An Exploratory Forecast Experiment to Predict Supercooled Liquid Water in the Sierra Nevada

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Abstract

The Sierra Cooperative Pilot Project (SCPP) was a ten year wintertime cloud modification research program dedicated to assessing the potential for increasing snowpack by cloud seeding in the Sierra Nevada. Based on some initial exploration of the cloud types and their characteristics, it was noticed that the shallow widespread cold orographic cloud contained substantial regions of supercoolded liquid water. These clouds often were linked with fronts and thus there was interest in predicting frontal activity and its associated liquid water. A two season (1985-86 and 1986-87) exploratory forecast experiment was planned, conducted, and evaluated using both old and new verification techniques. It was shown that considerable skill was present in forecasting frontal type and the associated concentration, onset, and duration of super-cooled liquid water. A derivative of the study was the ability to determine the importance, as assessed by the forecaster, of the various quantitative forecast inputs to the final forecast. For all weather conditions, the three most important inputs were satellite images, NMC numerical guidance, and real-time liquid water values from a research radiometer. It appears that one may be able to improve both the quality and validity of the precipitation forecasts on the west coast of the United States with proper data inputs and effort.

1.0 INTRODUCTION

The Sierra Cooperative Pilot Project (SCPP) was a ten year wintertime cloud modification research program sponsored by the Bureau of Reclamation to determine the potential for increasing the snowpack, through application of cloud seeding, in the American River Basin (see Fig. 1). An overview of the SCPP program and the design of two separate randomized exploratory cloud seeding experiments have been presented by Reynolds and Dennis (1986). The second of these two experiments, called the Fixed Target Experiment, focused on the shallow widespread cold orographic cloud as providing the best opportunity for increasing precipitation through glaciogenic seeding. These cloud types provided the longest lasting episodes of supercooled liquid water (SLW) as determined by a dual-channel microwave radiometer operating near the crest of the Sierra Nevada (Heggli and Rauber, 1988).

The shallow cold orographic clouds often appeared following the passage of a split-front or kata cold front (Heggli and Reynolds, 1985, and Reynolds and Kuciauskas, 1988). This preliminary finding provided project forecasters with some clues on which to base their forecast of conditions suitable for seeding activities. Therefore during the last two field seasons of SCPP (i.e., 1985-86 and 1986-87), an exploratory forecast experiment was undertaken to examine how well the timing of frontal passage could be translated into forecasting the onset, duration, and concentration of SLW over the Sierra Nevada.

It should be noted that the forecasting for a research field program is different than standard weather forecasting by the National Weather Service. The environment, the type of forecast, and the available data sets can be quite different. Typically the field research program first utilizes a planning or outlook forecast to alert the project to possible field operations. This outlook is based mainly on the large scale weather data available in most NWS offices (e.g. NMC products, satellite imaging etc.) If appropriate weather is likely, field personnel are put on stand-by and a tentative start-time is declared. Now the forecaster becomes a "nowcaster" and monitors more local scale data (e.g., radar, radiometer, mountain icing rate data, and three hourly serial rawinsondes) to "fine-tune" the outlook forecast for the commencement of the field research including the flight operations. Because of the length of research field operations (e.g., 8, 10, or 12 hours) and the danger of aircraft operations, particularly in adverse weather conditions, there typically are built in safety procedures requiring project stand-down if two operations are requested in any 12 hour period. Therefore a missed forecast, requiring project stand-by, could sacrifice the following day's operations (e.g., SCPP, 1984). Given the short field season (typically January through March) and the low frequency of the desired storms, one does not want to miss any qualifying weather events. Consequently, the pressure on the forecaster-nowcaster in substantial.

2.0 DESIGN AND IMPLEMENTATION

Prior to the 1985-86 SCPP field season an exploratory forecast experiment was designed to predict the presence of cloud liquid water conditions suitable for conducting the SCPP Exploratory Fixed Target Seeding Experiment. The objectives of this "outlook forecast" experiment were:

1. To quantitatively determine the skill in predicting the onset, duration, and concentration of SLW in shallow widespread orographic clouds over the central Sierra Nevadas,

2. To quantitatively determine the skill in predicting the important synoptic/mesoscale features when suitable cloud conditions were present, and
3. To determine which forecast inputs the forecasters believed were most important in making the forecasts.

The design, implementation, and preliminary results of this one year exploratory experiment were reported by Flueck and Reynolds (1986).

Based on the 1985-86 results, modifications appeared necessary both to sharpen the forecast experiment and to better quantify the results. Hence, the forecast design was changed and the modified experiment was continued during the 1986-87 SCPP field season.

