The Use of Microwave Radiometry to Determine a Cloud Seeding Opportunity

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ABSTRACT

A ground-based combination microwave radiometer-satellite receiver operating at 28.5 GHz (wavelength = 1.05 cm) was employed to measure liquid water in clouds during the 1979–80 field season of the Sierra Cooperative Pilot Project (SCPP) in northern California. We report upon the ability of the instrument to detect small amounts (~0.1 g m^{-3}) of liquid water in non-precipitating clouds which may not be observed by other remote sensing systems. A successful cloud seeding experiment, performed after cloud liquid was detected by the instrument, is described.

1. Introduction

During the winter of 1979–80, the Wave Propagation Laboratory of NOAA operated a ground-based microwave radiometric instrument in the Sierra Cooperative Pilot Project (SCPP), a weather modification experiment conducted by the Bureau of Reclamation in the northern Sierra Nevada of California. One objective of the radiometric observations was to study the usefulness of the technique as an aid to cloud seeding operations. Because the microwave radiometer is sensitive to emission from liquid water at any temperature, but not from ice, the system is able to detect the presence of supercooled liquid water that may respond favorably to seeding, i.e., result in conversion of liquid to ice. In this paper we report on one occasion during the 1979–80 field season when data from the radiometer were used, in part, to initiate a successful seeding experiment.

2. Radiometric measurement of liquid water in the SCPP

Radiometric measurements of the amount of a substance are based upon the absorption of electromagnetic energy by the substance. Although the radiometer actually measures the energy emitted by a substance, the absorption principle is employed, since emission is created by virtue of the absorption. If the absorption coefficient for the substance is known, the quantity of the substance along the path being observed by the radiometer can be readily calculated.

The absorption of microwaves by liquid water has received considerable study over the past several years. Accordingly, the theory of absorption and scattering of microwaves by liquid water (and water vapor) is well understood and has been verified experimentally. An extensive review of the general subject as well as a comprehensive list of references is given by Hogg and Chu (1975).

At wavelengths greater than ~0.3 cm, the total attenuation caused by liquid composed of droplets with diameters <100 μm is due primarily to absorption. This statement may not be true where droplet diameters are >100 μm and scattering of energy may be important. The magnitude of the absorption depends upon the liquid content and the temperature of the liquid. For example, for liquid temperatures between 265 and 293 K, the absorption decreases by a factor of 2 at a wavelength of 1 cm (Gunn and East, 1954). The variation with temperature is approximately quadratic. At these wavelengths, the total absorption is proportional to the volume of liquid present and independent of the drop-size distribution in the liquid. Therefore, the microwave radiometer has an advantage over those sensors whose accuracy is affected by drop-size distribution. Since absorption by ice is two orders of magnitude smaller than that by liquid, ice is nearly transparent to the transmission of microwaves. As a result, the microwave radiometer can detect liquid water at any temperature, but does not respond to ice.

The radiometric instrument used in the 1979–80 SCPP is a combination receiver–radiometer that has been previously described by Snider *et al.* (1980a). The instrument was developed to verify measurements of cloud liquid by a passive two-frequency system which also measures precipitable water vapor (Guiraud *et al.*, 1979). However, because of its ability to make continuous observations of liquid water in clouds, it was employed in the 1979–80 SCPP. Briefly, the instrument simultaneously but independently measures the absorption of a 28.5 GHz (wavelength = 1.05 cm) microwave signal radiated by a COMSTAR communications satellite and the associated microwave energy (brightness temperature) emitted by liquid-bearing clouds that pass through the propagation path. Independent, simultaneous measurement of the two quantities is accomplished using a unique design that allows coherent and incoherent reception with a single instrument. Operation in the two modes is made possible by means of a switched-bandwidth receiver. When measuring the signal from the satellite, a 200 kHz bandwidth is employed to obtain a high signal-to-noise ratio. However, when measuring the incoherent, noise-like emission from the cloud, a 500 MHz bandwidth is used so that the coherent signal from the satellite contributes a negligible amount to the total noise power received by the radiometer. As a result, the two measurements are independent. The receiving system switches between the two bandwidths at a 40 Hz rate so that the absorption and emission may be considered to be sampled simultaneously with respect to a relatively slow-moving cloud in the propagation path. The 40 Hz samples are averaged over 1 s intervals before conversion to liquid values.

