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A CASE STUDY OF THE VARIABILITY OF SNOWFALL IN COMPLEX TERRAIN: 9-10 FEBRUARY 1999

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Introduction

Precipitation prediction and the resulting snow water equivalent (SWE) in complex terrain has long been a challenge for both weather forecasters and hydrologists. Although several algorithms for both precipitation prediction and SWE have been developed, modified, and improved over the last century, orography still creates discrepancies that provide a unique forecasting challenge for several reasons:

- The organization of precipitation is greatly perturbed by upstream mountain ranges, such as in the Great Basin.
- Mountain ranges with steep windward and lee slopes are not well represented in current real-time forecast models.
- Radar blockage over the Great Basin impairs analysis of lee side activity (Vasiloff, 1997).

These factors, coupled with insufficient model resolution, initial condition uncertainty, and problems with model parameterization result in errors in numerical forecasts. Because of this, skill scores for both meteorological and hydrological models are lower over the Intermountain West than any other part of the United States (Gartner et al., 1996).

Advances in the ability to predict precipitation and SWE over complex terrain requires an increased understanding of synoptic scale forcing, orographic precipitation and precipitation processes. For the purpose of this study, research was focused on documenting the distribution of precipitation and the variability of SWE across the Wasatch Mountains during a precipitation event that occurred 9-10 February 1999. The meteorological factors that influenced this event were examined, and the collected data was validated with automatic precipitation gauges.

Methodology

Initially, an accurate, manual method of measuring snowfall and SWE was developed. 30cm x 30cm snowboards were cut and painted white. PVC pipe coring tubes (35 cm) with cross sectional areas of 14.5 cm^2 were made, and canning jars were collected for SWE samples. The 4"x4" Formica samples (approximately 1 mm thick) were cut to use as a slide card between the snowboard and the coring tube when the samples were taken.

The companion automated data were to be downloaded from the Utah Mesonet for three upper elevation ETI gauges and one heated tipping bucket after field work was completed. The ETI gauges are standpipe gauges charged with an anti-freeze mixture. The anti-freeze lowers the freezing point of the captured snow particles and allows them to blend with the solution, reducing the volume requirements of the standpipes. A thin layer of oil rests on top of the anti-freeze solution to discourage evaporation of the diluted anti-freeze/water solution. These gauges are equipped with a pressure transducer located inside the bottom of the tube that is capable of converting changes in weight to a calibrated depth or SWE in increments of 0.01 inches.

Once the necessary equipment had been gathered and data sources for the ETI gauges and heated tipping bucket had been located, a precipitation event with the potential for orographic enhancement for the Wasatch Mountain Range was planned for and forecasted. Storm total precipitation and SWE data were collected and analyzed and compared to the data from the ETI gauges and heated tipping bucket.

Physical locations and topography of observing sites

In order to document and examine the effects of the distribution of precipitation across the Wasatch Mountains during this precipitation event, eight manual snow measurement sites (some of which were coupled with automated sites) were set up on both the windward and the lee slopes of the portion of the range that is located due east of Ogden, UT. This region rises 1500 m in 5 km, while to the east the mountains rise 1000 m in 10 km. The area of this study includes the Snowbasin Ski Area. Figure 1 provides an aerial view of this range.

The following sections provide information about the physical locations and topographical influences the eight observation sites used in this field experiment.

- ***Weber State University***

  The Weber State University (WSU) site is located at an elevation of 4500 feet. It is on the windward bench of the Wasatch Range, more specifically next to Stewart Stadium at WSU. The snowboard was placed next to the ETI gauge at this site.

However, the gauge was not in working order at the time of this study, so only manual measurements were taken.

- ***Huntsville State Park***

  The Huntsville State Park site is located at an elevation of approximately 4960 feet. The state park is on the lee side of the range, and is located at the throat of the Snowbasin Access Road on Highway 39. Huntsville State Park is bordered by Pineview Reservoir to the north. The snowboard for this site was placed several hundred feet off of Highway 39 in an open grove of tall trees.

- ***Trappers Loop Highway***

  The Trappers Loop Highway site is located at an elevation of approximately 5280 feet, and is at the outlet for the new Snowbasin access road that is currently under construction. This site is on the lee slope of the range, and is the easternmost site in this study. The snowboard was placed about 50 feet off of Trappers Loop, and the site was guarded by low lying scrub oak to the north, west, and south.

- ***Snowbasin Access Road***

  The Snowbasin Access Road site is located at approximately 5680 feet. This site is also located on the lee side of the range. The snowboard for the Snowbasin Access Road was placed in a grove of trees to the east of the access road. This, coupled with an elevation drop of approximately 15 feet from the main road, helped protect the sample area from wind drifts.

- ***Base of John Paul Downhill***

  The base of the John Paul Downhill is located at an elevation of 6360 feet, and is on the lee side of the range. This site is in a flat, open area, and is therefore more vulnerable to wind transport. The snowboard was placed next to the ETI gauge site at this location.

- ***Top of John Paul Downhill***

  The top of the John Paul Downhill is located at an elevation of 8940 feet, and is on the lee side of the range. The snowboard for this site was placed just down from the top of the lift in an open area surrounded by evergreens. This was the least exposed part of the ridge. A heated tipping bucket maintained by Snowbasin is also located in this area.

