply to other mountain areas around the world.

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LIST OF FIGURES

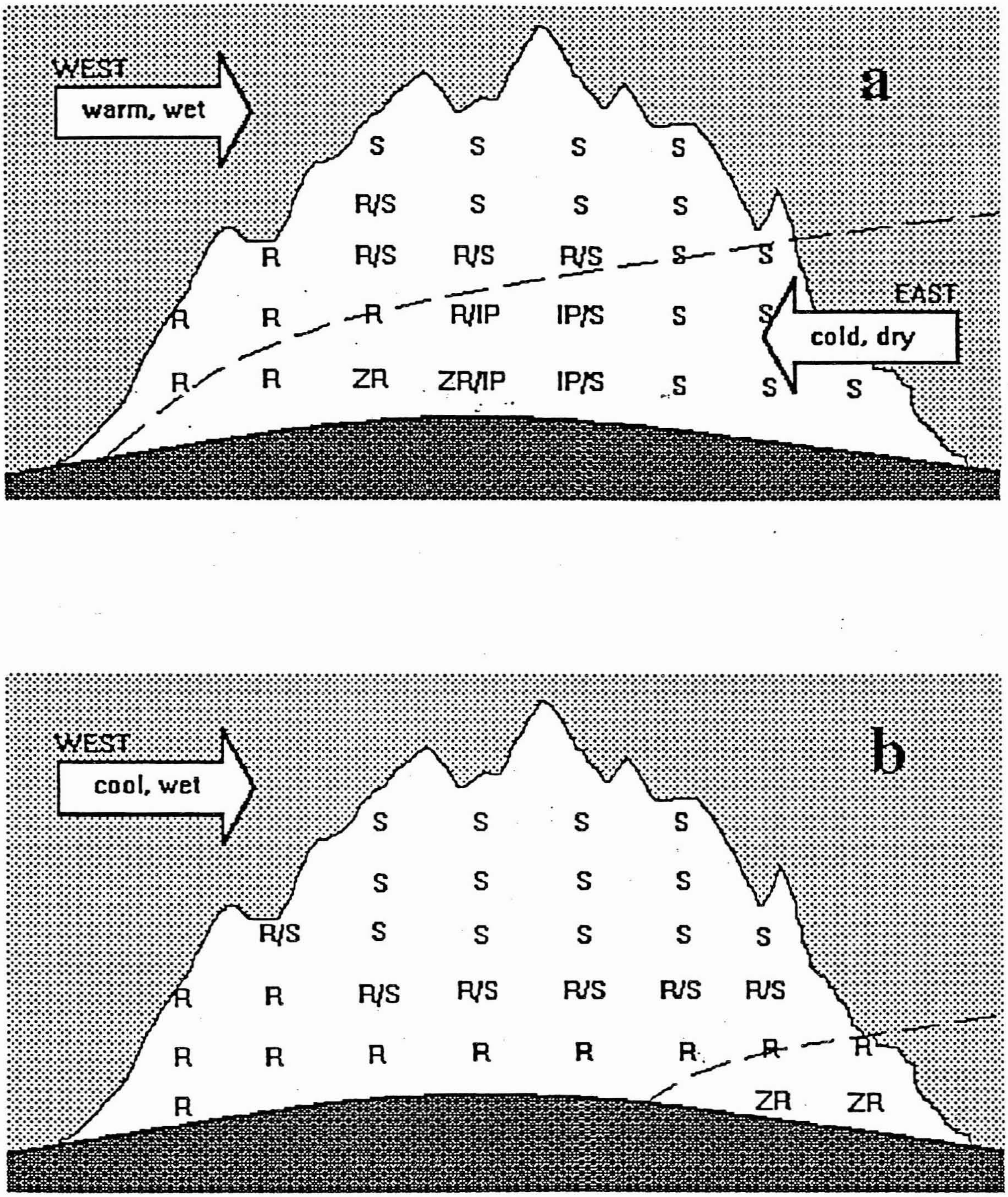