The two measurements are combined first to estimate an effective temperature of the liquid water in the cloud, and second, to determine the absorption coefficient which is a function of the liquid temperature. Once the absorption coefficient has been determined, the total amount of liquid is calculated from the measured absorption.

The effective temperature T_c of the liquid in the cloud is calculated from

$$T_c = \frac{T_b}{1 - \exp(\gamma_c/4.343)}, \tag{1}$$

where T_b is the increase in emission, expressed as brightness temperature, occurring when clouds pass through the antenna beam, and γ_c is the measured absorption (in decibels) caused by the liquid-bearing clouds. The effective cloud temperature is used to compute the absorption coefficient $\alpha(T)$ in dB km^{-1} g m^{-3}, using a quadratic fit to the absorption–temperature relationship reported by Gunn and East (1954):

$$\alpha(T) = 43.164 - 0.287T_c + 0.000482T_c^2. \tag{2}$$

Finally, L, the total amount of liquid per unit crosssection (g m^{-2}) along the propagation path, is calculated from

$$L = \gamma_c/\alpha(T). \tag{3}$$

Since the radiometer does not provide information on the dimensions of the cloud, it is convenient to normalize L to 1 km path length and to unit volume. The quantity L then represents the total liquid (mm) contained in the entire propagation path through the cloud, regardless of its length. If the total path length through the cloud is known from data obtained with other sensors, an equivalent liquid water content (LWC) in g m^{-3} can be obtained by dividing the total liquid by the path length. For example, a total liquid of 1 mm extending over a 1 km path length is equivalent to a LWC of 1 g m^{-3}. The threshold of liquid detection for the system is ~0.1 mm.

Because the radiometric method is based upon sound, well-understood physical principles, the technique is believed to produce accurate measurements of liquid water in non-precipitating clouds containing water droplets smaller than 100 μm. Indeed, a systematic comparison of cloud liquid measurements made by two independent ground-based systems showed consistent liquid values (within 0.28 mm rms) for clouds observed simultaneously by the two systems (Snider *et al.*, 1980b).

An example of the data output from the receiver–radiometer is shown in the lower curve of Fig. 1. Rainfall recorded at the Sheridan site using a weighing bucket raingage is plotted as vertical bars in the upper curve; each bar represents the amount of rain that has fallen in the previous 15 min. The rainfall data are used as flags to indicate when radiometric data may be suspect. Because raindrops are often larger than 100 μm, Eq. (1) may not be valid during rainfall. In addition, the larger attenuation in rain can obscure absorption by water droplets in clouds.

3. Airborne instrumentation in the SCPP

Liquid water content and cloud microphysical data were also measured by means of probes mounted on a Beechcraft King Air 200 cloud physics aircraft (N2UW) operated by the University of Wyoming. Instruments carried on the aircraft for measurement of LWC include a forward scattering spectrometer probe (FSSP) and a Johnson–Williams (JW) hot-wire probe. A series of imaging probes are available for sensing ice particle size and concentration. A decelerator and slide sampler are used to capture ice particles on oil-coated glass slides for later analysis. Other instruments measure the velocity and position of the aircraft, atmospheric turbulence, horizontal and vertical winds, state parameters and ice nuclei. A detailed description of the aircraft's instrumentation is given by Marwitz *et al.* (1978).

A second aircraft was employed in the 1979–80 SCPP to dispense seeding materials and to observe cloud characteristics. The second or "seeder" aircraft was an Aero Commander Turboprop operated by Aero Systems, Inc. of Boulder, CO; the aircraft had the capability of dropping silver iodide (AgI) flares and dry ice (CO_2) pellets. A fuselage-mounted acetone AgI generator was also available.