The specific objectives for the 1986-87 exploratory forecast experiment were:

1. To quantify the skill of predicting the passage of various types of fronts into the ARB,
2. To quantify the skill of predicting the onset, duration, and concentration of SLW and precipitation from clouds over the Sierra Nevada specifically at Kingvale (KGV) (see Fig. 1), and
3. To determine which forecast inputs the forecasters believed were most important in making these forecasts.

The changes to the design resulted in direct focus on the presence of fronts, the elimination of a specific prediction for the fixed target experimental conditions, and the addition of a forecast of precipitation (temperature forecasts at KGV also were requested but only as an after-thought).

The implementation of the experiment required the daily issuance, except for "selected" days-off, of two 12-hour forecasts; one by the morning forecaster at 9:00 a.m. and one by the evening forecaster at 9:00 p.m. A revised forecast form was utilized for this task, Fig. 2. The initial step in the forecast was to document the current synoptic/mesoscale situation and the current SLW concentration from either the KVG radiometer or a Rosemont icing rate meter (probe) situated atop Squaw Peak (2,500 m) (see Henderson and Solak, 1983). The radiometer data were available on a real-time printer in the SCPP forecast office, and the icing rate and precipitation rate data were available by interrogating the Bureau's remote data ingest computer in Denver. Precipitation data from a digital weighing gauge located at KGV, along with the KGV SLW information also were available within the SCPP forecast office. These data were provided in twelve 5 minute averages and updated hourly. The data were subjectively analyzed by each forecaster separately before a forecast was made.

~~Given this information~~, The forecaster issued predictions on the type, (SLW content (to the nearest tenth of mm), and timing of frontal passage within the ARB, ~~as well as~~ precipitation totals (to the nearest mm) and temperatures (to nearest °C) at KGV for the six 2-hour time blocks. These forecasts were made routinely irrespective of present conditions. The forecaster also was required to choose from a list of possible frontal types and then sketch its position, with significant features (cloud cover) on crude base maps (Fig. 2).

Finally, the forecaster was asked to assess proportionately the importance of the various forecast input information (e.g., satellite, radar, NMC products, local observations, etc.) to the production of his forecast. Once the form was completed it was sealed in an envelope and no changes or updates were allowed.

3.0 DATA AND STATISTICAL METHODS

In this article we will objectively evaluate the skill in forecasting the magnitude (i.e., concentration), onset, and duration of SLW, the frontal type expected during the 12-hour forecast period, and the contributions of a selected group of forecast inputs to the final forecast.

Post season frontal analysis was used to verify the predicted frontal type. These analyses largely relied on satellite data and rawinsonde time cross-sections which have been documented by Heggli and Rauber (1988). Verification of the SLW was based on quality controlled radiometer data averaged by 2-hour time blocks. The data base used was the 2-minute average radiometer data recorded to tape at KGV. If data were missing, then the icing rate data from Squaw Peak were used by quantitatively translating icing rate into SLW categories (Henderson and Solak, 1983). In the 1985-86 season the icing rate data were used 35% of the time for determining the liquid water concentration but only 9% in 1986-87. (It is understood that the icing rate data only are a crude back-up for the radiometer data.)

The verification analyses utilize the contingency table approach and its summarizations by graphical and statistical measures (e.g., bivariate frequency diagrams, conditional bias plots, conditional probability of detection (CPOD), and association measures; see Flueck, 1988 for more details). A number of measures of association are available (e.g., Conover, 1971) but the True Skill Statistic (TSS), which focuses on the residuals from the expected counts due to chance, seemed most appropriate (Flueck, 1987, 1988). This statistic produces a value of +1.0 when all residuals (i.e., observed minus predicted counts) reside on the left to right diagonal of a k x k table, -1.0 when all non-zero residuals reside on the opposite diagonal, and a value of zero when the rows all having the same proportions when compared to their marginal totals (i.e., no association). It should be noted that the TSS measure of association in an ordered 2 x 2 table is identical to Somers' statistic (Flueck, 1988).

Lastly, the experiment was conducted from 30/12/85 to 14/03/86 (225 possible forecasts) in the first season and from 01/11/86 to 07/01/87 (211 possible forecasts) in the second season. However, only about 67% of these forecast opportunities were utilized typically due to one forecaster also having project management duties and to the predesignated "down" days of the experiment.

4.0 ANALYSIS AND DISCUSSION

A. Liquid Water

Table 1, Panel A presents the 3 x 3 contingency table of counts and percentages (in parentheses) for the predicted versus the observed LW concentration for the first forecast period of 0-2 hours. We note that 76% of the forecasts exactly matched the observed results (highlighted by the dotted line) suggesting some forecasting ability. However, this percentage is dominated by the LW = 0 joint cell (i.e., 54.5%). Figure 3 presents this data in a 3-dimensional frequency diagram.