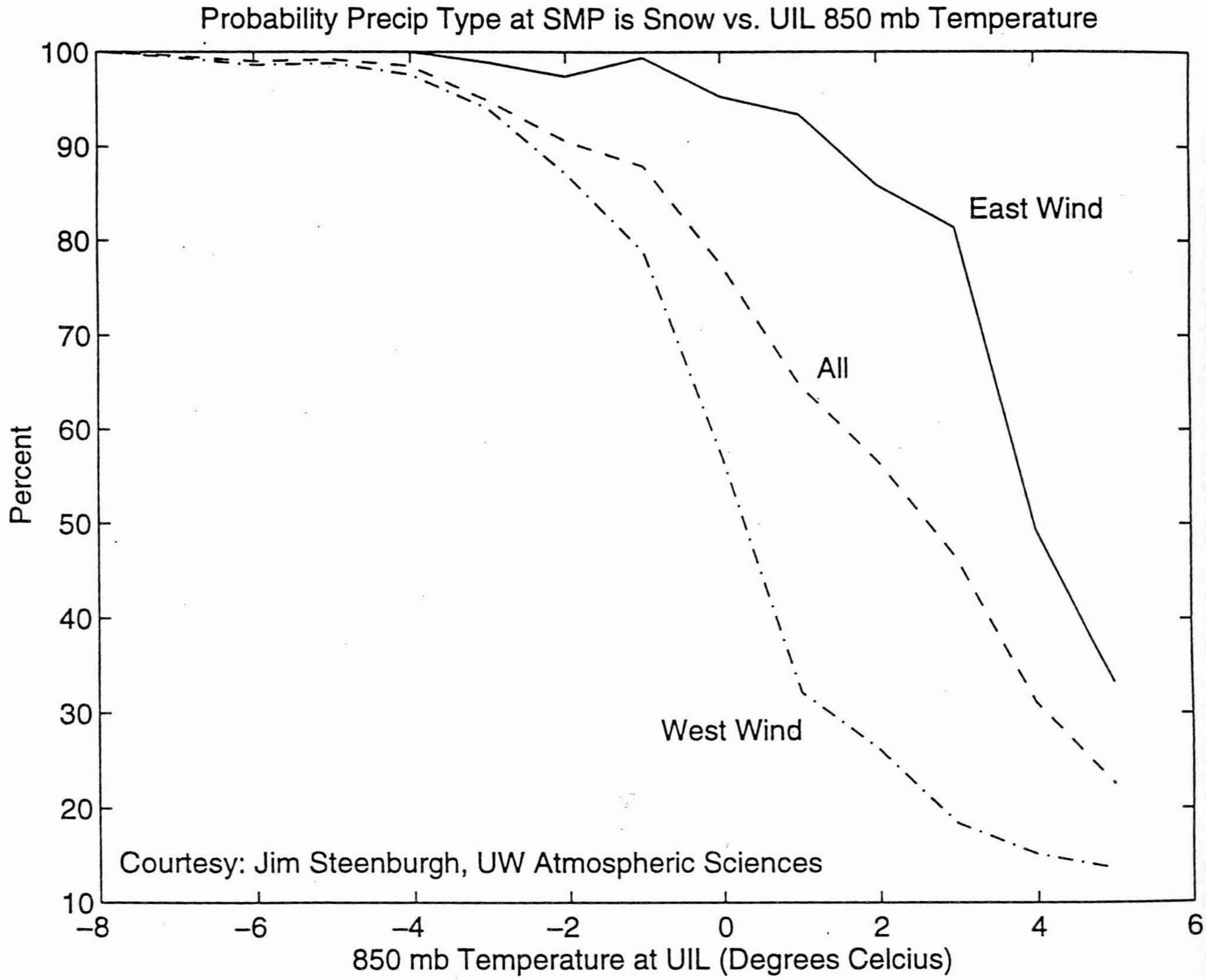
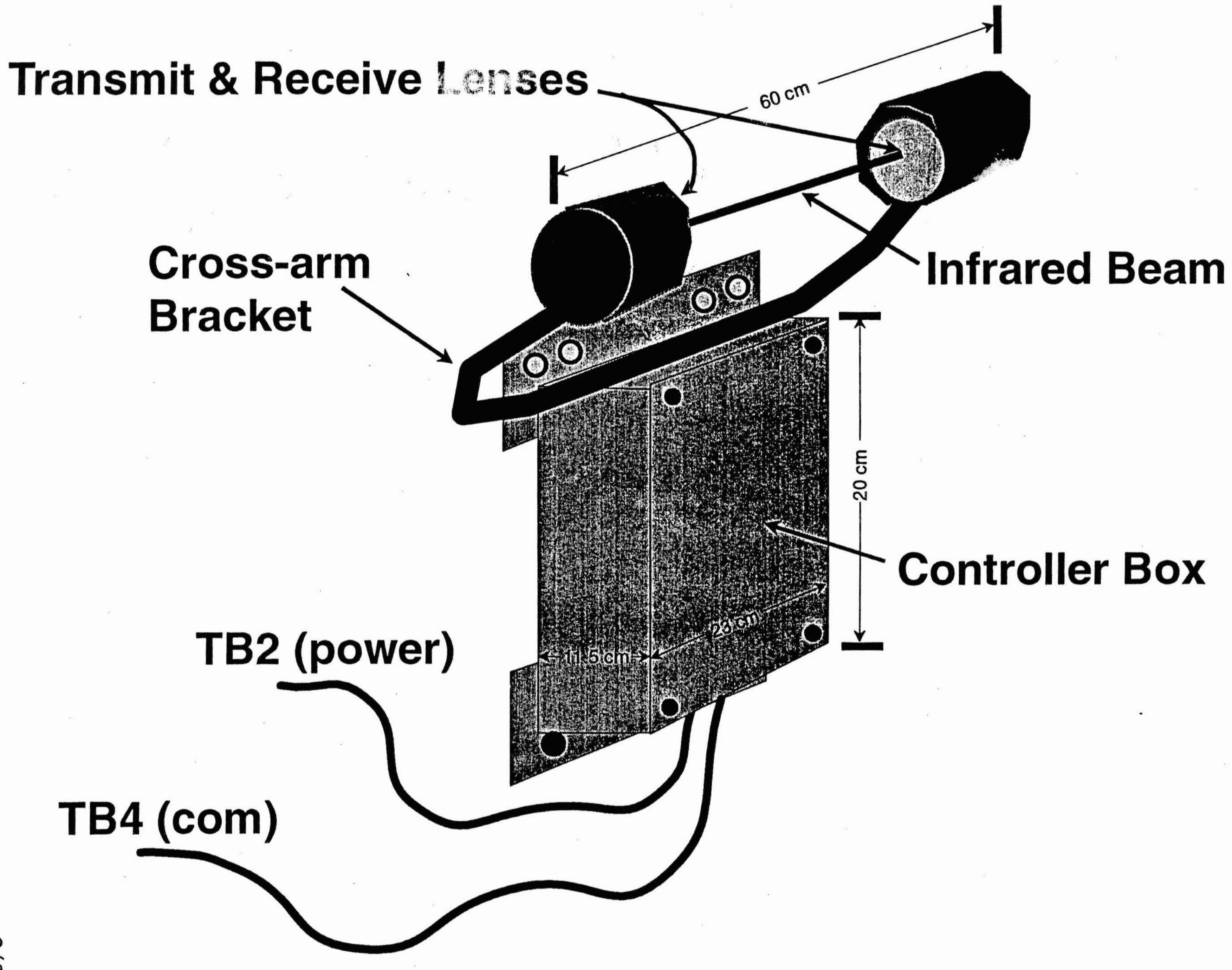
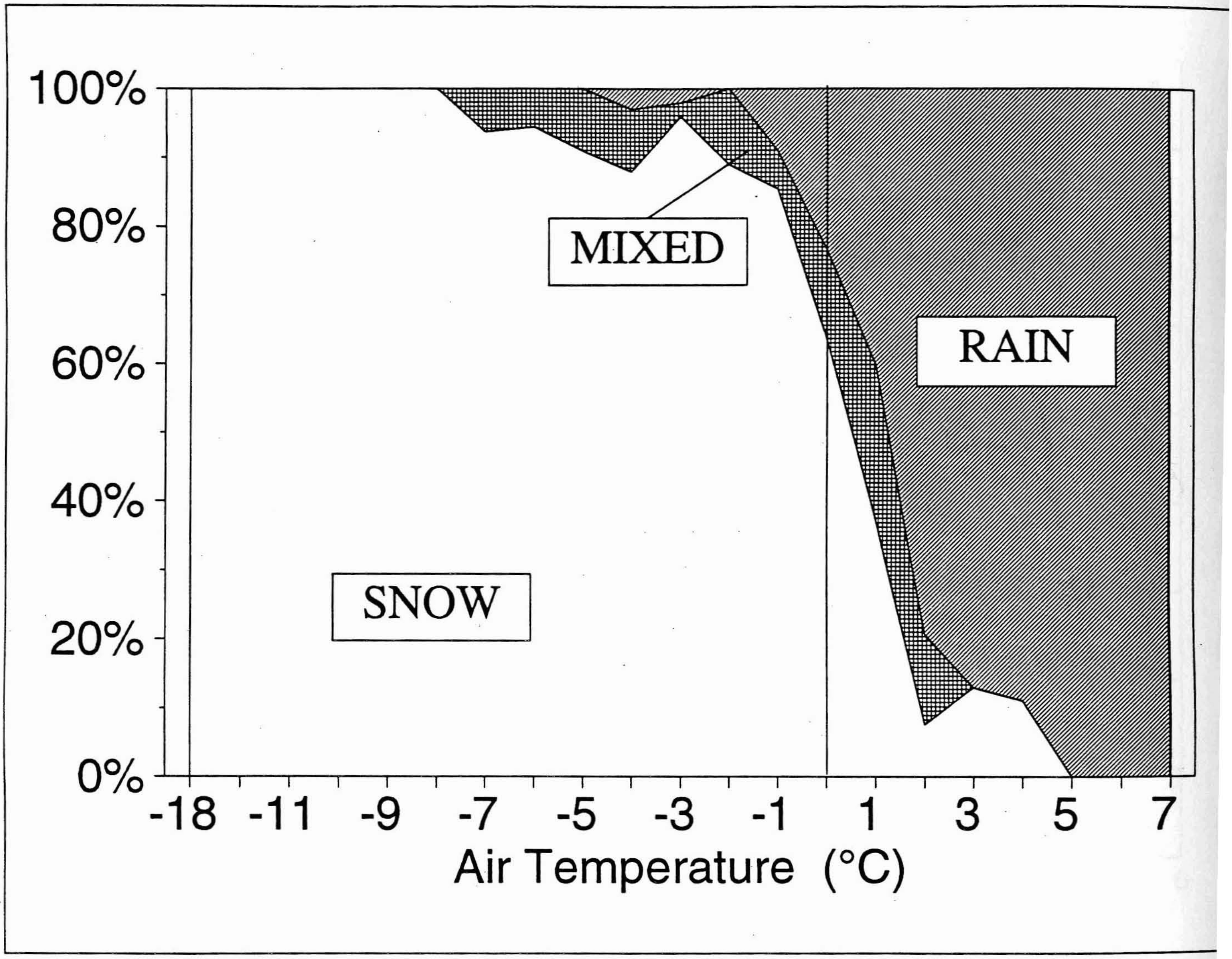