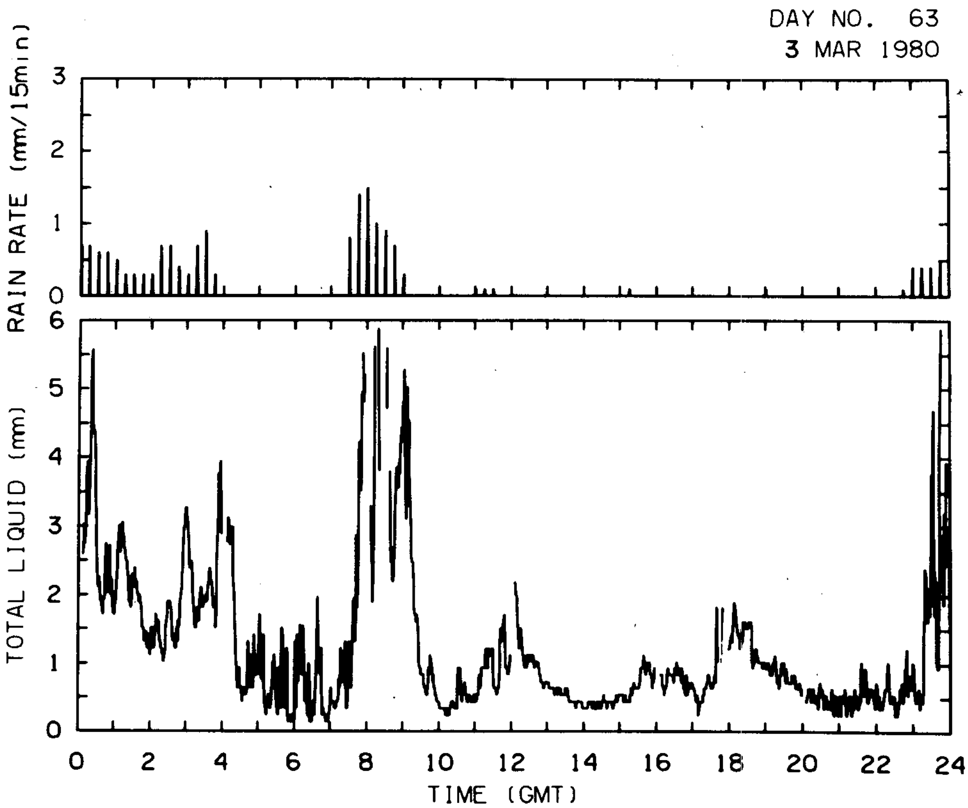

FIG. 1. Total path liquid measured by the radiometric system on 3 March 1980. Rainfall data were measured at the radiometer site using a weighing bucket raingage.

4. Location of ground-based instruments

In the 1979–80 SCPP field season, the satellite receiver–radiometer was located near Sheridan, California. From this location the elevation angle of the propagation path to the satellite is 32.6°. The half-power beamwidth of the system antenna is 0.6°; thus, the width of the beam is ~100 m at a range of 10 km from the receiver–radiometer. The instrument was located upwind from the SCPP test area (Fig. 2). During the three month field season, the system operated continuously and unattended, measuring the amount of liquid water contained in clouds as they drifted through the fixed antenna beam and into the SCPP test region.

Additional instrumentation at the Sheridan site included a 5 cm wavelength radar operated by the Bureau of Reclamation, a rawinsonde facility and instruments for standard meteorological surface data. The total liquid observed by the radiometric system was displayed in the radar van.

A second 5 cm wavelength Doppler radar, operated by the National Center for Atmospheric Research, was located 10 km south of the Sheridan site.

5. Cloud seeding in the SCPP

The primary objective of the SCPP is to develop a technology for augmenting winter precipitation and snow pack in the Sierra Nevada in California by cloud seeding. Until now, experiments have been conducted to study the microphysical response of clouds to seeding rather than to increase precipitation. Accordingly, the areas treated and the amounts of seeding materials used have been relatively small. Typical seeding rates of materials dispensed from aircraft are 0.5 kg min^{-1} for dry ice and 2–20 AgI flares min^{-1} (Carley *et al.*, 1980).

Initiation of cloud seeding experiments is controlled by the Bureau of Reclamation site director located at the Sheridan site. The site director utilizes available data from radars, soundings, forecasts and *in situ* observations by the aircraft to determine if a seeding experiment should be performed. It is generally accepted that successful seeding of cold clouds for the enhancement of precipitation requires, as a critical but not necessarily sufficient condition, the presence of supercooled liquid and a relative absence of ice. However, these conditions are not always readily recognized; therefore one objective of the SCPP is to develop improved techniques for identification of regions in clouds that have seeding potential. We now show that the microwave radiometer may provide part of the means to achieve this improvement.