Locking at the marginal percentages of the table indicates there was a tendency to under-forecast the 0 (i.e., 57.9 versus 61.0%) and the 0-.10 mm (i.e., 17.1 versus 25%) categories. Correspondingly, there was a tendency to over-forecast the LW $\geq$ .10 mm 25 versus 14%).

Table 1, Panel B, presents the results for two summary verification measures (i.e., TSS and CPOD) for each of the six 2 hour time blocks, each season separately and both seasons combined (number of forecasts are shown in parenthesis). We see clear evidence of the forecasting skill both in the TSS and the CPOD (remember pure guessing would produce a CPOD = .33). However, as expected the values of both summary measures decrease with time from the forecast valid time (0900 or 2100). Interestingly, the TSS (the preferred and more sensitive measure of forecasting ability) shows a rather sharp drop between the 2nd and 3rd two hour period (e.g., .61 to .53 for the TSS in the combined data). Furthermore, both seasons show evidence of this sharp degradation in performance. Perhaps, persistence ~~extrapolation~~ largely is the mode of forecasting up to four hours, and then a more detailed understanding of the atmosphere is needed to successfully predict future conditions.

B. Onset

The results from forecasting the onset time of SLW are displayed in Table 2. In Panel A we see that 80% of the predictions matched the observations. However, the first two diagonal cells dominate this picture (i.e., 76%), and thus extrapolation again seems to be the most successful mode of prediction for the near-time. Figure 4 presents a plot of the estimated conditional bias for this onset data based on the predicted and observed percentages in Table 2 (note that conditional bias = predicted percentage minus observed percentage, Flueck, 1988). We see that there is a slight tendency for conditional bias to increase as one predicts for later time blocks but it always is less than 3.5%.

Section B, Table 2, presents the results for the two verification summary measures. Sizable forecaster skill is suggested for each field season and the combined data (e.g., TSS = .76 and CPOD = .70 for the combined seasons). Comparing these results with those from concentration suggests that onset is the easier forecasting problem.

C. Duration

The contingency table of counts and percentages for the duration of liquid water on the barrier (i.e., length of the storm period) is given in Table 3. About 70% of the counts reside on the diagonal with the two extreme cells greatly dominating the results (i.e., a sub-total of 68.8%). The conditional POD's for these two categories are .86 and .92 respectively whereas the other five categories have values from .29 to .06.

The conditional bias plot is shown in Fig. 5, and one now sees a clear tendency to under-forecast the longer duration events. The overall, or unconditional, bias is very small (i.e., < 1%).

Section B., Table 3, presents the results of the two summary measures for the duration forecasts, and one can see that some skill is present in predicting the duration of liquid water at KGV (e.g., TSS = .64 for the combined two seasons). Comparing concentration, onset, and duration predictions, we see that forecasters are best able to predict onset, then duration, and finally concentration (e.g., TSS = .76, .64 and about .60 respectively). The presumed extrapolation mode of prediction for onset seems to aid this result.

D. Storm Conditions

It was believed that the forecasting task would differ depending on the weather conditions, and Table 4 presents the results for the breakout of "Non Storm Day" versus "Storm Day" based on Heggli and Rauber's (1988) storm classification. We quickly see that the CPOD's are uniformly higher for storm days than for the non storm days. In short, when there was a storm on the barrier the forecasters were able to better predict the concentration, onset, and duration of SLW than when there was no storm.

However, the picture is less clear for the association measure (TSS). Although, there continues to be evidence of a sharp drop in association after the 2nd two hour forecast period in concentration for both categories there is little support for better forecasting of concentration of SLW on "Storm" compared to "Non-Storm Days."

The comparison of onset versus duration predictions follows the previous results. Onset predictions continue to exhibit more skill than duration irrespective of storm category. For "Storm Day" the overall skill in predicting onset is almost twice that for duration (e.g., TSS = .67 versus .36).

E. Frontal Type

The question of how well forecasters were able to predict the frontal type as it approached the ARB is addressed in Table 5. Five frontal categories were used (i.e., none, cold, split, cutoff, and other), and all forecasts were re-examined and a few re-coded to eliminate multiple types and match the Heggli and Rauber storm categories (The "other" category included weak frontal system, advection of tropical moisture, etc.) Now 78.3% of the cases reside on the diagonal with no off-diagonal cell having greater than 3.5% of the counts.

There is some over-forecasting of the "none" or no front category (i.e., 58.2 versus 52%) and under-forecasting of cold fronts and cutoff lows. Nevertheless, over all forecasts there was indication of considerable forecaster skill in that both the CPOD and the TSS values were positive and sizable (i.e., .60 and .73 respectively). The breakout by season also shows evidence of substantial and consistent forecaster skill.