- ***Bottom of Middle Bowl Chair***

  The bottom of the Middle Bowl chair is located at an elevation of 7560 feet, and is on the lee side of the range. The snowboard for this site was placed near an ETI gauge in an area with trees to the south and the east and a large fetch zone to the north and west. The site was exposed to winds from the north and west.

- ***Bottom of Strawberry Express Chair***

  The bottom of the Strawberry Express chair is located at an elevation of 6560 feet, and is on the lee side of the range. The snowboard for this site was placed above the lift and 10 feet into the trees, next to an ETI gauge. There was an open area to the east and north of the snowboard. The ETI gauge for this site was not in working order, so only manual measurements were taken.

Figure 2 shows the placement of all roadside, lower elevation observation sites while Fig. 3 shows the locations of all observation sites that were placed on the mountain at Snowbasin Ski area.

9-10 February 1999 Case

Once a methodology was determined and suitable observation sites were found, a case study was conducted. The following sub-sections explain the experimental procedures that were used to measure the SWE that resulted from this particular precipitation event.

a. Selecting a storm

In order to select a storm that displayed the characteristics necessary for a strong precipitation event, forecast models were monitored on a daily basis. On 09 February 1999, the 0000 Z run of the Eta model indicated a possibility for such an event at 30 hours. Figure 4 shows a 4-panel of the 30-hour Eta forecast. At this time, high values of vertical velocity, high 700 mb moisture values, and strong pressure and thermal troughs were present over the area of interest. The synoptic features, coupled with the prognosis for strong cross-barrier flow, indicated the potential for a strong precipitation event with orographic enhancement. With this knowledge, it was determined that this storm would be used to collect SWE data.

b. Measuring new snow depth (HN)

On 9 February 1999, several hours before the storm was forecasted to reach the Wasatch Range, a snowboard was placed flat on top of the snow at each predetermined observation site and marked with a crevasse flag for ease in finding and retrieving the boards after the storm had passed. The onset of precipitation occurred at approximately 0400Z on 10 February 1999.

On 10 February 1999 after precipitation had ended, all sites were revisited via foot and ski and data SWE were collected. During this particular field study, it was only possible to collect one set of samples.

Ascertaining the SWE by the manual method involved first measuring the height of the new snow (HN) that had accumulated on the snowboard. This was accomplished by taking several readings with a ruler and averaged to find a representative depth. After finding an average depth of snow, a snow core sample was taken by pushing the PVC coring tube straight down into the snow until it rested firmly against the snowboard. After brushing the unwanted snow away from the exterior of the coring tube, a Formica card was slid under the core sample. Using the card as a temporary bottom for the tube, the snow was transferred into a glass jar, making sure that all snow that was captured by the tube was successfully transferred into the container.

Once the data had been collected and snow samples had been taken from each observation site, the SWE for each site was determined. Using the cross sectional area of the sampling tube, the height of the snow sample and the density of the water, the density of the snow and its SWE at each site was determined. The following equations were used for calculations:

$$SWE = \frac{1}{\rho_{\omega}} \int_{0}^{HS} \rho \partial Y$$

Where: HS is the height of the snow
Rho is the density of the snow
Rho(w) is the density of the water

A derivation of this equation leads to the following equation, which was used to determine the SWE for each sample:

$$\text{SWE} = \frac{\textit{Volume of water } (cm^3)}{\textit{Cross sectional area of tube } (cm^2)}$$

Results

The SWE findings from this study can be evaluated and correlated to meteorological analyses of the precipitation event. These results can also be validated using the data from the automated gauges that were co-located with several of the manual observation sites.

Tables 1 and 2 list the volumes of snow and water and the calculated density, SWE, and automated ETI gauge data for each observational site.

The large snow depth value at the Weber State site can be attributed to the feeder-seeder phenomenon (Bluestein 1993), and the variation in SWE noted in Table 2 can be partially explained by the height difference between the manual measurements at the surface and the elevated automatic precipitation gauges. The only exception to this height differential was at the top of the John Paul Downhill, where the automated precipitation gauge is a heated tipping bucket that is also on the surface.

Due to the effects of wind transport throughout the storm, the relationship of the observational sites in reference to fetch and deposition areas becomes critical. For example, consider the site at the base of the John Paul Downhill. With northerly winds averaging approximately 10 knots, this location is considered a fetch area. It is likely that snow was removed from the snowboard by the saltation process which transports and alters the snow crystals, thus increasing the density of the newly deposited snow (Mellor 1965). The automated precipitation gauge that is elevated above the surface at this site would not be susceptible to the same mode of snow transport and therefore, would not lose as much snow. Conversely, the Middle Bowl snowboard was located in a deposition area near the trees. This site experienced a westerly wind averaging 10 knots, and the snowboard most likely gained snow that was transported by saltation and rolling, while the precipitation gauge would not register this increase due to its elevated status.

a. ETI Gauge Data

In this study, automated ETI gauge data from the following sites were collected:

- Top of the John Paul Downhill (SBW) - elevation 8940 feet
- Bottom of Middle Bowl chair (SNI) - elevation 7560 feet
- Base of the John Paul Downhill (SBE) - elevation 6360 feet

Figures 5a, 5b and 5c show the time series for these three sites, respectively. In these time series, cold frontal passage can be identified by a sharp drop in temperature, pressure checks, and abrupt shifts in wind direction at the surface. As expected, the cold front reached lower elevations first. The base of the John Paul Downhill experienced frontal passage just after 0400Z, with Middle Bowl and the top of the John Paul Downhill following at 0430Z and 0500Z, respectively. Note that at both the base of the John Paul Downhill and the Middle Bowl sites, the onset of precipitation occurred after surface frontal passage, while the top of the John Paul Downhill experienced small amounts of pre-frontal precipitation.

b. Correlation between ETI Gauge data and 700 mb winds

During a precipitation event in complex terrain, the orientation of the 700 mb winds is important. The largest amounts of precipitation are expected to fall during the period of maximum cross-barrier flow when additional orographic lifting is present. In order to verify the orographic enhancement in this study, three GEMPAK plots of 700 mb winds were generated for the time period of heaviest precipitation. Figure 6 shows the 700 mb winds for 0500Z, 0700Z, and 0900Z.

The first panel (990210/0500Z) shows the 700 mb winds just prior to upper-level frontal passage, the second panel (990210/0700Z) shows the winds at the point just prior to maximum cross-barrier flow, and the third panel (990210/0900Z) shows post frontal northerly flow over the Wasatch Range. The correlation these plots have with the precipitation measured by the ETI gauges is as follows:

- The left panel of Fig. 5 is the time that the main band of precipitation begins. The predominant flow is southeasterly, and precipitation rates measured by the ETI gauges are small. However, as seen in Table 4, precipitation rates quickly begin to rise throughout the period.
- The center panel of Fig. 5 shows the beginning stages of strong westerly flow. It is evident when comparing both precipitation rates measured by the ETI gauge in Table 4 and the 700 mb wind flow for this period that the strongest precipitation occurred when the winds at this level were, indeed, oriented in a cross-barrier direction.
- The right panel of Fig. 5 shows that 700 mb winds continued to veer to the northwest through the period, and upon comparison with ETI gauge measurements, it can be seen that precipitation rates diminished during this time. (Table 4)

c. Correlation Between ETI Gauge Data and Radar Reflectivity

To test the validity of the ETI gauges during this precipitation event, a comparison was made between the timing and intensity of the precipitation measured by the ETI gauges and the radar echoes from the correlating times.

In the pre-frontal environment (990209/1800Z - 990210/0415Z), radar echoes show spotty precipitation in mountain areas over northern Utah. During this time, the Wasatch Range was under southwesterly flow. Most of the radar returns at this time were virga, which accounts for the fact that the only observation site that measured any precipitation was the top to the John Paul Downhill (Table 4). Data from this site confirms that a total of 0.11 inches of precipitation fell during this time period. Larger dBZ returns through this period correlate with the times that precipitation was measured at the top of the John Paul Downhill. Thus, during this initial period, there is a correlation between precipitation measurements and radar reflectivities at the highest observational site.

The period when the pre-frontal and the post-frontal precipitation bands merged over northern Utah (990210/0500-1000Z) showed the strongest radar reflectivities, as well as the greatest precipitation measurements. This relationship can be shown directly by comparing the reflectivity image from 990210/0735Z (Fig. 6) and the precipitation rates of the three ETI gauges (SBW, SNI, SBE) from the same time (Table 4). The precipitation measured over the fifteen-minute period between 990210/0730-0745Z was the greatest of this event for each of the three stations (.10", .04", .06", respectively). During this same period, radar reflectivities reached 40 dBZ, the highest of the event. This shows a strong correlation between the radar reflectivities and the precipitation measurements of the ETI gauge during the time of frontal passage.

In the post-frontal environment (remainder of study period), both radar reflectivities and measured precipitation amounts decreased. During this time, the predominant 700 mb flow veered northwesterly and only convective snow showers remained in the area. Although precipitation amounts decreased during this time, reflectivities and measured precipitation amounts continued to correlate. Table 3 summarizes this relationship.

Conclusions

After reviewing the results of 700 mb wind flow, radar reflectivities and the precipitation measured by manual and automated methods, it can be concluded that the data from the ETI gauges were both temporally and intensity consistent with the meteorological conditions associated with this event. The greatest precipitation during this event was measured during the period where the highest reflectivities and the strongest cross-barrier flow were occurring, which indicates orographic enhancement in this particular event.

A comparison between the manual snow measurements and the ETI gauge measurements can also be made. Table 5 shows the manual data versus the ETI gauge data.

Although direct correlations can be made between manual and automated precipitation measurements and the meteorological aspects of this particular orographically enhanced precipitation event, the distribution of precipitation and the resulting SWE in complex terrain is still a difficult subject. Meteorological factors never play the same hand twice, and the current observational systems are not capable of giving totally representative results. Continued study of precipitation in complex terrain is necessary to better understand its physical processes and results.

