SUPERCOOLED LIQUID WATER CONCENTRATIONS IN WINTER OROGRAPHIC CLOUDS FROM GROUND-BASED ICE ACCRETION MEASUREMENTS

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Abstract. An icing rate detector originally designed for aircraft is used to measure supercooled liquid water in winter orographic clouds at a fixed mountain-top site in the central Sierra Nevada of California. Supercooled liquid water concentrations have been determined using continuous records of rime ice accretion and windspeed. It is shown that supercooled liquid water is occurring within larger portions of storms than prior airborne observations over the operational area have indicated, particularly during pre-frontal periods. In many instances, supercooled liquid water occurs below safe aircraft operational altitudes over the mountainous project area. The ground-based measurement system provides an effective tool for semi-quantitative determination of supercooled liquid water within specific cloud volumes heretofore unmeasured.

1. INTRODUCTION

A crucial factor in any program designed to investigate the potential for winter-time precipitation enhancement by application of freezing nuclei is the measurement of supercooled liquid water (SLW) within clouds traversing the project area. The amount and areal distribution of SLW may be the single most important indicator of seeding potential among the enormous number of physical and chemical properties of clouds and storm systems. The scientific literature contains frequent references to the presence of SLW as a key condition to be investigated in weather modification research efforts and applied in operations programs. Past investigations have involved a variety of measurement techniques.

Modern measurement efforts involving aircraft have included the Johnson-Williams hot-wire device (Neel and Steinmetz, 1952; Neel, 1955), the Rosemount icing rate detector (Brown, 1981), the Particle Measurement Systems imaging probes (Knollenberg, 1970, 1972), and a variety of dropsondes (Hill and Woffinden, 1977). Ground-based efforts have employed microwave radiometers (Guiraud, et al, 1979), snow and ice crystal sampling and photography (Vardiman and Hartzell, 1976) and balloon born sondes (Hill and Woffinden, 1980). Ground-based in-situ measurements of SLW include microscope slide sampling of ice crystals and the analysis of ice accretion on cylinders (Schaefer, 1945; Howe, 1960). Each technique offers unique capabilities. The attendant advantages and limitations are related to both the measurement conditions and funding levels.

The Sierra Cooperative Pilot Project (SCPP) is a winter precipitation enhancement research program funded by the Bureau of Reclamation and conducted in the central Sierra Nevada Range of California. Recognition of the value of documenting the distribution of SLW has been reflected in the program's research efforts since its inception. Airborne measurement techniques employed in SCPP have included coated microscope slides, the standard Johnson-Williams instruments, a variety of probes from Particle Measurement Systems, and certain Rosemount devices (Lamb, et al., 1976; Marwitz, et al., 1978; Marwitz, 1979; Stewart and Marwitz, 1980). Additional techniques include remote sensing by radiometer (Snider and Rottner, 1982) and ground-based snow crystal sampling and photography (Humphries and Moore, 1981; Humphries, 1982).

Since the 1977/78 winter season, the SCPP investigations have yielded a somewhat varied indication of the concentration and temporal occurrence of SLW. Although SLW has been noted during a number of the project's cloud physics measurement flights, airborne indications have rarely reached the abundant levels suggested by ground-based ice crystal sampling, moderate to heavy icing noted on seeding aircraft flown over the Sierra Range during the past 30 years, and ground observations of considerable riming on structures and trees. This apparent discrepancy fueled the suspicion that substantial quantities of SLW actually traverse the project area for extended periods and below allowable flight altitudes, generally at temperature levels warmer than -10°C. The need for SLW measurements within that lower range of altitudes has always been acute, with continuous measurements being most desirable.

Toward resolving this particular problem, a new development in SCPP investigations has been the use of a Rosemount icing rate detector and supporting systems at a mountain-top installation to document in-cloud SLW content and distributions via ice accretion measurements. (Figure 1).

This paper presents (1) a description of the prototype icing rate detection system, (2) the initial method used to calculate cloud SLW from ice accretion and wind data, and (3) some preliminary findings from the data analysis.