E. Forecast Inputs

One of the interesting questions in all forecasting problems is how important were the various inputs to the final forecasts? Table 6 presents the results for this question as assessed by the forecasters. For all days combined, the satellite (45%), NMC numerical guidance (22%), and radiometer inputs (12%) are the most important. If one separates the local from the regional or national scale inputs then 75% of the forecast is based on regional or national data. The more specific local inputs (e.g., Sheridan radar, (4%) local rawinsondes (4%), icing probes (3%) etc.) are not very important.

However, when the forecast days are partitioned by the presence or absence of storms on the barrier, the results are rather different. On Storm Days the synoptic or larger scale data systems (e.g., satellite and numerical guidance) get decreased attention and the more local systems (e.g., Sheridan radar, icing probes, etc.) get increased attention.

This probably is due to a forecaster's desire to gain finer resolution of the storms both in time and space. During non storm days the major emphasis again is on the large scale or synoptic inputs (now, the first three items account for 85%). In short, the forecasters probably are looking at the large scale to see when the next storm might arrive.

Finally, it is notable to see that a relatively new observing system, the radiometer, already is a valued (12%) tool in forecasting liquid water conditions in the Sierras.

5.0 CONCLUDING COMMENTS

We have taken the view that whether it is operations or research, if one forecasts in earnest then one should formally evaluate or verify the forecasts. It is only through such feedback that forecasters and science can better understand the atmosphere and its many faces.

The results have indicated that one can predict the occurrence of various types of cold fronts, and their associated liquid water, on the west coast of the United States with substantial skill. Furthermore, such predictions could have a significant impact on the economics of the area as it relates to construction, agriculture, transportation, local flood management, etc.

This exploratory forecast experiment has begun to identify the needed forecast inputs and relations by which these events can be predicted. A new observing tool, the radiometer, already has shown its importance as an input to the local precipitation forecasting problem. It now appears that one may be able to relate the type of cold front to the timing and intensity of liquid water and the potentially associated precipitation.

Lastly, the indications of forecasting skills shown in this study are sizable and encouraging and further efforts to implement and improve these skills are warranted.

Table 1. The 3 x 3 Contingency Table of counts (percentage) and summary measures for verification of the predictions of <u>concentrations</u> of liquid water (gms/m^3).

A. Contingency Table, 0-2 hours, 1985-86 and 1986-87 seasons combined.

		Observed			
		LW = 0	0 < LW < 0.1	LW > 0.1	
Predicted	LW = 0	159 (54.5)	10 (3.4)	0 (0.0)	169 (57.9)
	0 < LW < 0.1	15 (5.1)	28 (9.6)	7 (2.4)	50 (17.1)
	LW ≥ 0.1	4 (1.4)	35 (12.0)	34 (11.6)	73 (25.0)
	Total	178 (61.0)	73 (25.0)	41 (14.0)	292 (100)

B. Summary Measures

Time Period	1985-86 (170)		1986-87 (122)		Combined (292)	
	TSS	CPOD	TSS	CPOD	TSS	CPOD
1. 0-2 Hrs	.53	.56	.60	.50	.60	.54
2. 2-4 Hrs	.53	.54	.60	.59	.61	.55
3. 4-6 Hrs	.45	.50	.40	.59	.53	.52
4. 6-8 Hrs	.44	.51	.37	.38	.49	.45
5. 8-10 Hrs	.45	.46	.36	.38	.48	.44
6. 10-12 Hrs	.43	.41	.40	.43	.48	.42

Table 2. The 7 x 7 Contingency Table of Counts (percentages) and summary measures for verification of the predicted <u>onset</u> times of liquid water (2 hour interval).

A. Contingency Table, 85-86 and 1986-87 seasons combined.

Predicted \ Observed	None	T0-2	T2-4	T4-6	T6-8	T8-10	T10-12	
None	118 (40.4)	6 (2.1)	1 (.3)	0 (0)	4 (1.4)	0 (0)	3 (1.0)	132 (45.2)
T0-2	3 (1.0)	104 (35.6)	5 (1.7)	1 (.3)	4 (1.4)	4 (1.4)	2 (.7)	123 (42.1)
T2-4	1 (.3)	2 (.7)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (1.0)
T4-6	3 (1.0)	0 (0)	1 (.3)	1 (.3)	3 (1.0)	0 (0)	2 (.7)	10 (3.4)
T6-8	5 (1.7)	2 (.7)	0 (0)	0 (0)	2 (.7)	2 (.7)	1 (.3)	12 (4.1)
T8-10	7 (2.4)	0 (0)	0 (0)	3 (1.0)	0 (0)	1 (3)	0 (0)	11 (3.8)
T10-12	1 (.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (.3)
	138 (47.3)	114 (39.0)	7 (2.4)	5 (1.7)	13 (4.5)	7 (2.4)	8 (2.7)	292 (100)

B. Summary Measures

	1985-86 (170)	1986-87 (122)	Combined (292)
TSS	.78	.59	.76
CPOD	.72	.65	.70

Table 3. The 7 x 7 Contingency Table of Counts (percentage) and summary measures for verification of the durations of liquid water (2 hour interval).