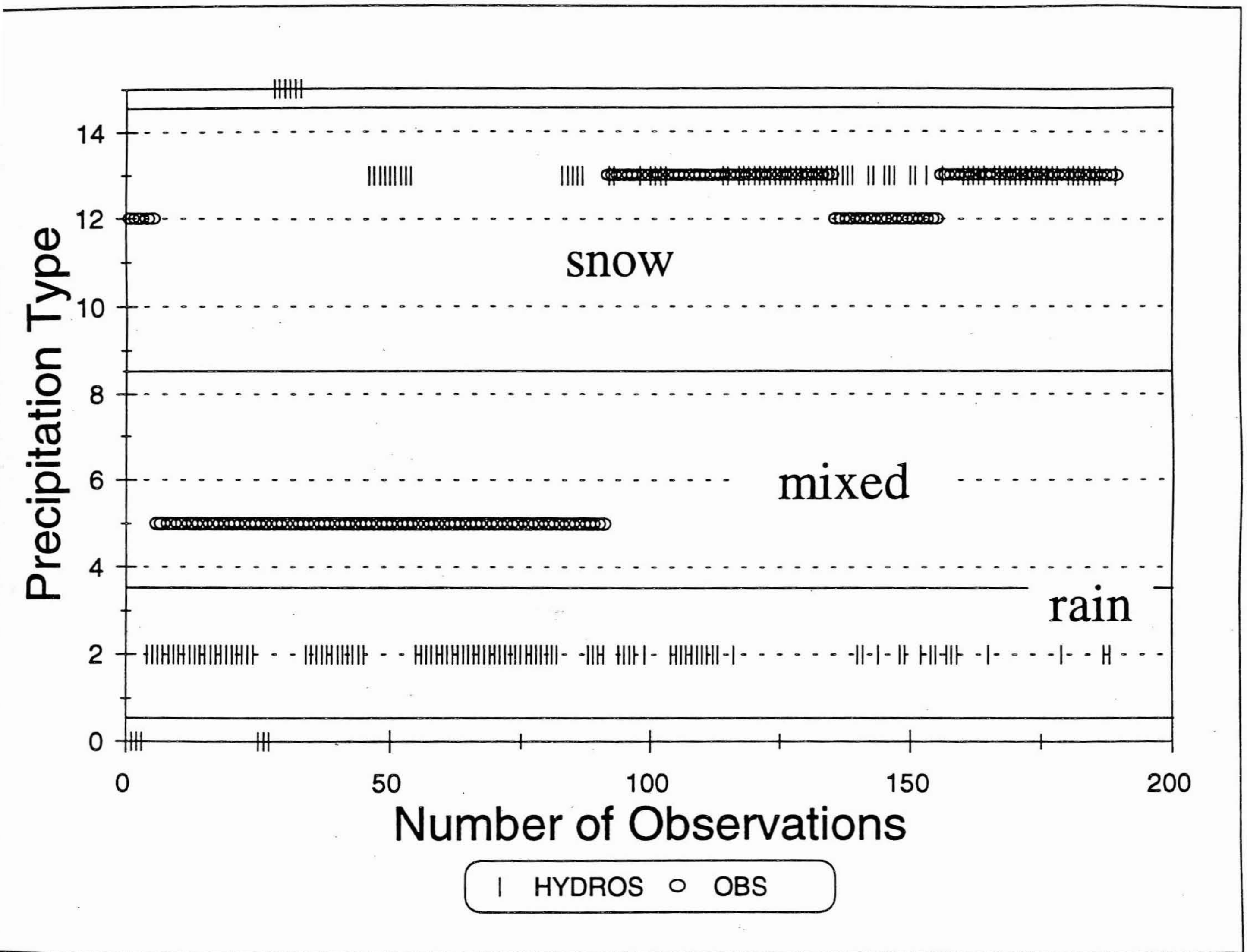
Figure 1. Cascade pass precipitation patterns. Dashed line shows temperature inversion boundary. S=snow, R=rain, ZR=freezing rain, and IP=ice pellet. a) During moderate inversion. b) Moments after inversion was eroded.