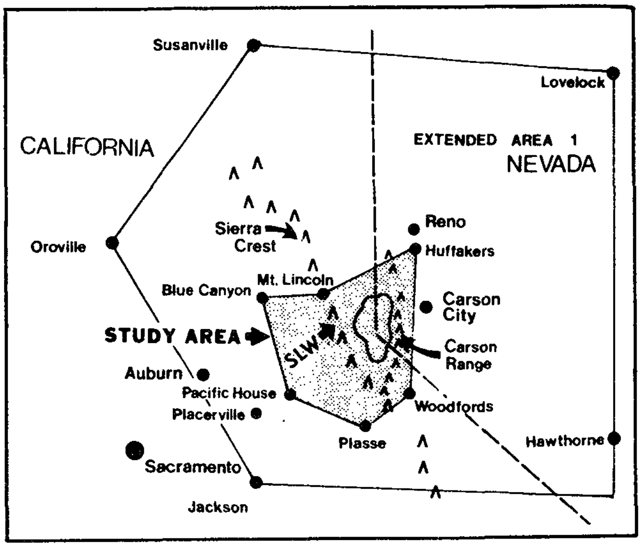

FIGURE 1. Research area and location of the measurement site for SLW.

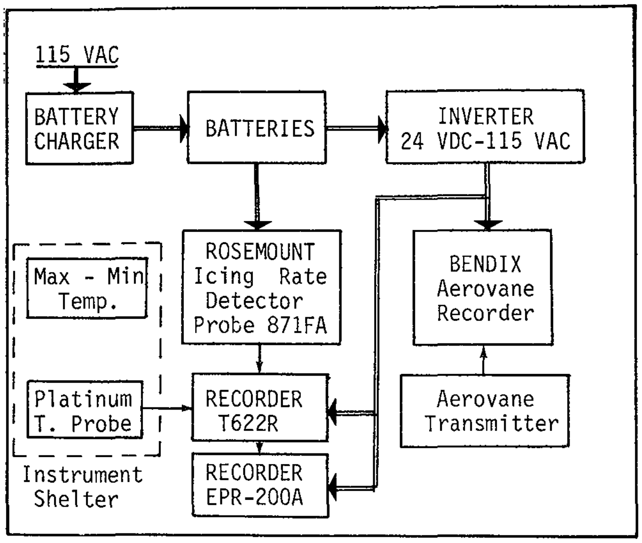

FIGURE 2. Supercooled Liquid Water Measurement System

2. THE MEASUREMENT SYSTEM

For the initial SLW measurements, Atmospherics Incorporated (AI) provided and installed a number of individual components which comprised the total icing rate detection system. These components were:

- Rosemount Ice Detector Model 871FA
- Bendix Aerovane Transmitter Model 120
- Bendix Aerovane Recorder Model 141
- AI Platinum Resistance Temperature Probe
- WeatherMeasure Strip Chart Recorder Mod T622R
- WeatherMeasure Polyrecorder EPR 200A
- Science Associates Max-Min Thermometer
- Science Associates Instrument Shelter
- Batteries, Battery Charger, Inverter, Control and Relay Boxes, Cables

The electrical arrangement of each component is accomplished in such a manner that operations can be maintained throughout moderate-duration commercial power outages. The 115 VAC commercial power source is fed through a battery charger to the two series connected 12 VDC wet cell batteries. In turn, these feed a 24 VDC-to-115 VAC inverter which provides power to the relevant instrumentation. The 24 VDC requirement for certain instrumentation comes directly from the batteries. When power outages occur, the wet cell batteries are able to maintain operation of all instrumentation for a continuous period of at least 24 hours, regardless of the ice detector's deicing requirements.

The general layout of the total system as established at the Squaw Peak area during the 1980/81 season is shown in Figure 2.

The ice detector and wind sensor are installed approximately 10 m above ground level atop the upper terminal of the Siberia ski lift at the Squaw Valley ski area on the eastern edge of the American River Basin. The site overlooks a nearly vertical drop-off to the west of approximately 300 m and provides unobstructed exposure from about 140° through 350° magnetic. The site elevation of 2,625 m positions the sensors typically in the 0° to -10°C temperature range during stormy periods of the winter months. The power and recording equipment are housed within a small maintenance building made available by the Squaw Valley Ski Corporation.

The operational procedure throughout each six-month winter season includes a site visitation each 14-day interval to change strip charts, obtain comparative wind and temperature measurements, and check the full system for proper operation. Access is generally by ski lift, although helicopters are occasionally used.

For many years, icing rate detectors have been used on aircraft and ground-based structures where measurements of icing are required for operation of deicing equipment or warning systems, as well as in engineering studies for structure design in icing-prone locations (Tattelman, 1982). Most of these instruments are labor-intensive and require on-site personnel for operations. The use of a Rosemount icing rate probe operating continuously at a fixed ground-based location for the purpose of determining specific quantities and distributions of in-cloud SLW is unique.