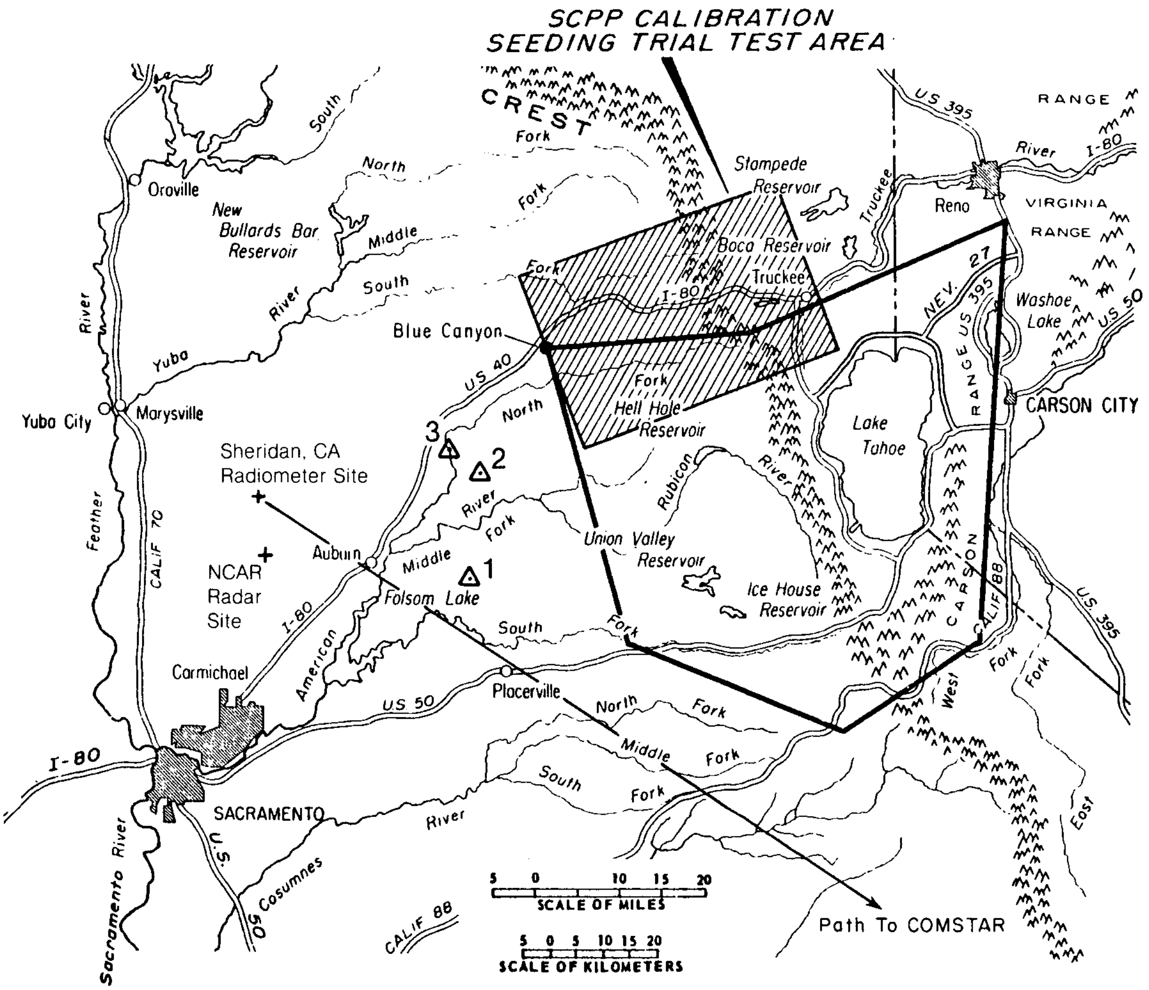

FIG. 2. Map of SCPP test area showing propagation path to COMSTAR satellite. Numbered triangles mark locations of three regions seeded on 3 March 1980.