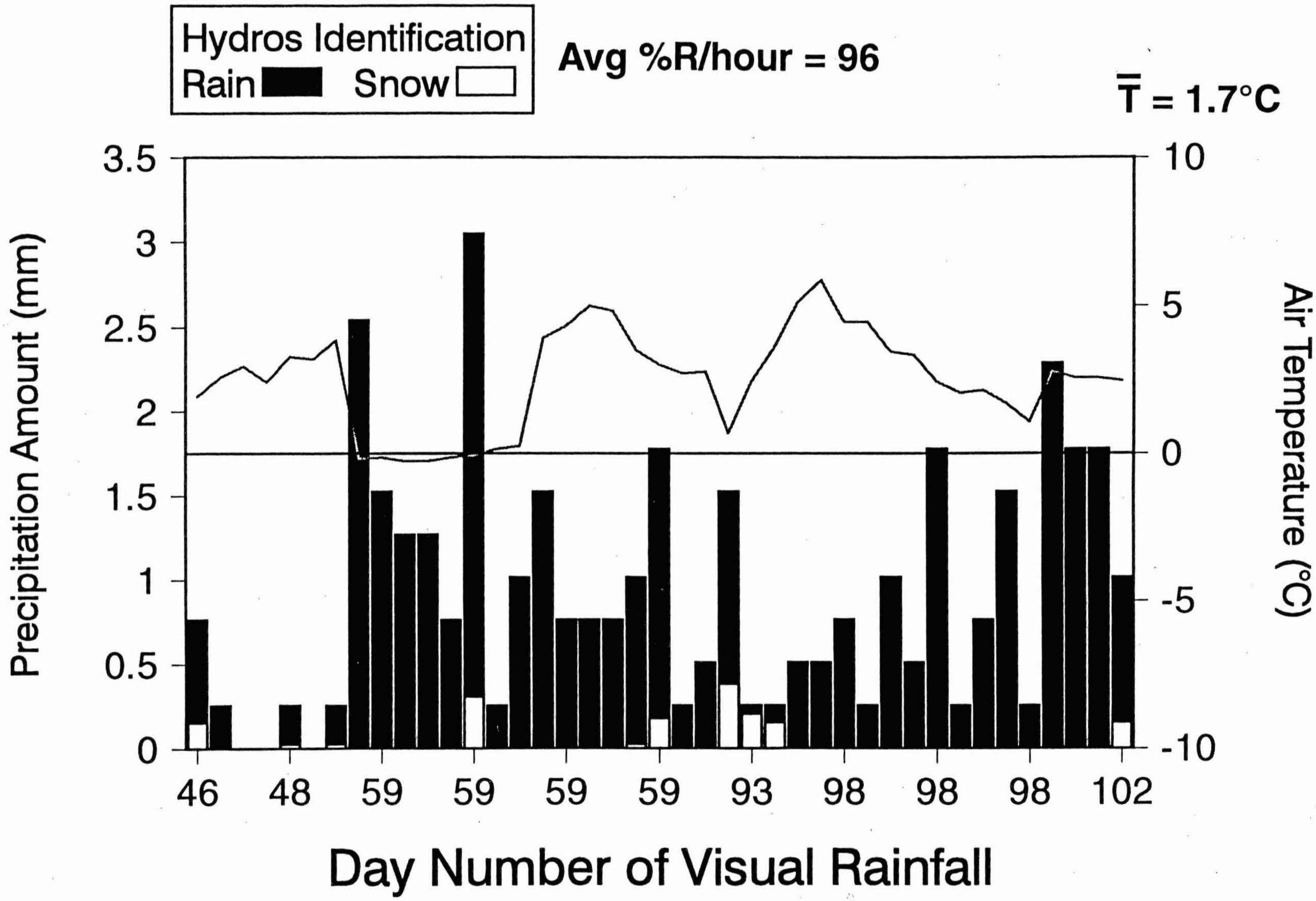


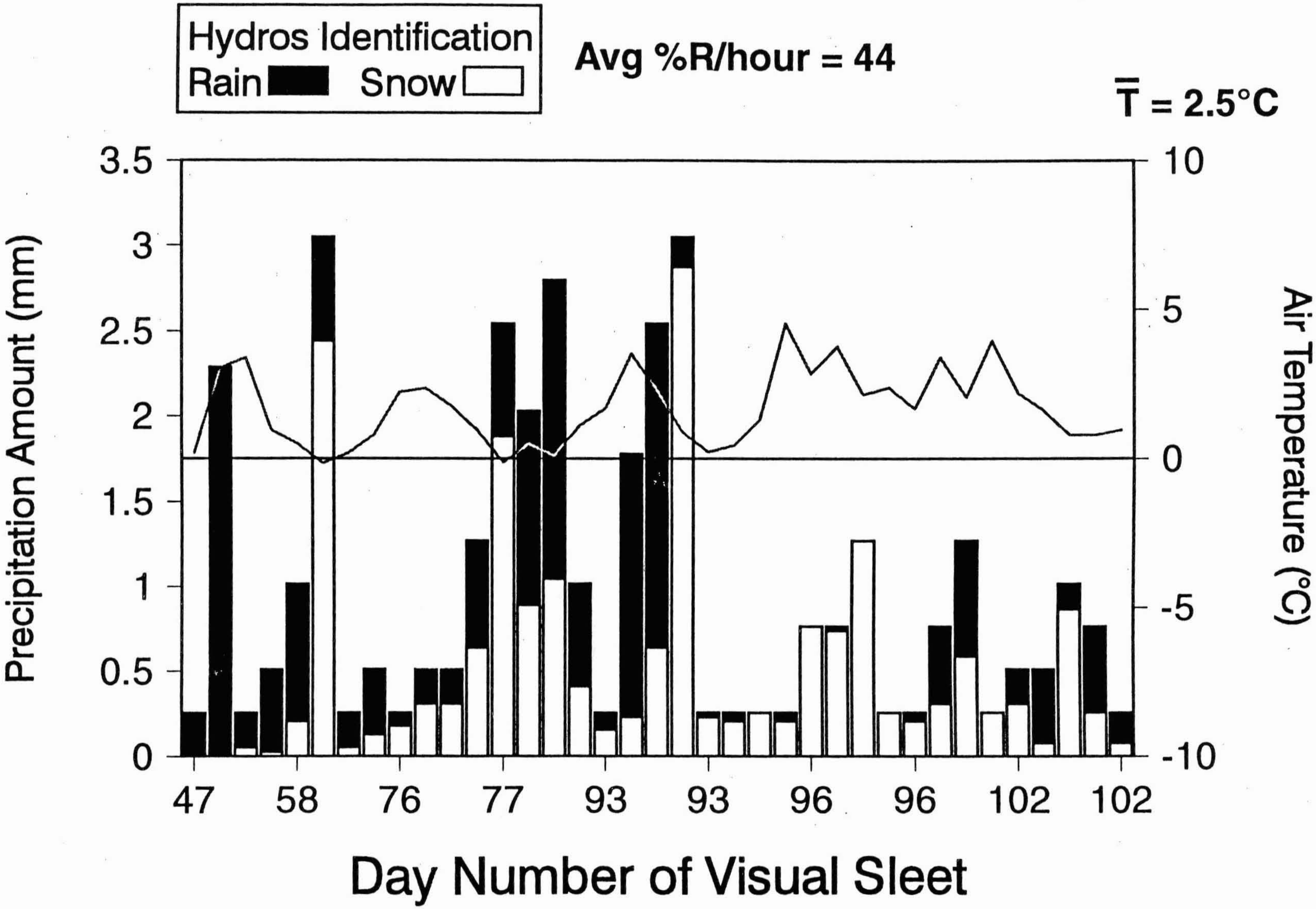
Probability Precip Type at SMP is Snow vs. UIL 850 mb Temperature
Percent
850 mb Temperature at UIL (Degrees Celcius)
100
90
80
70
60
50
40
30
20
10
−8
−6
−4
−2
0
2
4
6
East Wind
All
West Wind
Courtesy: Jim Steenburgh, UW Atmospheric Sciences