The Rosemount icing rate detector is an electro-mechanical device which transmits a signal when a specified amount of ice is present on the sensing element. This element is an axially vibrating tube (24.5 x 6.4 mm) protruding from a strut airfoil (Figure 3). The airfoil contains a heater for deicing the probe with the heater wires interfaced to the ice detector's electronics.

The 40 KHz vibration frequency of the probe is of such low magnitude that it cannot be seen or felt. This is achieved through a property of certain metals known as magnetostriction and hook-up to a magnetostrictive oscillator (MSO). The

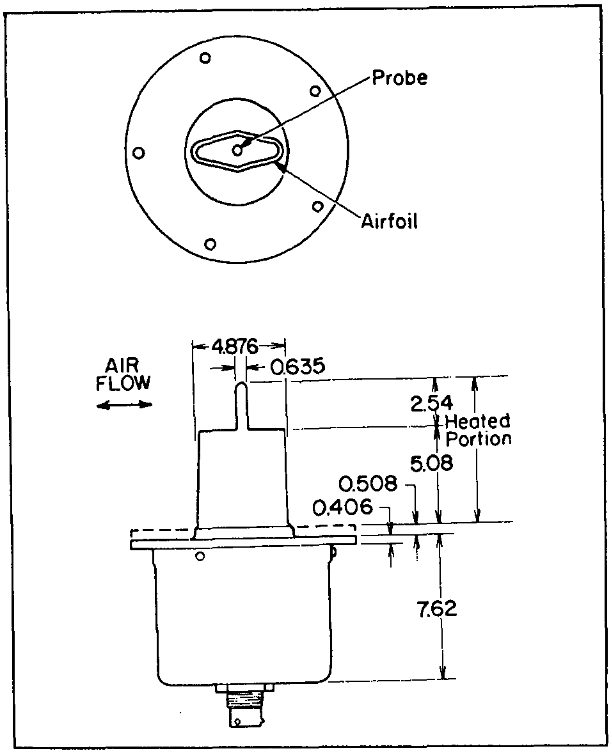

FIGURE 3. Schematic drawing of the Rosemount icing rate detector Model 871FA

reference signal of the oscillator is summed with the signal from the MSO to produce a difference frequency which serves as the output of the instrument. The frequency-to-voltage converter changes the difference frequency to a voltage. When this voltage reaches a preset level corresponding to an accumulation of ice equal to the mass of a uniformly-distributed 0.5 mm film of water on the probe, an output signal is provided to two timers. These timers control the duration of the 24 VDC deicing signal and the 1.8 ampere current supplied for 7 seconds to the detector deicing heaters. An analog output corresponding to ice accretion is also provided as a test point or monitoring voltage. Both the trip-point and the analog output corresponding to the rate of ice accretion are recorded. The response time of the ice detector is inversely proportional to the liquid water content of the air times its velocity at a specified ambient temperature and water droplet diameter.

Due to the adhesion property of ice, its effect on the probe vibration is different from other substances such as oil, grease, dirt, insects or other contaminants. As a result, valid icing signals are produced only when ice is actually formed. Due to the high collection efficiency of the probe, ice forms on this sensor before it collects on other surfaces. The key to the ice detection performance is the design simplicity which virtually eliminates false signals. Additionally, if the probe is damaged the resultant frequency shift causes the unit to produce a continuous offset base line signal, thereby providing a fail-safe indication of operational status.

Of particular importance to the application within SCPP is the fact that the instrument responds accurately to ice mass accumulated in any physical configuration on the sensing probe. Although usually stated by Rosemount as ice thickness, this ice mass at trip-point is actually the equivalent of a uniformly distributed water film of 0.5 mm thickness. This is a unique and valuable feature.

3. DATA REDUCTION AND LWC CALCULATIONS

During the 1980/81 and 1981/82 winter seasons, continuous records were obtained in analog form on strip charts. Measurements obtained during storm periods of particular interest were coded as 15-minute average values of wind speed, wind direction, air temperature and, for the riming measurements, the number of deicing cycles ("trips") of the icing rate detector.

Calculation of liquid water content from this measurement system hinges on the fact that the Rosemount device cycles when the probe senses the ice mass equivalent of a uniformly distributed 0.5 mm thick film of water. It has been assumed this mass is independent of the physical configuration of the rime ice build-up on the probe.