A. Contingency Table, 1985-86 and 1986-87 combined.

Observed

Predicted	None	T0-2	T2-4	T4-6	T6-8	T8-10	T10-12	
None	118 (40.8)	7 (2.4)	3 (1.0)	1 (.3)	1 (.3)	1 (.3)	1 (.3)	132 (45.7)
T0-2	2 (.7)	1 (.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3 (1.0)
T2-4	9 (3.1)	1 (.3)	1 (.3)	0 (0)	3 (1.0)	0 (0)	0 (0)	14 (4.8)
T4-6	5 (1.7)	1 (1.3)	3 (1.0)	1 (.3)	0 (0)	0 (0)	2 (.7)	12 (4.2)
T6-8	1 (.3)	3 (1.0)	3 (1.0)	4 (1.4)	2 (.7)	1 (.3)	2 (.7)	16 (5.5)
T8-10	1 (.3)	2 (.7)	0 (0)	0 (0)	0 (0)	0 (0)	2 (.7)	5 (1.7)
T10-12	1 (.3)	3 (1.0)	7 (2.4)	4 (1.4)	1 (.3)	10 (3.5)	81 (28.0)	107 (37.0)
	137 (47.4)	18 (6.2)	17 (5.9)	10 (3.5)	7 (2.4)	12 (4.2)	88 (30.4)	289 (100)

B. Summary Measures

	1985-86 (n = 168)	1986-87 (121)	Combined (289)
TSS	.76	.49	.64
CPOD	.62	.43	.57

Table 4. Summary measures of verification for liquid water concentration, onset and duration partitioned by storm conditions, 1985-86 and 1986-87 seasons combined.

A. Concentration

Time Period	Non Storm Day (153)		Storm Day (139)	
	TSS	CPOD	TSS	CPOD
1. 0-2 hr.	.36	.29	.46	.58
2. 2-4	.51	.50	.41	.56
3. 4-6	.23	.38	.31	.53
4. 6-8	.31	.47	.22	.48
5. 8-10	.23	.33	.23	.45
6. 10-12	.30	.28	.24	.44

B. Onset

.45	.41	.67	.76

C. Duration

.35	.14	.36	.65

Table 5. The 5 x 5 Contingency Table of counts (percentage) and summary measures for verification of the predicted frontal types.

A. Contingency Table, 1985-86 and 1986-87 combined

Observed

		None	Cold	Split	Cutoff	Other	
Predicted	None	145 (49.3)	10 (3.4)	7 (2.4)	2 (.7)	7 (2.4)	171 (58.2)
	Cold	2 (.7)	9 (13.3)	5 (1.7)	1 (.3)	1 (.3)	48 (16.3)
	Split	3 (1.0)	6 (2.1)	40 (13.6)	8 (2.7)	0 (0)	57 (19.4)
	Cutoff	2 (.7)	0 (0)	0 (0)	4 (1.4)	0 (0)	6 (2.0)
	Other	1 (.3)	8 (2.7)	1 (.3)	0 (0)	2 (.7)	12 (4.1)
		153 (52.0)	63 (21.4)	53 (18.0)	15 (5.1)	10 (3.4)	294 (100)

B. Summary Measures

	1985-86 (171)	1986-87 (123)	Combined (294)
TSS	.73	.66	.73
CPCD	.62	.56	.60

Table 6. Percentage contribution of the quantitative forecast inputs to the liquid water forecasts by Non-Storm and Storm Days, 1985-86 and 1986-87 seasons combined.

Inputs	Non-Storm (153)	Storm (139)	Combined (292)
1. Satellite images	50*	39	45
2. Numerical guidance	26	17	22
3. Other NMC products	9	6	8
4. Local radar	0	8	4
5. Local rawinsondes	2	7	4
6. Local precip. rates	0	0	0
7. Radiometer	11	14	12
8. Icing probe rates	1	5	3
9. Orographic formula	0	2	1
10. Other	1	2	1
TOTAL	100	100	100