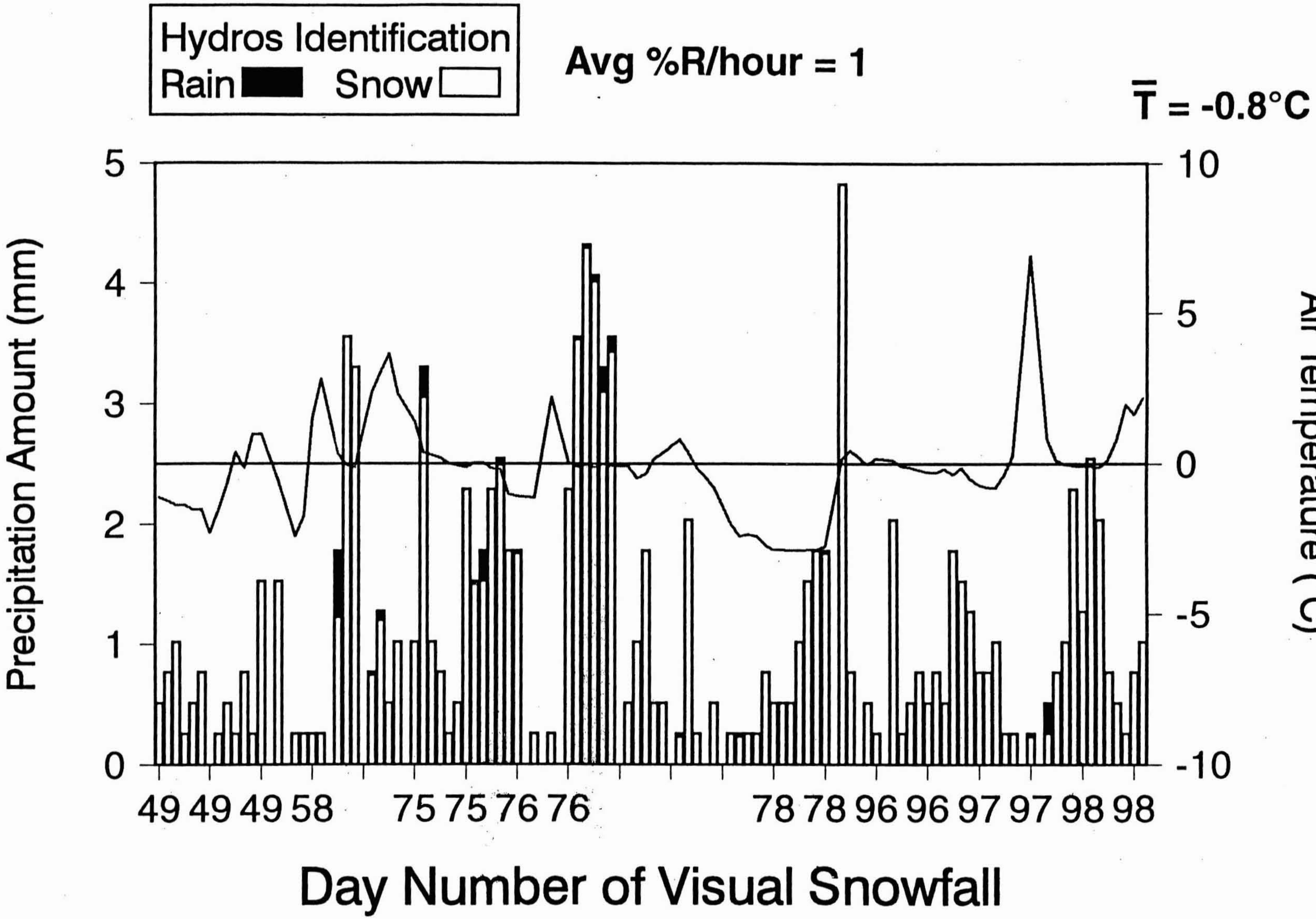

Transmit & Receive Lenses
60 cm
Cross-arm Bracket
Infrared Beam
20 cm
Controller Box
23 cm
11.5 cm
TB2 (power)
TB4 (com)