The physical and operational characteristics of the icing rate probe pertinent to the LWC calculations are:

- Length (l) = 25.40 mm
- Diameter (d) = 6.35 mm
- Probe cross-section presented to airflow = 1.613 cm^2
- Mass of ice necessary to initiate "trip" = 0.51 mm uniform water thickness

To determine the mass of 0.51 mm water thickness on the probe we use,

$$V_3 = V_2 - V_1$$

where V_1 = volume of the dry probe and V_2 = volume of the probe with a 0.51 mm thick coating of water. The volume of water required to cycle the instrument = 0.279 cm^3. Therefore, the mass of a 0.51 mm water thickness on the probe = 0.279 grams.

The volume of air sampled between "trip" points is obtained using,

$$V_4 = \bar{v}tA$$

where $\bar{v}$ = the mean wind speed (cm sec^{-1}) for the icing accumulation period since the previous "trip", t = time (sec) since the previous "trip", and A = probe area exposed to the wind (cm^2).

The uncorrected liquid water content is then,

$$LWC = V_3/V_4$$

LWC values through extended storm periods are calculated at 15-minute intervals using,

$$LWC = \frac{\text{number of trips} \times V_3}{V_4}$$

As an example, a 15-minute period which includes three ice detector trips and windspeeds averaging 11.6 m $\sec^{-1}$ would yield,

$$\mathrm{LWC} = \frac{3 \times 0.279\ \mathrm{g}}{1160\ \mathrm{cm\ sec^{-1}} \times 900\ \mathrm{sec} \times 1.613\ \mathrm{cm^2}}$$

$$= \frac{0.837\ \mathrm{g}}{1.684 \times 10^6\mathrm{cm}^3} = 0.497\ \mathrm{g\ m^{-3}}$$

Obviously, the calculation of LWC values can be strongly influenced by the collection efficiency of the sensing probe. For cylinders, collection efficiency varies directly with ventilation rate and droplet size, and inversely with sensor diameter. The efficiency is also affected to a much smaller degree by other factors, such as the density of the sample air. Recent work by Tattleman (1982) testing Rosemount probes under chamber and field conditions, indicates that the instrument is a very efficient collector. Rosemount has also conducted some exhaustive laboratory tests and notes that the probe output is highly correlated with the mass and thickness of ice measured on this particular diameter cylinder.

We have not yet attempted to adjust the results based upon calculations of collection efficiency of the probe used in this particular application. More measurements are required with an observer onsite during storm episodes before we can adequately address this issue. Visual observations will also be particularly helpful in determining the probe performance and identification of chart record characteristics during conditions of freezing drizzle and freezing rain.

As a confirming measurement to the Rosemount icing rate detector, a number of LWC calculations have been made using cloud droplet size and concentration data from both mineral oil and formvar coated slides exposed at the ice detection site during a storm period of 23-24 February 1981. These data show reasonably good correspondence with the LWC values calculated from the icing rate detector system. In most cases, the comparisons between LWC calculated from measurements of supercooled cloud droplets and LWC calculated from the Rosemount data show correspondence within a factor of two or three.

Calibration checks of the Rosemount probe have also been conducted in the limited laboratory facility at AI head office. This work involves bonding a variety of materials to the probe and documenting the mass required to cycle the device. Of particular interest has been the bonding of aluminum 10 mg balance weights with 3M adhesive products. In these preliminary tests, the analog output voltage of the icing rate detector shows excellent correspondence with each balance weight bonded to the probe, and the "trip" point occurs reasonably close to the total bonded weight of 0.279 grams. The range of values occuring at each "trip" point has been from 0.240 to 0.295 grams.

It should be emphasized that additional laboratory calibration work should be conducted before the assumed physical characteristics of the probe ouputs are accepted. From tests of three probes operating simultaneously in the laboratory, there is evidence to suggest that each individual probe may have its own calibration curve and the mass required to "trip" any individual probe may be as low as 0.08 grams and as high as 0.36 grams.

4. ANALYSIS

The purpose of initiating the measurements at the Squaw Peak site was to strengthen the documentation of temporal and spatial distribution of SLW over the SCPP project area at elevations below those allowed for safe aircraft operations. The continuous nature of the observations produces additional value, although the fixed-point measurements sacrifice space resolution available from the aircraft for time resolution available from continuous measurements.