* All values rounded to nearest one percent

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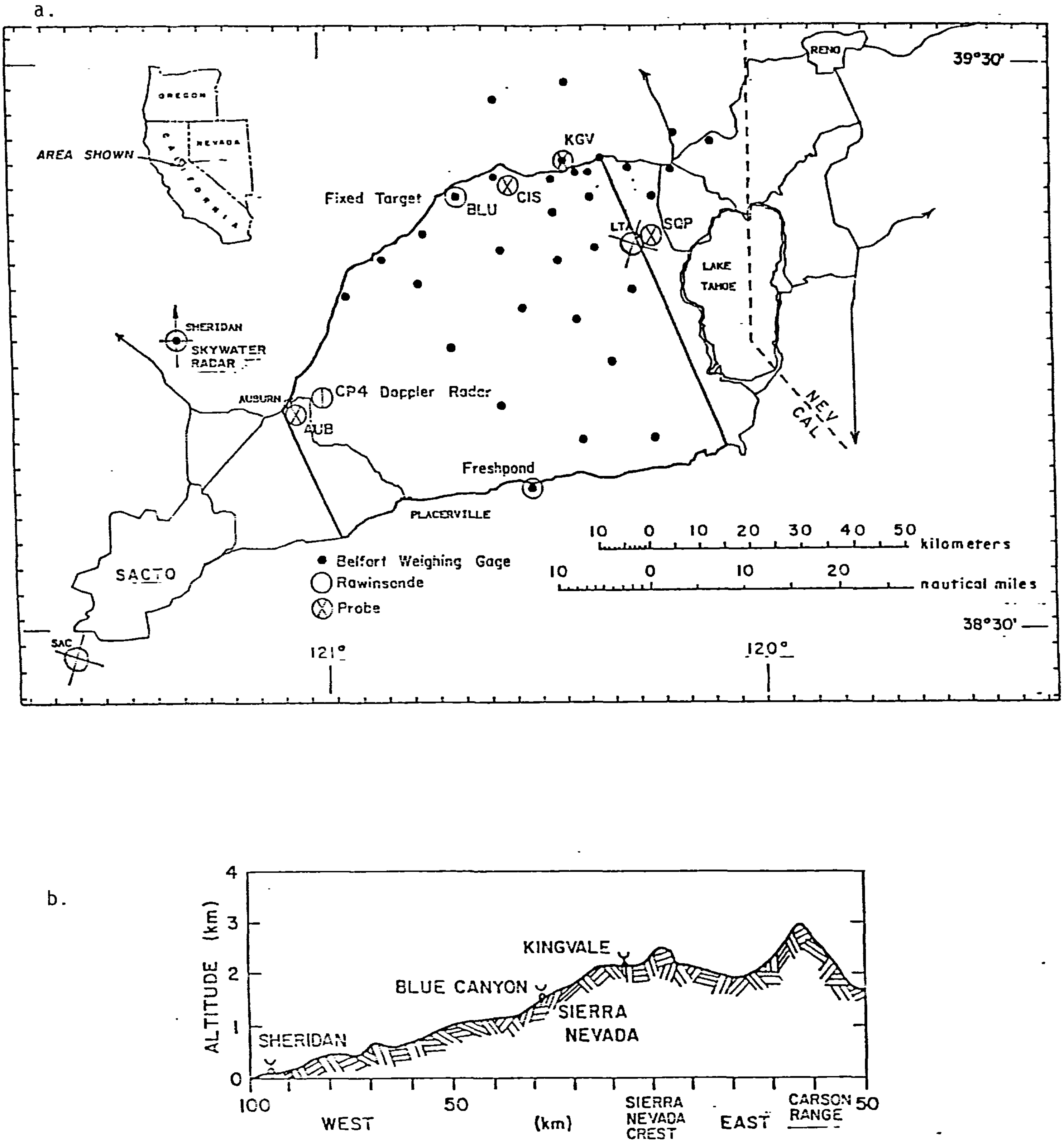


Fig. 1. a) American River Basin with SCPP instrument locations noted. b) Elevation transect over the American River Basin.

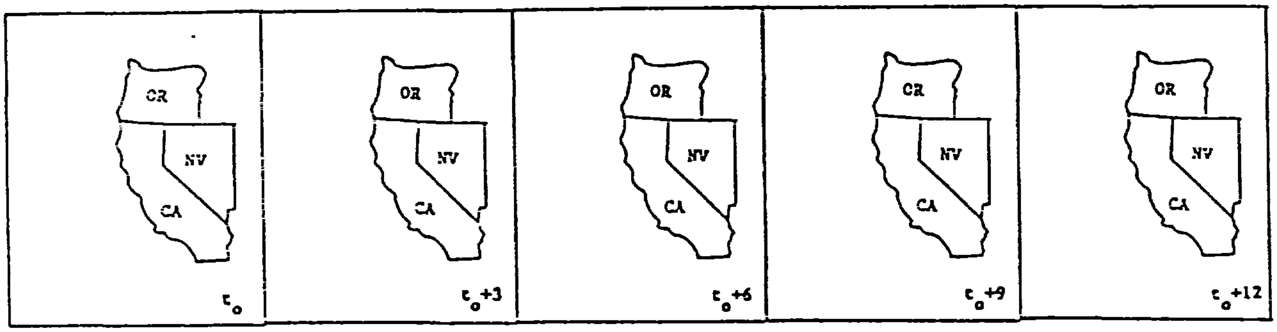
FORECAST EXPERIMENT

Date____________ Time Issued: 9am / 9pm Forecaster__________

Current LW at KGV (10 min avg): __________mm Time of obs.: ___________
SLW indicated at project icing rate meters: Yes No (circle one)
Current synoptic/mesoscale situation:_______________________________