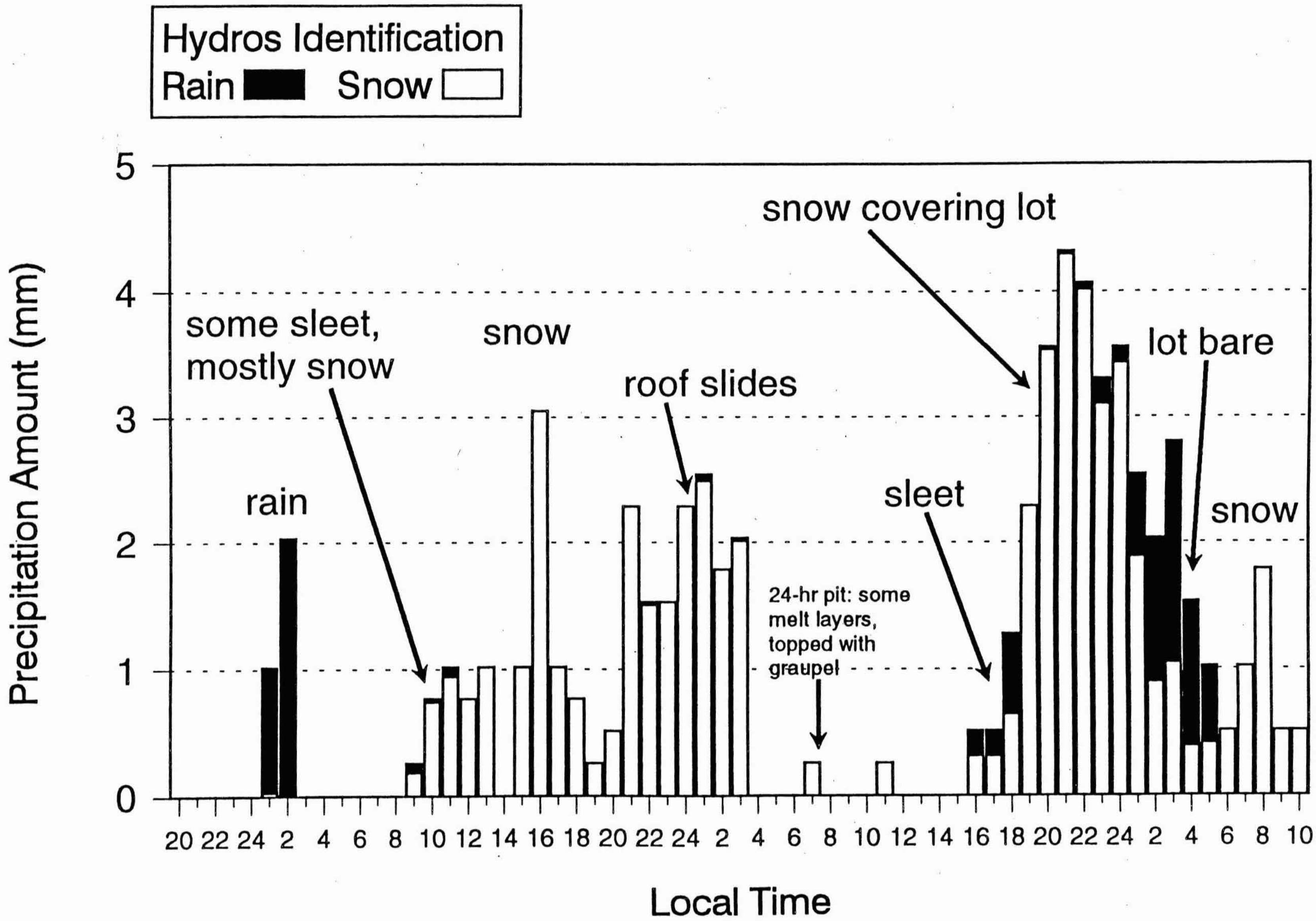

100%
80%
60%
40%
20%
0%
MIXED
RAIN
SNOW
-18 -11 -9 -7 -5 -3 -1 1 3 5 7
Air Temperature (°C)

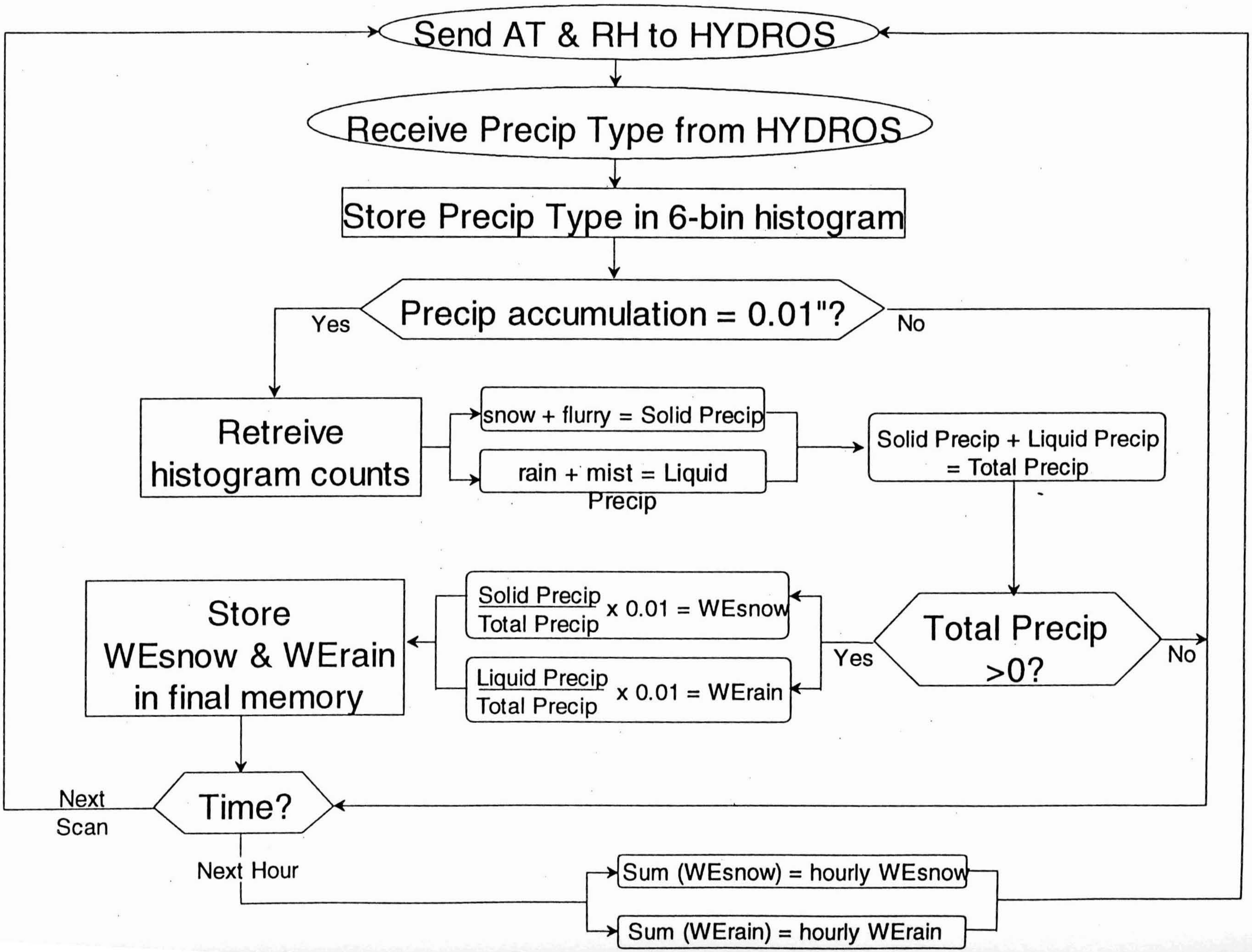

Precipitation Type
14
12
10
8
6
4
2
0
snow
mixed
rain
0
50
100
150
200
Number of Observations
| HYDROS
○ OBS