This section presents some preliminary results from analyses within the overall goals of SCPP, including the seasonal distribution and character of SLW at the Squaw Peak site, the relationship of the occurrence of SLW with precipitation events in the project area, and the distribution and character of SLW related to specific cloud types. The results are drawn from the 1981/82 field season when radar and other SCPP systems were operated as well.

4.1 Seasonal distribution and character of SLW

Given the availability of continuous observations, a key question concerning the occurrence of SLW was that of seasonal distribution. Aircraft measurements conducted during past SCPP seasons have suggested that significant SLW occurrence over time was disappointingly infrequent, particularly during pre-frontal stable orographic storm conditions (Marwitz, et al., 1978; Marwitz, et al., 1979; Stewart and Marwitz, 1980).

Our suspicion has been that the airborne results are greatly influenced by altitude restrictions on aircraft operations over the mountainous project area, plus the limitations of on-station time during total storm periods. These airborne measurement difficulties may be somewhat offset by the limitations associated with a fixed-point sensor, but proper site location coupled with the distinct advantage of a continuous record have produced a most useful system for assessment of seeding potential over this particular project area.

The 1981/82 records were analyzed to determine the full-season frequency of icing occurrence by tabulating positive icing indications within 15-minute intervals for the six-month period of record. The results are summarized in Table 1. The values strongly suggest a substantial occurrence of SLW during the winter season at an elevation of 2,625 m asl.

The temperature distribution at the Squaw Peak site during icing periods throughout the six-month season is shown in Figure 4. The plot is based on a tabulation of values from 15-minute intervals whenever icing was indicated. The distribution shows that nearly 60% of the total 15-minute icing periods occurred in the range of 0°C to -5°C, and that 90% occurred at -10°C or warmer.

Table 1. Total hours of positive icing

Month	Hours	Month	Hours
Nov'81	175.0	Feb'82	126.5
Dec'81	155.5	Mar'82	253.5
Jan'82	68.0	Apr'82	101.0
		Season total:	879.5

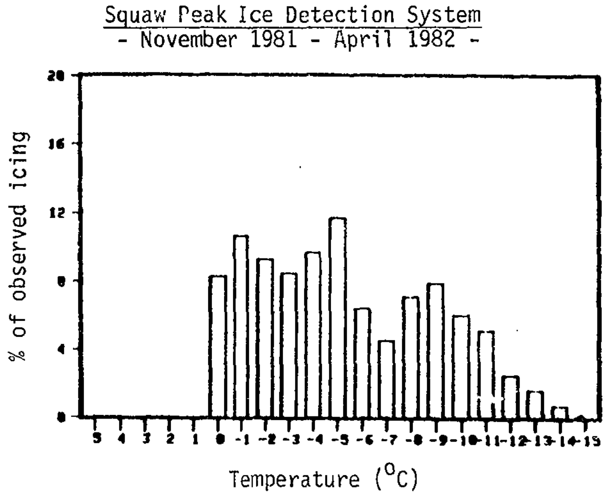

Fig. 4. Distribution of temperature at the Squaw Peak site during periods of icing within the 6-month measurement season of November 1981 through April 1982. Values were determinted at 15-minute intervals.

The magnitude of the full-season occurrence shown earlier, combined with the temperature distribution in Figure 4, supports the suspicion that significant quantities of SLW can and do occur at altitudes below safe aircraft operational limits.

4.2 Occurrence of SLW relative to precipitation events

The monthly and seasonal values of icing indications presented in Table 1 assume additional meaning when compared with the occurrence of precipitation across the project area. Toward this type analysis, the combined duration of "significant precipitation periods" was compared with the season total icing duration. By definition, the blocks of time begin with the first measurable precipitation at any gage in the SCPP network and end with the last precipitation at any location. Within this definition, the "significant precipitation periods" over-estimate the actual duration of precipitation at any fixed point within the network's large geographical area. A computer generated map of the precipitation gage network is presented in Figure 5.