Acknowledgments

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Figure 1. Aeral view of the Wasatch Range looking toward the south. Ogden Canyon can be seen cutting through the range at the bottom of the figure, and the Snowbasin Access Road and Ski Area can be seen at the left center of the figure. (Courtesy of Jeff Cole)

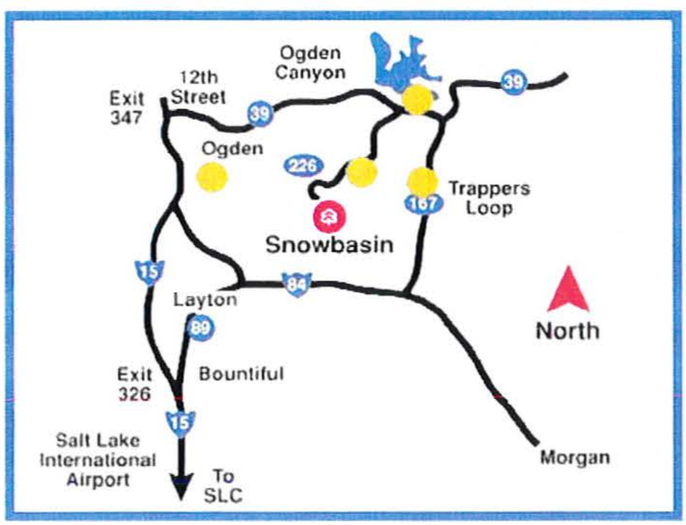

Figure 2. Yellow dots indicate the location of roadside observation sites, in particular, Weber State, Huntsville State Park, Trappers Loop Highway and the Snowbasin Access Road.

Figure 3. Yellow dots indicate the location of observation sites placed on the mountain at Snowbasin Ski Area. From left to right, observation sites are the base of Strawberry Bowl, the base of Middle Bowl, the base of the John Paul Downhill, and the top of the John Paul Downhill. A portion of the Snowbasin Access Road site can also be seen at the bottom right corner of the figure.

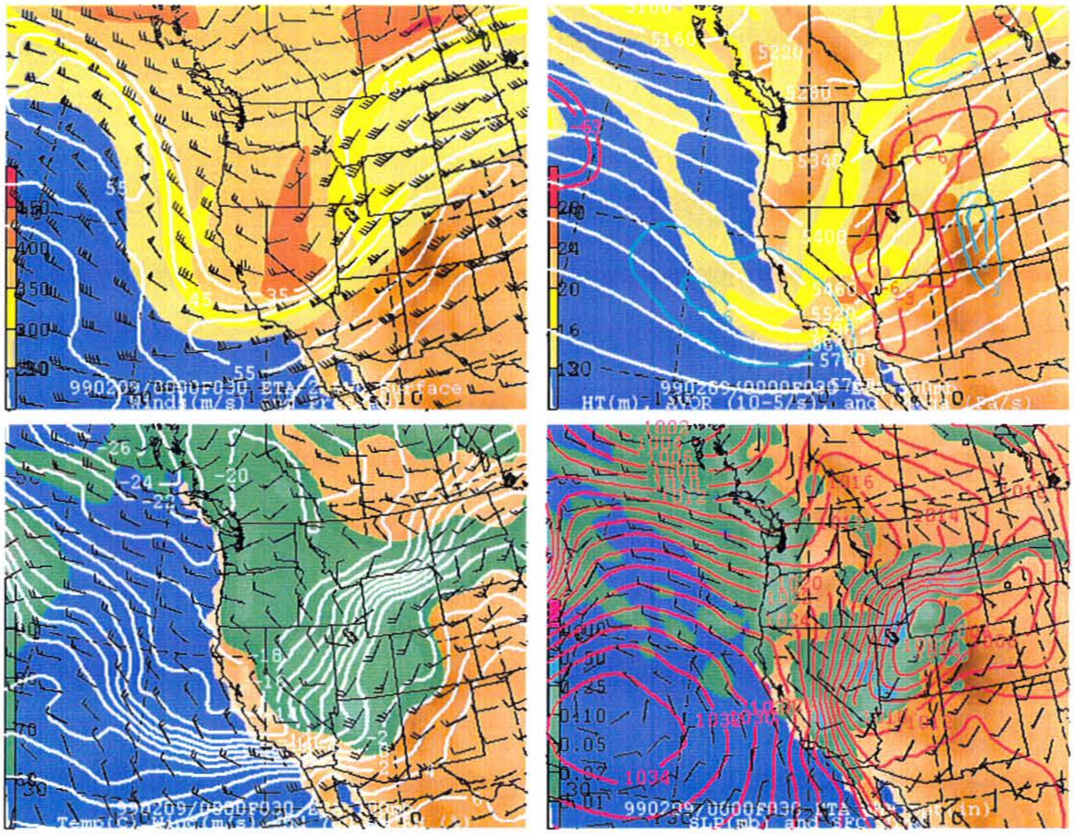

Figure 4. 990902/0000F030 Eta model 4-panel. Large values of vertical motion over the area of interest can be seen in the upper right panel, high values of relative humidity and a strong thermal front can be seen in the lower left panel, and a strong pressure trough and high precipitation values can be seen in the lower right panel.