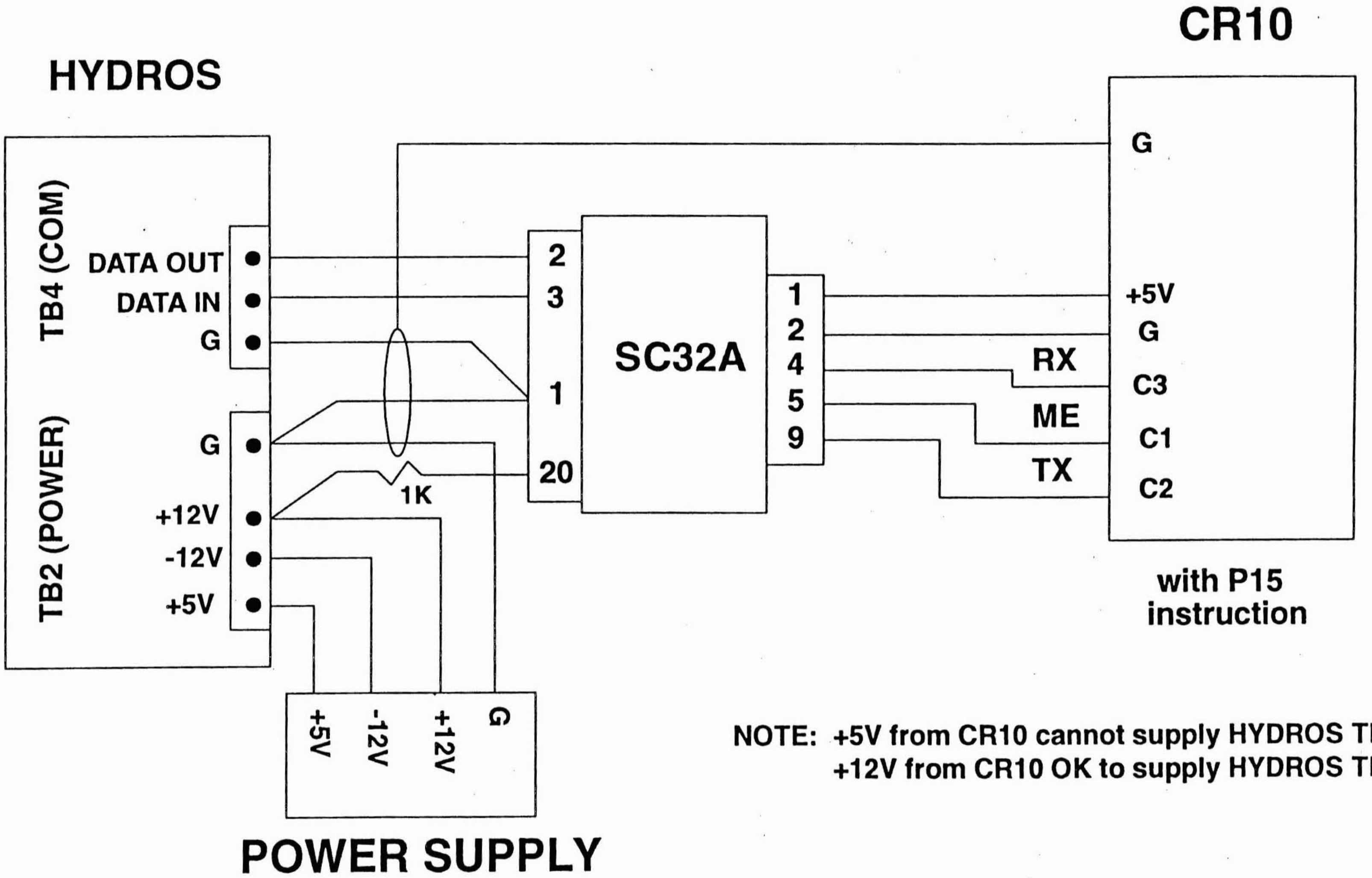

Hydros Identification
Rain
Snow
Avg %R/hour = 96
T̄ = 1.7°C
Precipitation Amount (mm)
3.5
3
2.5
2
1.5
1
0.5
0
10
5
0
-5
-10
Air Temperature (°C)
46
48
59
59
59
59
93
98
98
98
102
Day Number of Visual Rainfall


Hydros Identification
Rain
Snow
Avg %R/hour = 44
T̄ = 2.5°C
Precipitation Amount (mm)
Air Temperature (°C)
3.5
3
2.5
2
1.5
1
0.5
0
10
5
0
-5
-10
47
58
76
77
93
93
96
96
102
102
Day Number of Visual Sleet


Hydros Identification
Rain
Snow
Avg %R/hour = 1
T̄ = -0.8°C
Precipitation Amount (mm)
Air Temperature (°C)
0
1
2
3
4
5
10
5
0
-5
-10
49 49 49 58 75 75 76 76 78 78 96 96 97 97 98 98
Day Number of Visual Snowfall


Hydros Identification
Rain
Snow
Precipitation Amount (mm)
0
1
2
3
4
5
rain
some sleet, mostly snow
snow
roof slides
24-hr pit: some melt layers, topped with graupel
sleet
snow covering lot
lot bare
snow
20 22 24 2 4 6 8 10 12 14 16 18 20 22 24 2 4 6 8 10 12 14 16 18 20 22 24 2 4 6 8 10
Local Time


Send AT & RH to HYDROS
Receive Precip Type from HYDROS
Store Precip Type in 6-bin histogram
Precip accumulation = 0.01"?
Yes
No
Retreive histogram counts
snow + flurry = Solid Precip
rain + mist = Liquid Precip
Solid Precip + Liquid Precip = Total Precip
Total Precip >0?
Yes
No
Solid Precip / Total Precip x 0.01 = WEsnow
Liquid Precip / Total Precip x 0.01 = WErain
Store WEsnow & WErain in final memory
Time?
Next Scan
Next Hour
Sum (WEsnow) = hourly WEsnow
Sum (WErain) = hourly WErain



NOTE: +5V from CR10 cannot supply HYDROS TB2
+12V from CR10 OK to supply HYDROS TB2

```
Program: Hydros (Snoq. Pass ) 3/10/94
Flag Usage: flag2 for 5min temp averages FLAG 0 FOR
            Histogram output to Loc 9-14
            oUTPUT Histg. to FS#2 also
Input Channel Usage: 4=temp, 5=rh, rg=3 pt=6
Excitation Channel Usage:E1=temp, E3=rh
Control Port Usage:C1 CONFIGERED for Hydros COMMS
Pulse Input Channel Usage:p1 rain gauge
Output Array Definitions:
Final Storage #1 output:
Id,JD,Time,BV,AT,RH,Pgage,Ptype,WEsnow,WErain


*      1        Table 1 Programs
  01: 20        Sec. Execution Interval

01:  P10        Battery Voltage
  01: 1         Loc [:BAT VOLTS]

02:  P11        Temp 107 Probe
  01: 1         Rep
  02: 7         IN Chan
  03: 1         Excite all reps w/EXchan 1
  04: 4         Loc [:AIR TEMP ]
  05: 1         Mult
  06: 0.0000    Offset

03:  P4         Excite,Delay,Volt(SE)
  01: 1         Rep
  02: 5         2500 mV slow Range
  03: 8         IN Chan
  04: 3         Excite all reps w/EXchan 3
  05: 80        Delay (units .01sec)
  06: 2500      mV Excitation
  07: 5         Loc [:RH       ]
  08: .1        Mult
  09: 0.0000    Offset

04:  P37        Z=X*F
  01: 4         X Loc AIR TEMP
  02: 1.8       F
  03: 8         Z Loc [:AT Hydros]

05:  P34        Z=X+F
  01: 8         X Loc AT Hydros
  02: 32        F
  03: 8         Z Loc [:AT Hydros]

06:  P37        Z=X*F
  01: 8         X Loc AT Hydros
  02: .0001     F
  03: 8         Z Loc [:AT Hydros]
```

```
07:  P37        Z=X*F
  01: 5         X Loc RH
  02: .0001     F
  03: 9         Z Loc [:RH Hydros]

08:  P86        Do
  01: 41        Set high Port 1

09:  P15        Control Port Serial
  01: 1         Repetitions
  02: 1         Configuration code
  03: 10        CTS/Delay
  04: 1         First control port
  05: 8         Output start Loc AT Hydros
  06: 2--       Number of locations to send
  07: 13        Input termination character
  08: 6         Maximum number of characters
  09: 200       Time out for CTS
  10: 6         Input start Loc [:PREC Type]
  11: 1         Multiplier
  12: 0.0000    Offset

10:  P86        Do
  01: 51        Set low Port 1

11:  P3         Pulse
  01: 1         Rep
  02: 1         Pulse Input Chan
  03: 2         Switch closure
  04: 3         Loc [:PREC Gage]
  05: .01       Mult
  06: 0.0000    Offset

Create histogram of PrecType for each .01 accum. of WE

12:  P89        If X<=>F
  01: 3         X Loc PREC Gage
  02: 3         >=
  03: .01       F
  04: 10        Set high Flag 0 (output)

13:  P80        Set Active Storage Area
  01: 3         Input Storage Area
  02: 10        Array ID or location

14:  P75        Histogram
  01: 1         Rep
  02: 6         No. of Bins
  03: 1         Closed form
  04: 6         Bin Select Value Loc PREC Type
  05: 0         Frequency Distribution
  06: 1         Low Limit
  07: 6         High Limit

Add Snow+Flurry and Rain+Mist
```

```
15:  P33        Z=X+Y
  01: 13        X Loc snow
  02: 15        Y Loc flury
  03: 16        Z Loc [:Solids   ]

16:  P33        Z=X+Y
  01: 12        X Loc rain
  02: 14        Y Loc mist
  03: 17        Z Loc [:Liquids  ]
```