A. Frontal Type Expected Over the ARB:

_____1. Classic cold front
_____2. Split front
_____3. Warm frontal overrunning
_____4. No frontal boundary expected
5. Other (explain):__________



B. Forecast for Kingvale:

Avg LW (mm) for 2 hr period (amount)							
	T_0	T_2	T_4	T_6	T_8	T_{10}	T_{12}
Precip (mm) for 2 hr period							
	T_0	T_2	T_4	T_6	T_8	T_{10}	T_{12}
Temperature (°C) for 2 hr period							
	T_0	T_2	T_4	T_6	T_8	T_{10}	T_{12}

C. % contribution of observational tools to the above forecast:
(Totals should add up to 100%)

Radiometer	______%	Satellite pictures	______%
Rawinsondes	______%	Orographic formula	______%
SH radar	______%	Probe icing rates	______%
Zephyr Wx Products	______%	Precipitation data	______%
Numerical Fcst Guidance	______%	Other (specify)______________	______%
			100%

D. Comments:

Figure 2. LW Forecast Experiment form.

Figure 3. The three dimensional frequency diagram, 0-2 hour predicted versus observed concentrations of liquid water, 1985-86 and 1986-87 seasons.

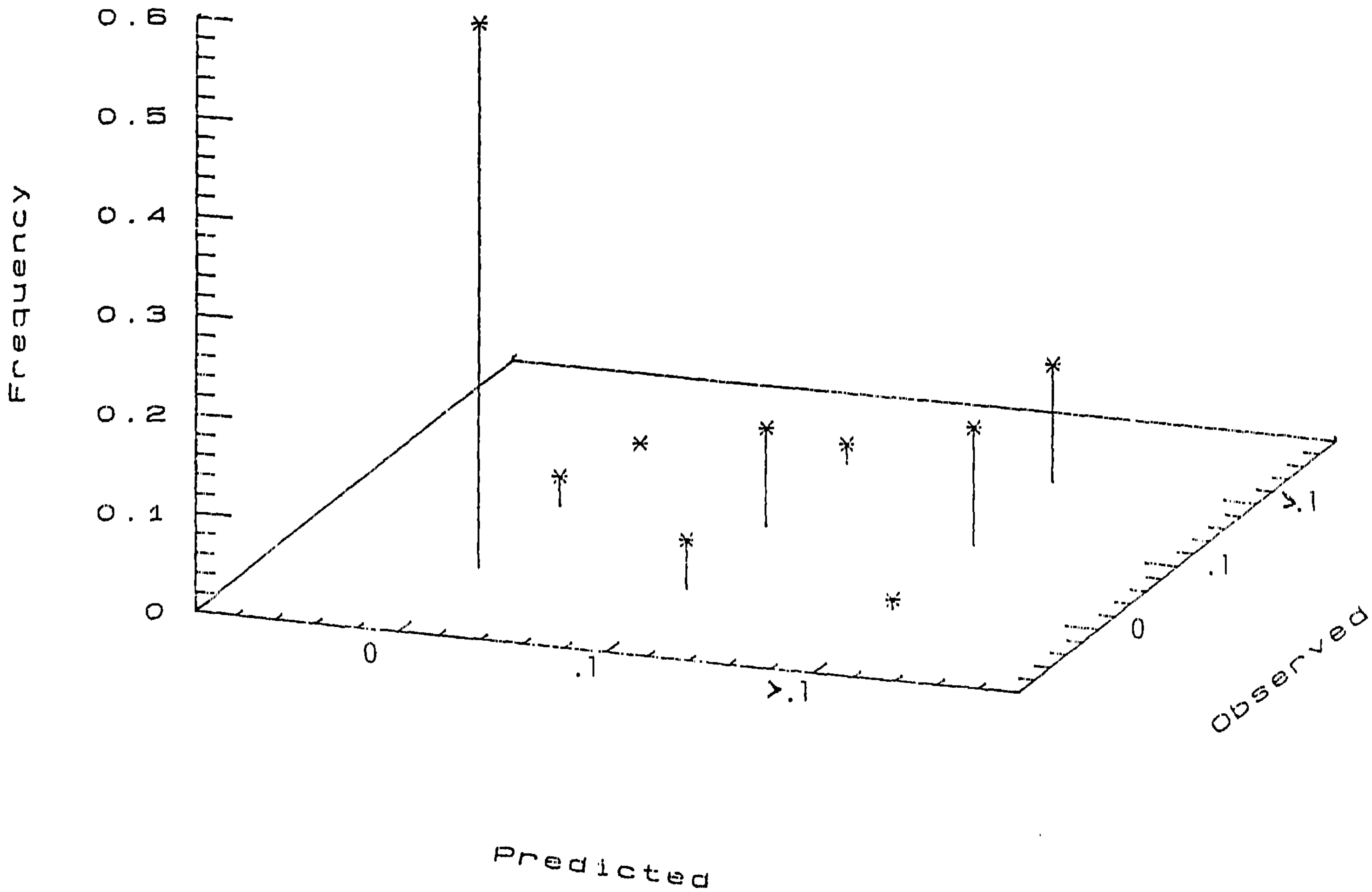


Figure 4. The conditional bias plot, onset percentage differences, 1985-86 and 1986-87 seasons.

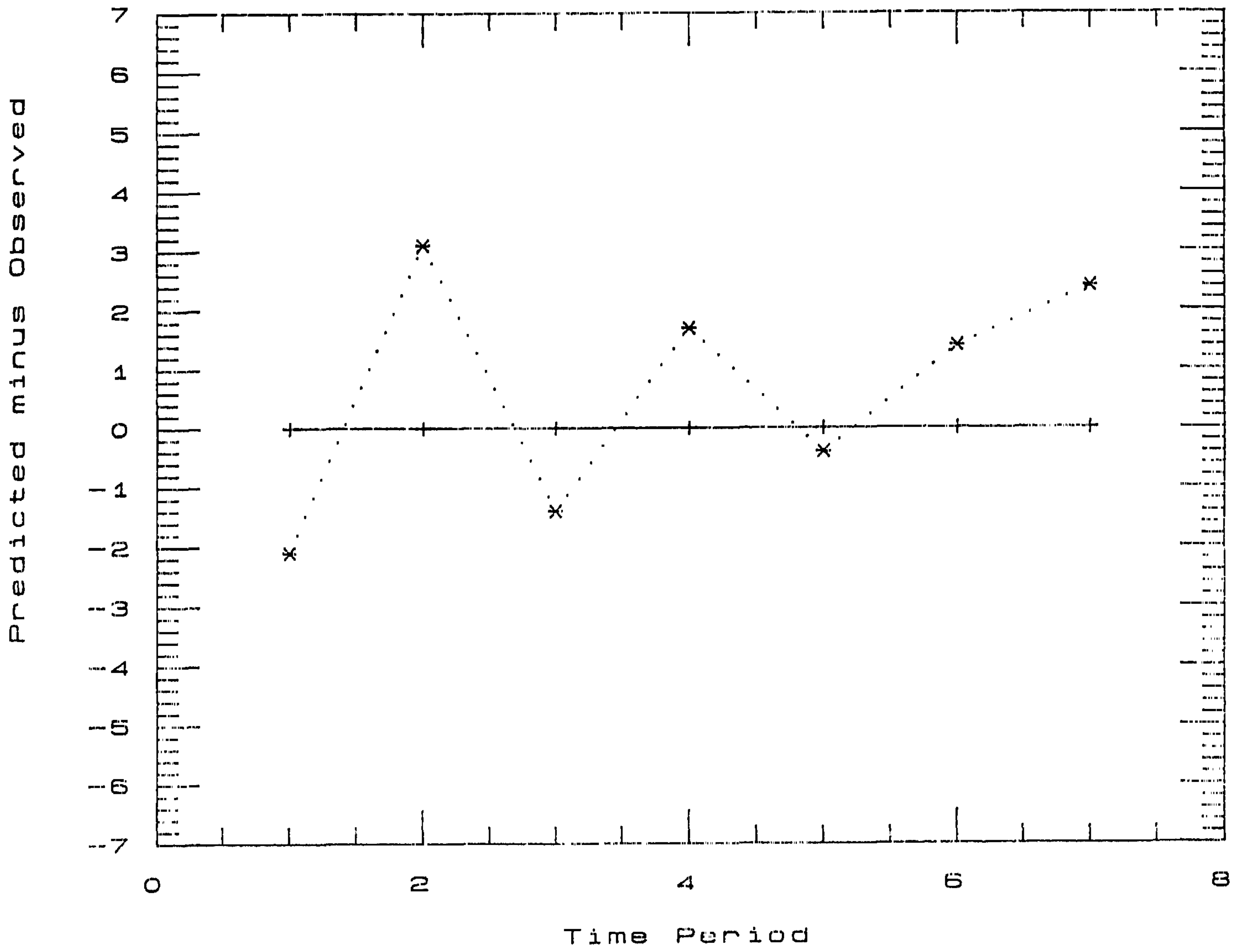


Figure 5. The conditional bias plot, duration percentage differences, 1985-86 and 1986-87 seasons.