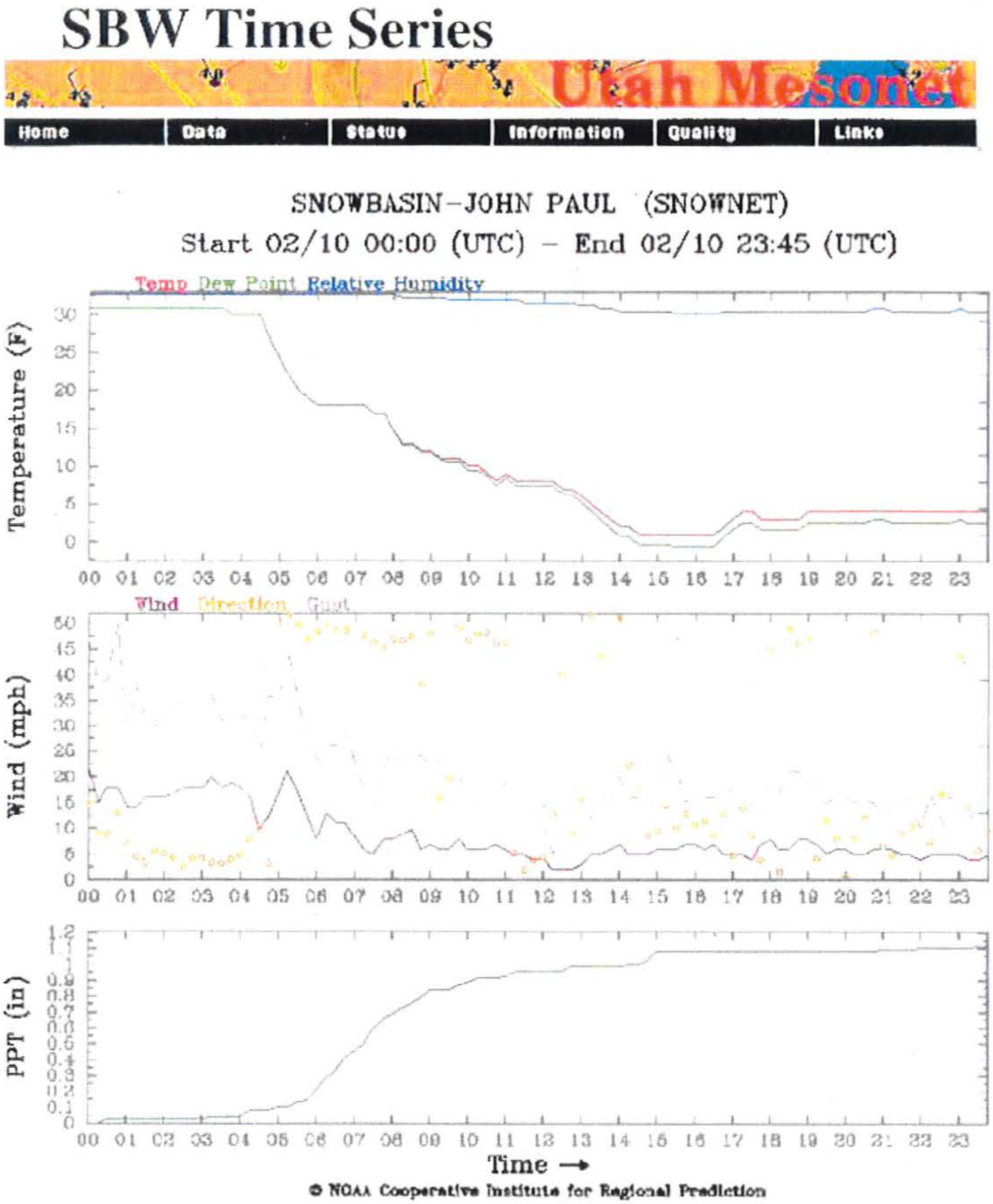

Figure 5a. Utah Mesonet time series for the top of the John Paul Downhill.