Add Solids and Liquids to determine %precip

```
17:  P33        Z=X+Y
  01: 16        X Loc Solids
  02: 17        Y Loc Liquids
  03: 20        Z Loc [:%Precip  ]
```

Determine WE of solids and liquids

```
18:  P89        If X<=>F
  01: 20        X Loc %Precip
  02: 2         <>
  03: 0         F
  04: 30        Then Do

19:  P38        Z=X/Y
  01: 16        X Loc Solids
  02: 20        Y Loc %Precip
  03: 21        Z Loc [:WE Snow  ]

20:  P37        Z=X*F
  01: 21        X Loc WE Snow
  02: .01       F
  03: 23        Z Loc [:WE Snow2 ]

21:  P38        Z=X/Y
  01: 17        X Loc Liquids
  02: 20        Y Loc %Precip
  03: 22        Z Loc [:WE Rain  ]

22:  P37        Z=X*F
  01: 22        X Loc WE Rain
  02: .01       F
  03: 24        Z Loc [:WE Rain2 ]

23:  P95        End

24:  P89        If X<=>F
  01: 20        X Loc %Precip
  02: 1         =
  03: 0         F
  04: 30        Then Do
```

Page 4 Table 1

```
25:  P31        Z=X
  01: 16        X Loc Solids
  02: 23        Z Loc [:WE Snow2 ]

26:  P31        Z=X
  01: 17        X Loc Liquids
  02: 24        Z Loc [:WE Rain2 ]

27:  P95        End
```

Write histogram to FS#2 for comparison

```
28:  P80        Set Active Storage Area
  01: 2         Final Storage Area 2
  02: 12        Array ID or location

29:  P77        Real Time
  01: 110       Day,Hour-Minute

30:  P75        Histogram
  01: 1         Rep
  02: 6         No. of Bins
  03: 1         Closed form
  04: 6         Bin Select Value Loc PREC Type
  05: 0         Frequency Distribution
  06: 1         Low Limit
  07: 6         High Limit

31:  P92        If time is
  01: 0         minutes into a
  02: 60        minute interval
  03: 10        Set high Flag 0 (output)

32:  P80        Set Active Storage Area
  01: 1         Final Storage Area 1
  02: 7         Array ID or location

33:  P77        Real Time
  01: 110       Day,Hour-Minute

34:  P70        Sample
  01: 1         Reps
  02: 1         Loc BAT VOLTS

35:  P92        If time is
  01: 55        minutes into a
  02: 60        minute interval
  03: 12        Set high Flag 2

36:  P91        If Flag/Port
  01: 12        Do if flag 2 is high
  02: 30        Then Do
```

```
37:  P71        Average
  01: 1         Rep
  02: 4         Loc AIR TEMP

38:  P95        End

39:  P71        Average
  01: 1         Rep
  02: 5         Loc RH

40:  P72        Totalize
  01: 1         Rep
  02: 3         Loc PREC Gage

41:  P70        Sample
  01: 1         Reps
  02: 6         Loc PREC Type

42:  P72        Totalize
  01: 2         Reps
  02: 23        Loc WE Snow2

Zero out intermediate storage

43:  P87        Beginning of Loop
  01: 0         Delay
  02: 14        Loop Count

44:  P30        Z=F
  01: 0         F
  02: 0         Exponent of 10
  03: 10--      Z Loc [:no       ]

45:  P95        End

46:  P91        If Flag/Port
  01: 10        Do if flag 0 (output) is high
  02: 22        Set low Flag 2

47:  P          End Table 1


*     2         Table 2 Programs
  01: 0.0000    Sec. Execution Interval

01:  P          End Table 2


*     3         Table 3 Subroutines

01:  P          End Table 3
```

```
*     A       Mode 10 Memory Allocation
  01: 28      Input Locations
  02: 64      Intermediate Locations
  03: 2000    Final Storage Area 2

*     C       Mode 12 Security
  01: 0000    LOCK 1
  02: 0000    LOCK 2
  03: 0000    LOCK 3
```

Input Location Assignments (with comments):

Key:
T=Table Number
E=Entry Number
L=Location Number

```
T:  E:  L:
1:  1:  1:  Loc [:BAT VOLTS]
1: 11:  3:  Loc [:PREC Gage]
1:  2:  4:  Loc [:AIR TEMP ]
1:  3:  5:  Loc [:RH       ]
1:  9:  6:  Input start Loc [:PREC Type]
1:  4:  8:  Z Loc [:AT Hydros]
1:  5:  8:  Z Loc [:AT Hydros]
1:  6:  8:  Z Loc [:AT Hydros]
1:  7:  9:  Z Loc [:RH Hydros]
1: 44: 10:  Z Loc [:no        ]
1: 15: 16:  Z Loc [:Solids    ]
1: 16: 17:  Z Loc [:Liquids   ]
1: 17: 20:  Z Loc [:%Precip   ]
1: 19: 21:  Z Loc [:WE Snow   ]
1: 21: 22:  Z Loc [:WE Rain   ]
1: 20: 23:  Z Loc [:WE Snow2 ]
1: 25: 23:  Z Loc [:WE Snow2 ]
1: 22: 24:  Z Loc [:WE Rain2 ]
1: 26: 24:  Z Loc [:WE Rain2 ]
```

Page 8 Input Location Labels:

1:BAT VOLTS	8:AT Hydros	15:flury	22:WE Rain
2:________	9:RH Hydros	16:Solids	23:WE Snow2
3:PREC Gage	10:no	17:Liquids	24:WE Rain2
4:AIR TEMP	11:yes	18:________	25:HOURS
5:RH	12:rain	19:________	26:MINUTES
6:PREC Type	13:snow	20:%Precip	27:SECONDS
7:	14:mist	21:WE Snow	28:________