The 26 precipitation periods identified during the 1981/82 season had a total duration of 1,489.5 hours. The total season duration of icing divided by the total precipitation duration is 879.5/1489.5 = 59%. With a few notable exceptions, icing periods at the Squaw Peak site were found to correspond well with the "significant precipitation periods". Icing indications generally preceded by

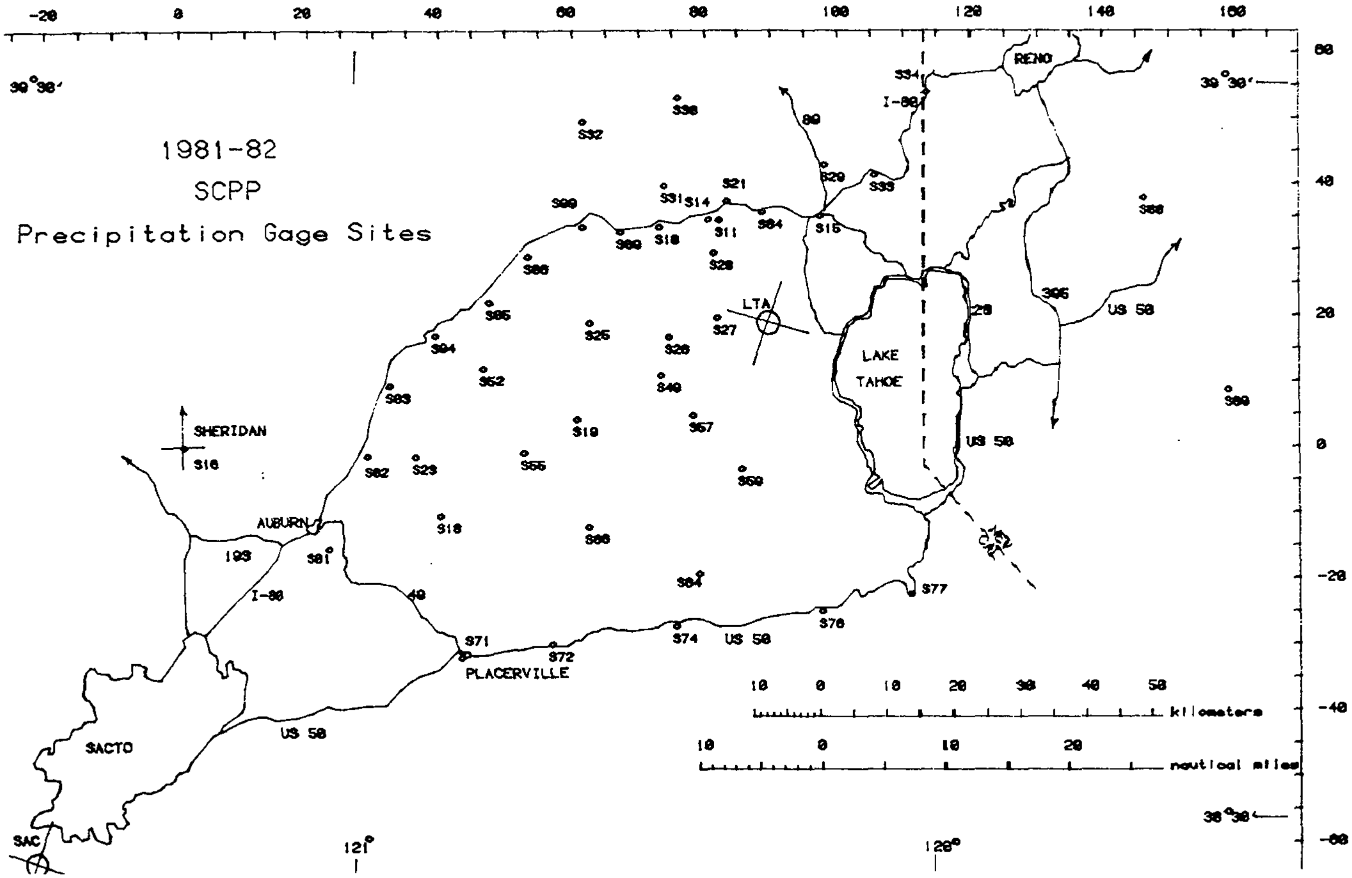

Fig. 5. SCPP project area map showing the location of the SLW measurement system at the position labeled LTA west of Lake Tahoe, and the SCPP precipitation gage network as operated during the 1981/82 field season.

one to six hours the occurrence of measurable precipitation anywhere within the SCPP gage network in approximately 35% of the observed storm sequences.

During three storms no icing was indicated, although temperatures at the SLW detector site were well below freezing for their full durations. In one instance of no icing at the site, project personnel observed considerable riming on trees and structures at elevations centered approximtely 1 km lower than the detector site. On five occasions, icing was indicated for several hours but no precipitation was measured in the gage network. During those periods, the temperatures at the site were generally between $0^{o}C$ and $-10^{o}C$, although in one case icing was observed for more than 10 hours when temperatures were between $-10^{o}C$ and $-12^{o}C$.