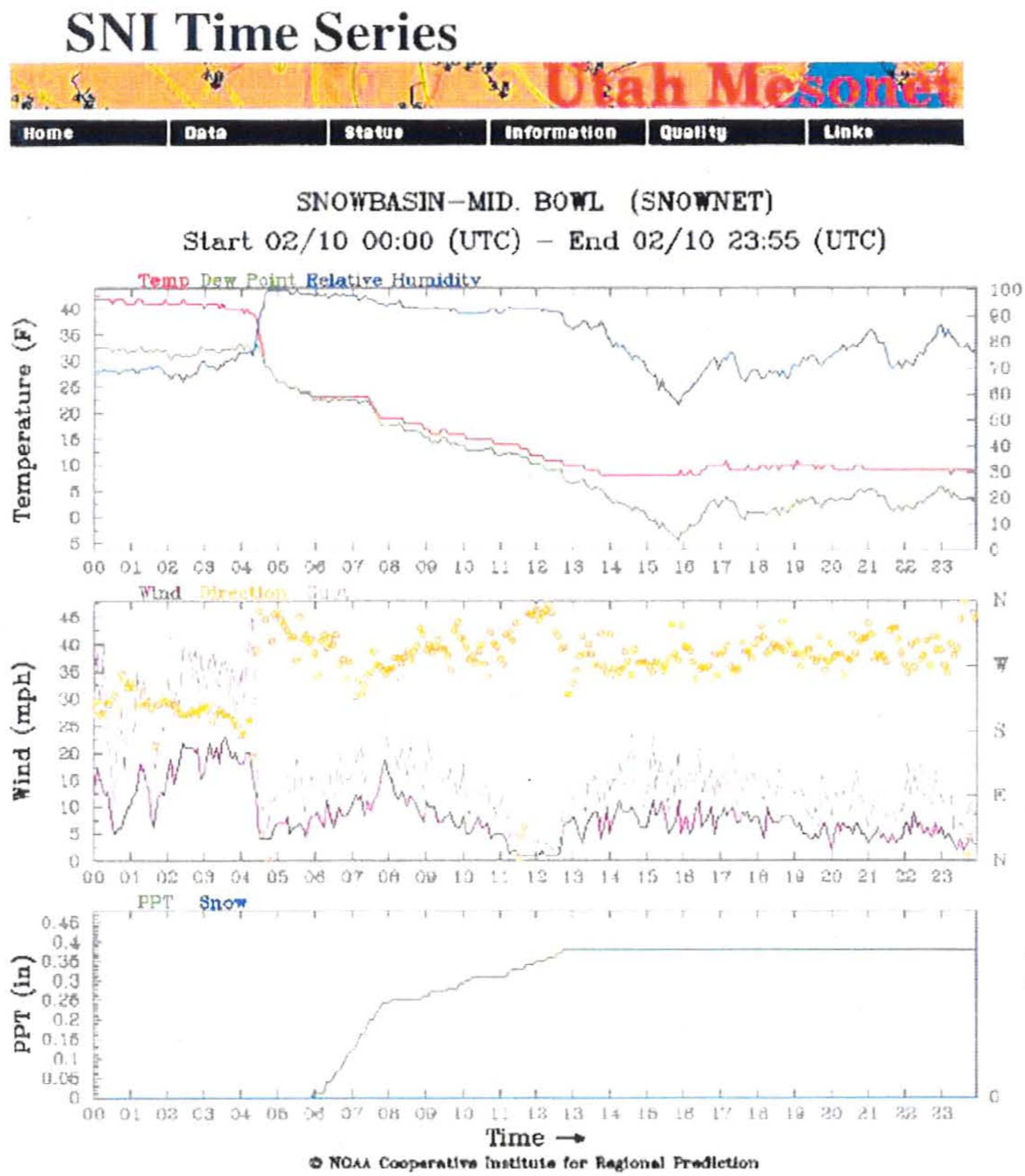

Figure 5b. Utah Mesonet time series for Middle Bowl.