6. 3 March 1980 seeding experiments

On the morning of 3 March 1980, an overcast composed of non-precipitating stratiform clouds covered the test area including the region of sky observed by the radiometer. At 0745 PST (1545 GMT) the radiometric system indicated ~1 mm of total liquid (Fig. 1). However, both 5 cm radars observed few if any echoes. Since liquid water was detected by the radiometer, the site director decided to launch the cloud physics aircraft (N2UW) for measurements of LWC in the vicinity of the earth-satellite propagation path.

Table 1 summarizes the radiometric and *in situ* aircraft measurements of cloud liquid observed during two flights near the propagation path. The first flight was a descent from 3100 to 900 m; the second flight was an ascent over the same height interval. Both flights were along a 135° radial extending from the Sheridan site.

For the comparison shown in Table 1, the measured data have been converted to the average LWC ($g\ m^{-3}$) contained in an equivalent vertical column through the clouds. The path-integrated liquid data (mm) recorded by the radiometer were converted to average LWC using a cloud-thickness estimated from the aircraft data and from soundings made at Sheridan at 1500 and 1800 GMT. Liquid data recorded along the flight path were averaged as a function of vertical height. Very little ice was detected by imaging probes carried on the aircraft.

Although similar LWC's are obtained with the airborne and ground-based techniques, the radiometric method shows somewhat higher values than were observed by the aircraft probes. Surface observations made near the flight times show the cloud ceiling to be ~600 m. Therefore, the radiometer may be detecting liquid that is present below the minimum allowable flight altitude of 900 m. Part of the difference could also be caused by different paths being sampled by the two techniques; the aircraft instruments sampled cloud liquid along an ~7° slope rather than along the 32.6° elevation angle of the propagation path.

Other possible reasons for the difference in LWC are that the FSSP sampled a limited spectrum of dropsizes (2–30 μm) and the accuracy of the JW probe (±50%). However, the significant point is that the aircraft verified the presence of supercooled liquid water detected by the ground-based instrument. Based upon the information from both the aircraft and the radiometer, the site director elected to perform a randomized seeding experiment.

In the randomized seeding mode, the seeding material is known only by the crew of the seeder aircraft. During a given seeding run, the dropped material will be either silver iodide flares, dry ice pellets or a placebo, i.e., no material. For the placebo case, although no materials are actually dropped, the seeder aircraft is flown as if materials were being dispensed. After seeding, the crew of the cloud physics aircraft attempts to locate the seeded curtain and, by observing hydrometeors and other cloud characteristics, determine a unique seeding signature from which the seeding material can be deduced. The numbered triangles in Fig. 2 show the locations of the three seeding runs performed on 3 March 1980. Note that the three seeding runs were conducted downwind from the radiometer beam. During each of the three seeding runs, the crew of the cloud physics aircraft correctly identified the seeding material from the microphysical signatures observed in the seeded plume.

The following discussion briefly summarizes selected data collected by the cloud physics aircraft before and after seeding; a detailed treatment of the microphysical observations is given by Stewart and Marwitz (1982). The cloud physics aircraft locates the seeded plume by using a computerized position-referencing routine that uses the horizontal winds as an input and assumes that there is no vertical or horizontal shear. This assumption is probably valid in stratiform clouds with little convection as reported here. Microphysics data recorded after seeding, shown in Table 2, are averages of data recorded when the position-referencing routine indicated that the aircraft was within the seeded plume. The general decrease in LWC and the observed increase in ice particle concentration after the first two seedings occurred, are considered to be verification that the aircraft is within the seeded plume. Since similar changes in the microphysical signatures were not found following the placebo "seeding," the previous changes are believed to result from the artificial seeding.

7. Discussion

Because the crew of the cloud physics aircraft correctly identified the seeding agents from the microphysical signatures, and since a decrease in LWC and increase in glaciation followed seeding with active agents, the 3 March 1980 seeding experiment must be considered to have had a positive outcome. The fact that the radiometric instrument gave the first indication of a seeding opportunity, i.e., detected supercooled liquid, when other ground-based sensors did not, clearly demonstrates the utility of the microwave radiometer in cloud seeding research.