4.3 SLW character during stable pre-frontal cloud conditions

A sample of observations in stable pre-frontal cloud conditions was analyzed to determine the character and distribution of SLW during those periods. The 137-hour sample included all storm periods classified as orographic (OR), area-wide (AW) and embedded band (EB), as described in the SCPP Operations Plan (Huggins, 1981). Tabulation of positive icing indications at 15-minute intervals within the 137-hour sample indicated icing was in progress during approximately 45% of the periods.

Because the calculation of SLW content is very sensitive to airspeed, the wind records were scrutinized to eliminate periods when the unheated aerovane showed evidence of data degradation due to ice loading. Elimination of periods when the sensor appeared to be carrying ice, and periods when the sensor was damaged or lost due to wind and icing, reduced the original 137-hour sample to approximately 24 hours. This collection of shorter periods was analyzed to yield the characteristics shown in Figure 6a, 6b, and 6c. The key findings can be summarized as follows:

- $\overline{LWC}$ during riming periods = 0.40 g m^{-3}
- frequency of LWC $\leqslant$ 0.5 g m^{-3} = 75%
- frequency of LWC $\leqslant$ 1.0 g m^{-3} = 94%
- frequency of riming 0^{o} to $-5^{o}C$ = 57%
- frequency of riming 0^{o} to $-10^{o}C$ = 85%

5. CONCLUSIONS

Based on two winter seasons of operation and the preliminary work reported in this paper, we conclude that the Rosemount icing rate detector model 871FA combined with reliable wind and temperature sensors provides an effective system for ground-based measurements of in-cloud supercooled liquid water. The measurements strongly support the conclusion that SLW is occurring throughout larger portions of stormy periods, particularly in pre-frontal portions, than past airborne observations over the SCPP project area have indicated. In many cases, the SLW simply occurs over the mountainous area below the altitudes considered safe for aircraft operations.

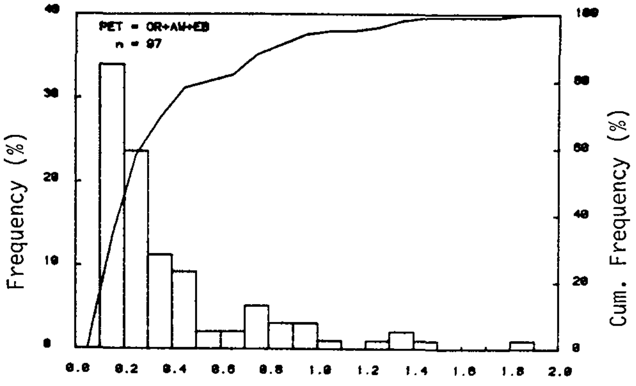

Fig. 6a.

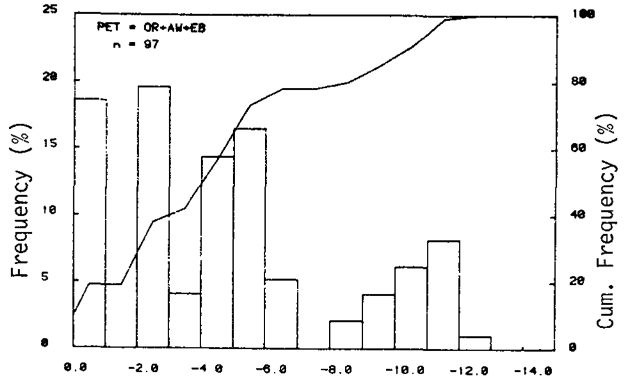

Fig. 6b.

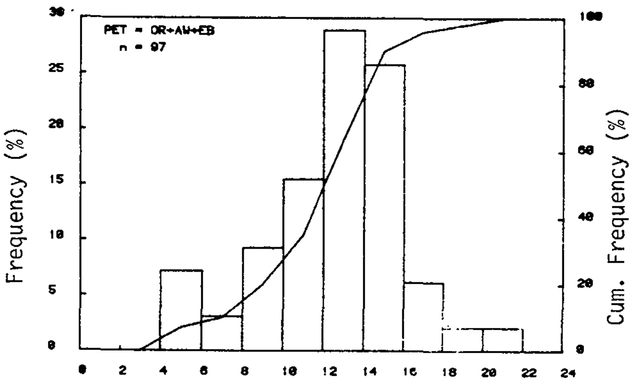

Fig. 6c.