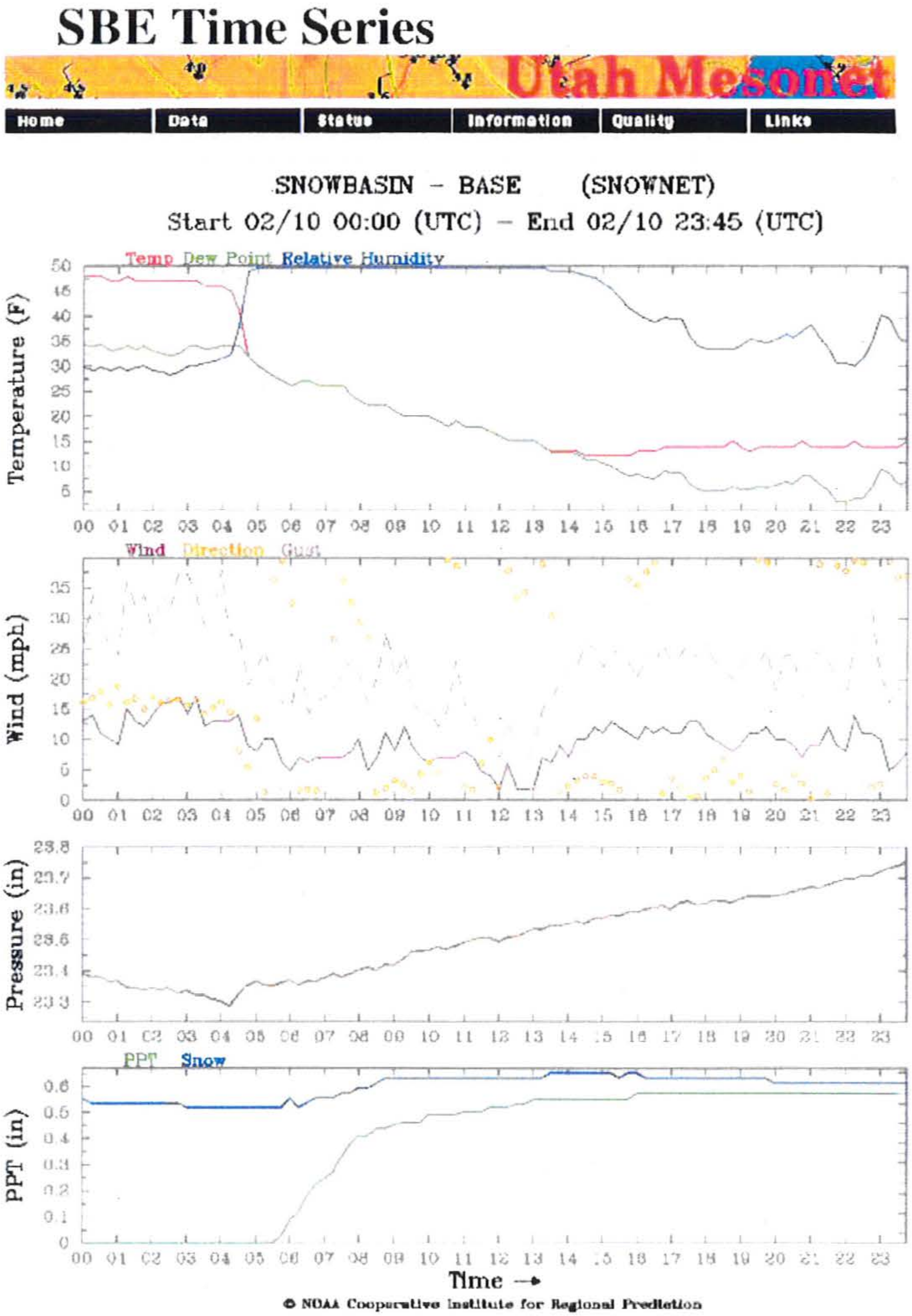

Figure 5c. Utah Mesonet time series for the base of the John Paul Downhill.

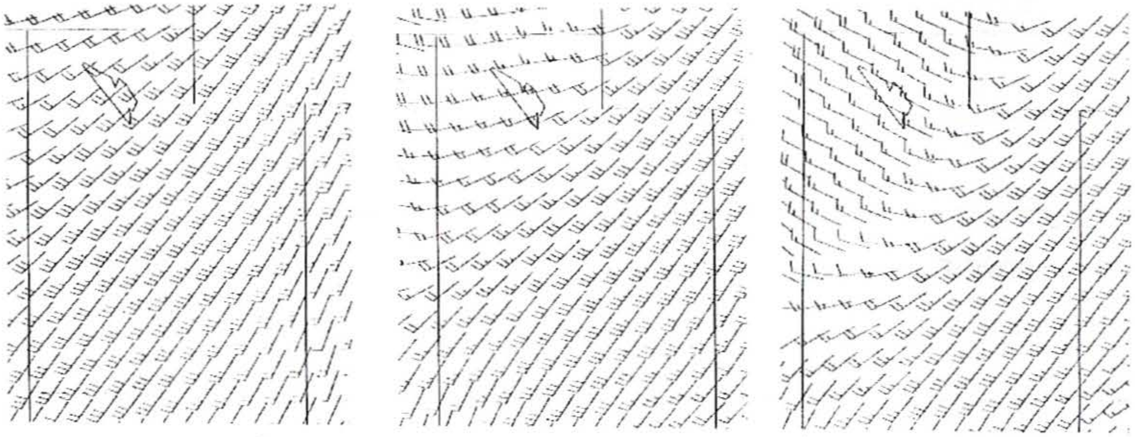

Figure 6. 700 mb winds for 990210/0500 (left panel), 990210/0700 (center panel), and 990210/0900 (right panel).