TABLE 1. Comparison of average cloud liquid water content measured by radiometer and by probes on aircraft, 3 March 1980. Values within parentheses indicate maximum measured LWC.

Time (GMT)	Average liquid water content in a vertical column ($g\ m^{-3}$)		
	FSSP	JW	Radiometer
1636–1640	0.10 (0.4)	0.14 (0.5)	0.33 (0.36)
1643–1647	0.09 (0.3)	0.06 (0.25)	0.30 (0.33)

A microwave radiometer offers the advantage of being able to detect small amounts of path-integrated liquid (≤0.5 mm) which appear to be characteristic of winter orographic clouds in the Sierra Nevada (Snider and Hogg, 1981). As was the case on 3 March 1980, such small amounts of liquid may go unobserved by radars operating at wavelengths ≥ 3 cm. Therefore, we believe that continuous liquid data from a microwave radiometer, when used in conjunction with data from other systems, will continue to reveal seeding opportunities which would otherwise go undetected.

A limitation to the receiver–radiometer technique is that a suitable microwave beacon may not always be available. In addition, the radiometric system used in the experiments reported here has a fixed-direction antenna beam. As a result, the ability to locate clouds with seeding potential is severely limited. However, use of a passive microwave radiometer with a steerable antenna system will permit observation of clouds in any direction and at ranges up to ~60 km from the radiometer. Although in the passive system one must employ an average temperature for the liquid (calculated from a suitable history of radiosonde data), it has been found that use of an average temperature results in little error. A two-frequency system, described by Guiraud *et al.* (1979), was operated alongside the satellite receiver–radiometer for a three-month period at Denver, CO. The antennas were aligned so that clouds drifting through the antenna beams were observed simultaneously by each instrument. The two sets of measurements agreed with an rms error of 0.28 mm and a bias of ~11% (the two-frequency system being high). This result confirmed satisfactory accuracy for the passive method even though an independent measurement of the liquid temperature was not made (Snider *et al.*, 1980b). A two-frequency steerable system was employed in the 1980–81 SCPP field season. It is expected that the steerable radiometric system will be used extensively in the future.

TABLE 2. Average values of temperature, liquid water content, cloud droplet concentration and mean diameter, and ice particle concentration as a function of size observed by the University of Wyoming cloud physics aircraft before and during three cloud seeding experiments on 3 March 1980 (after Stewart and Marwitz). Δt is the time relative to the start of seeding with each agent.

			LWC (g m^{-3})				Ice particle concentration (L^{-1})		
Seeding agent	Δt (min)	Temperature (°C)	JW	FSSP	Concentration (cm^{-3})	$\bar{D}$ (μm)	(12.5–187.5 μm)	(25–800 μm)	(200–6400 μm)
AgI	−4	−7.7	0.05	0.16	64	13	0	0	0.0
	13.4	−5.4	0.03	0.13	35	12	8	3	0.0
	20	−5.5	0.06	0.23	75	16	15	8	1.4
	26	−5.6	0.05	0.22	76	16	37	25	2.5
	31	−5.8	0.03	0.12	59	15	37	40	3.7
	37	−3.6	0.00	0.00	0	0	27	14	2.0
	44	−7.7	0.07	0.23	69	14	9	2	0.1
	48	−5.6	0.02	0.02	28	10	46	19	2.7
	53	−6.0	0.00	0.01	19	13	20	7	0.8
	57	−5.8	0.01	0.01	25	9	15	6	0.6
CO_2	−8	−7.7	0.04	0.21	60	17	7	2	0.4
	4	−7.3	0.02	0.09	53	13	100	25	0.0
	8.5	−7.2	0.04	0.14	52	15	79	36	0.4
	14	−5.4	0.03	0.16	56	12	100	32	6.8
None	0	−6.9	0.07	0.32	102	15	25	1	0.0
	8	−6.8	0.06	0.39	106	17	0	1	0.0
	12	−6.9	0.07	0.28	103	14	0	1	0.0
	15	−6.9	0.07	0.36	131	15	0	1	0.0
	20	−5.2	0.14	0.41	189	14	101	3	0.0
	24	−3.2	0.14	0.37	139	13	238	24	1.8
	29	−7.0	0.14	0.44	138	16	31	1	0.2

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