Fig. 6a, 6b, 6c. Distributions of LWC, temperature and wind speed measured at 15-minute intervals during icing periods at the Squaw Peak site. The sample consists of periods classified as stable orographic cloud occurrences over the project area.

The icing rate system offers the potential for a strong input to three major aspects of winter orographic weather modification programs as follows

- in the assessment of seeding opportunities as input to design work and operations
- as an operational tool for key input to real-time decision processes
- as a potential means for stratifying the evaluation efforts regarding apparent seedability within experimental units

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REFERENCES

Brown, E.N., 1981: An evaluation of the Rosemount ice detector for aircraft hazard warning and for undercooled cloud water content measurements. NCAR Tech. Note TN-183+EDD, 13 pp.

Guiraud, F.O., J. Howard and D.C. Hogg, 1979: A dual-channel microwave radiometer for measurement of precipitable water vapor and liquid. I.E.E.E. Trans. Geosci. Electron., GE-17, 129-136

Hill, G.E. and D.S. Woffinden, 1977: Vertical motion sensing by parachute dropsonde. J. Appl. Meteor., 16, 851-854

Hill, G.E., and D.S. Woffinden, 1980: A balloon-borne instrument for the measurement of vertical profiles of supercooled liquid water concentration. J. Appl. Meteor., 19, 1285-1292

Howe, J.B., 1960: Handbook for the rotating multi-cylinder method. Technical Note No. 568. Aeronautical Icing Research Laboratories, Air Research and Development Command, Wright Patterson Air Force Base, Ohio

Huggins, A.W., 1981: Classification and distribution of radar echoes for the Sierra Cooperative Pilot Project. Proceedings, Eighth Conference on Inadvertent and Planned Weather Modifification Reno, Nevada, 36-37

Humprhies, J.H. and J.A. Moore, 1981: Ground microphysics characteristics from a 3-year Sierra Nevada sample. Preprints, Eighth Conference on Inadvertent and Planned Weather Modification Reno, Nevada, 64-65.

Humphries, J., 1982: Ground based microphysical observations using a Knollenberg 2D probe. Preprints, Fifth Symposium on Meteorological Observations and Instrumentation, Toronto, CAN

Knollenberg, R.G., 1970: The optical array: an alternative to scattering or extinction for airborne particle size determination. J. Appl. Meteor., 9, 86-103

Knollenberg, R.G., 1972: Comparative liquid water content measurements of conventional instruments with an optical array spectrometer. J. Appl. Meteor. 11, 501-508

Lamb, D., K.W. Nielsen, H.E. Klieforth and J. Hallett, 1976: Measurements of liquid water content in winter cloud systems over the Sierra Nevada. J. Appl. Meteor., 15, 763-775

Marwitz, J.D., R.E. Stewart, T.S. Karacostas and B.E. Martner, 1978: Cloud physics studies in SCPP during 1977-78. Univ. of Wyoming Report AS 121, to U.S. Bureau of Reclamation, 203 pp.

Marwitz, J.D., R.E. Stewart, T.S. Karacostas and B.E. Martner, 1979: Cloud physics studies in SCPP during 1978-79. Univ. of Wyoming Report AS 123, to U.S. Bureau of Reclamation, 154 pp.

Neel, C.B., and C.P. Steinmetz, 1952: The calculated and measured performance characteristics of a heated-wire liquid water content meter for measuring icing severity. NACA Tech. Note 2615, 37 pp.

Neel, C.B., 1955: A heated-wire liquid-water content instrument and results of initial flight tests in icing conditions. NACA Res. Memo. A54123, 33 pp.

Schaefer, V.J., 1945: Rotating multi-cylinder units for measuring liquid water content and particle size of clouds. General Electric Research Laboratory.

Snider, J.B. and D. Rottner, 1982: The use of microwave radiometry to determine a cloud seeding opportunity. J. Appl. Meteor., 21, 1286-1291.

Stewart, R.E. and J.D. Marwitz, 1980: Cloud physics studies in SCPP during 1979-1980. Univ. of Wyoming Report No. AS 125, to U.S. Bureau of Reclamation, 96 pp.

Tattelman, P., 1982: An objective method for measuring surface ice accretion. J. Appl. Meteor., 21, 599-612.

Vardiman, L. and C. Hartzell, 1976: Final report on an investigation of precipitating ice crystals from natural and seeded winter orographic clouds. WSSI Report No. SR-359-47, to U.S. Bureau of Reclamation, 129 pp.