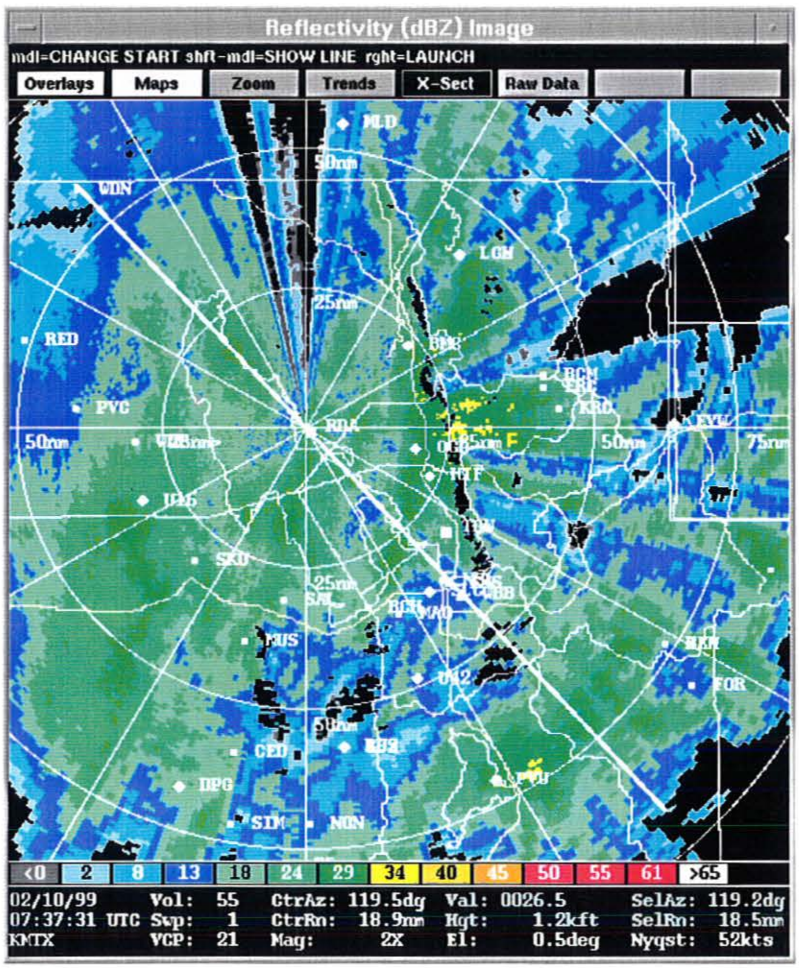

Figure 7. 990210/0737 KMTX radar reflectivity. Returns approaching 40 dBZ can be seen over the northern Wasatch / Snowbasin Ski Area.

Table 1. Volume of snow and water from samples. This table is broken into two sections, with the first section displaying the results from the east portion of the Snowbasin ridge line and the second section displaying the results from the west portion of the Snowbasin ridge line.

Snowbasin ridge line - East

Location (decreasing elevation)	Snow Depth (cm)	Snow Depth (In)	Volume of Snow (cm^3)	Volume of Water (cm^3)
John Paul top	14.8	5.8	214.8	40.5
Middle Bowl	8.1	3.2	117.6	16.5
Strawberry Bowl	7.8	3.1	113.2	21.5
John Paul base	3.8	1.5	55.2	14.5
Access Road	9.0	3.5	130.6	16.0
Trappers Loop	12.6	5.0	182.9	19.5
State Park	3.9	1.5	56.8	7.5

Snowbasin ridge line - West

Location (decreasing elevation)	Snow Depth (cm)	Snow Depth (In)	Volume of Snow (cm^3)	Volume of Water (cm^3)
Weber State	17.5	6.9	254.0	23.5

Table 2. Calculated SWE-to-snow depth ratio x 100 and SWE/Automatic rain gauge data from samples. This table is broken into two sections, with the first section displaying the results from the east portion of the Snowbasin ridge line and the second section displaying the results from the west portion of the Snowbasin ridge line.

<u>Snowbasin ridge line - East</u>

Location (decreasing elevation)	SWE-to-snow depth ratio x 100	SWE (cm)	SWE (in)	ETI Gauge (in)
John Paul top	18.9%	2.74	1.08	1.10
Middle Bowl	14.0%	1.13	0.45	0.38
Strawberry Bowl	19.0%	1.50	0.59	No data
John Paul base	26.3%	1.00	0.39	0.55
Access Road	12.2%	1.35	0.43	na
Trappers Loop	10.7%	1.10	0.53	na
State Park	12.5%	0.49	0.19	na

<u>Snowbasin ridge line - West</u>

Location (decreasing elevation)	Density	SWE (cm)	SWE (in)	ETI Gauge (in)
Weber State	9.3%	1.63	0.64	No Data

Table 3. ETI rain gauge measurements and radar reflectivities for the pre-frontal, frontal, and post-frontal environments for the observation sites with coupled observations.

Site Location	Pre-frontal (in)	Reflect-ivity (dBZ)	Frontal (in)	Reflect-ivity (dBZ)	Post-frontal (in)	Reflect-ivity (dBZ)
John Paul Top	0.11	<30	0.80	35-40	0.21	<30
Middle Bowl	0.0	<30	0.29	35-40	0.09	<30
John Paul Bottom	0.0	<30	0.49	35-40	0.08	<30

Table 4. 15 minute precipitation amounts (in) measured by the ETI gauges at the top of the John Paul Downhill (SBW), Middle Bowl (SNI) and the base of the John Paul Downhill (SBE) on 10 February 1999.

TIME (UTC)	SBW	SNI	SBE
0500	.02	.00	.00
0515	.00	.00	.00
0530	.03	.00	.00
0545	.01	.00	.03
0600	.07	.01	.06
0615	.07	.00	.03
0630	.06	.04	.06
0645	.07	.03	.04
0700	no data	.04	no data
0715	.08	.04	.05
0730	.10	.04	.06
0745	.06	.03	.05
0800	.03	.01	.03
0815	.04	.01	.00
0830	.04	.00	.03
0845	.03	.00	.00
0900	.05	.01	.01
0915	.00	.01	.01
0930	.00	.00	.00
0945	.03	.01	.00
1000	.01	.01	.03
1015	.04	.02	.00
1030	.00	.00	.00
1045	.00	.00	.00
1100	.01	.00	.01

Table 5. Manual precipitation data vs. ETI rain gauge precipitation data. All measurements are in inches.

Site Location	Manual SWE (in)	ETI gauge (in)	% Difference
John Paul Top	1.08	1.10	-1.8%
Middle Bowl	0.45	0.38	15.6%
Strawberry Bowl	0.59	No data	No data
John Paul Base	0.39	0.57	-31.6%
Weber State	0.64	No data	No data