NOTES

Radiometric Observations of Supercooled Liquid Water within a Split Front over the Sierra Nevada

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ABSTRACT

A storm bearing close structural resemblance to a katafront was observed from the ground with microwave radiometry and a vertically pointing Ka-band radar over the Sierra Nevada of California. The onset and duration of supercooled liquid water was determined and matched to a split front model used to describe the synoptic features of a katafront. Results indicate that prior to the passage of the upper front no supercooled liquid water was observed. This portion of the storm provided the deepest cloud and coldest cloud tops. Supercooled liquid water was most prevalent after the upper front passage, and persisted until the suspected surface front passage. The duration of measured supercooled water was 16 hours.

This information broadens the knowledge regarding the presence of supercooled liquid water, and thus possible seeding potential, within winter storms so that treatment can be confined to the period of storms amenable to cloud seeding. Future studies may well confirm the ease with which these periods can be predicted on an operational basis in the Sierra Nevada.

1. Introduction

The potential for precipitation enhancement can be defined in part by the presence of supercooled liquid water (SLW). Ideally, winter storms should be treated on the basis of the measurement or existence of SLW. Conditions indicating seeding potential should be treated, while more efficient precipitation processes indicated by the absence of supercooled water should remain untreated. A problem for most operational precipitation enhancement programs is the prediction and exclusive treatment of periods based on seeding potential.

The Sierra Cooperative Pilot Project (SCPP), administered by the Bureau of Reclamation, has been interested in identifying seeding opportunities as part of an overall objective to develop and improve a precipitation enhancement technology for the American River Basin of California. The SCPP has relied on direct measurements of SLW through the use of a microwave radiometer and project aircraft to guide this research. Microwave radiometry has provided the capability to make continuous observations of liquid water, integrated over the depth of cloud, which have not been possible with aircraft. Continuous observations of SLW throughout the storm life cycle have allowed a relationship to be developed between storm characteristics and the presence and magnitude of SLW.

The objective of this note is to show the transition of SLW as measured through an evolving synoptic winter storm having characteristics of a katafront[1] near the Sierra Crest. The existence of SLW observed during the selected case day has been fit to a split front model developed by Browning and Monk (1982) which characterizes the general features of a katafront. The split front may be one mechanism which provides suitable cloud conditions for precipitation enhancement to be successful.

2. SCPP project area and instrumentation

The SCPP operates over the American River Basin, which is located in the Central Sierra Nevada. Figure 1a shows a plan view of the project area while Fig. 1b shows the barrier profile as one transects the barrier from Sacramento east to Lake Tahoe and beyond.

During the 1983–84 field season, a large array of meteorological equipment was operated to support the cloud seeding research studies. Of primary interest were the measurements made at Kingvale, CA, located at 1860 m elevation approximately 8 km upwind of the Sierra Crest. A dual wavelength passive microwave radiometer capable of measuring integrated liquid water and water vapor collected data in the zenith at

[1] The prefixes "ana" and "kata," as Browning and Monk describe, were first used by Bergeron (1937). Anafronts refer to a general rising of air at all levels, whereas katafronts have general descending air in all but the lowest layers.

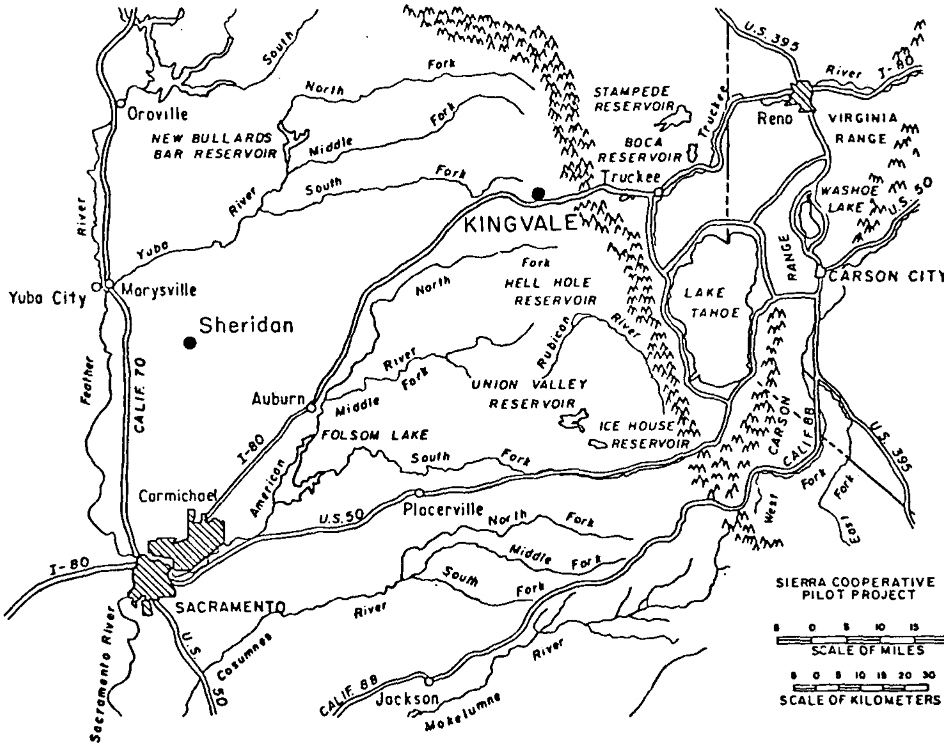

FIG. 1a. The 1983–84 Sierra Cooperative Pilot Project study area. Rawinsondes were launched from Sheridan. Kingvale hosted a variety of meteorological equipment consisting of a dual channel radiometer, Ka-band radar, precipitation gage and other more common state measurements.

Kingvale. The SCPP radiometer is very similar to that described by Hogg *et al.* (1983). Figure 1b shows the placement of the radiometer in perspective with the mountain barrier and large-scale lift region. Kingvale rests in a small valley away from local lift regions (individual peaks). If SLW is measured at the site it may then be attributed to a larger scale event. The distance between Kingvale and the crest allowed the radiometer SLW measurements to serve as a measure of possible enhancement opportunity, by sensing the air which is about to pass over the crest. Simply, if SLW is present in appreciable amounts the upwind precipitation process may be considered inadequate and possibly amenable to cloud seeding.

To determine a path length over which the liquid water resides, a Ka-band radar (0.86 cm), provided by the Desert Research Institute, was collocated with the radiometer. The radar was also used to identify cloud characteristics associated with the measurement of SLW. The radar had a minimum detectable signal of −30 dbZ at 0.25 km (minimum range) and −2 dBZ at 8 km (maximum range). A Portable Remote Observations of the Environment (PROBE) station which used satellite telemetry to transmit surface temperature, windspeed, and wind direction, was also located at Kingvale. Precipitation data were available from a weighing bucket gage (~29 cm oriface size) located 3.5 km west of Kingvale. Rawinsonde observations discussed in this article were taken at Sheridan, CA, which is identified in Fig. 1a.

For the case day to be presented, detailed visual observations of crystal habit and rime were made and will also be discussed.

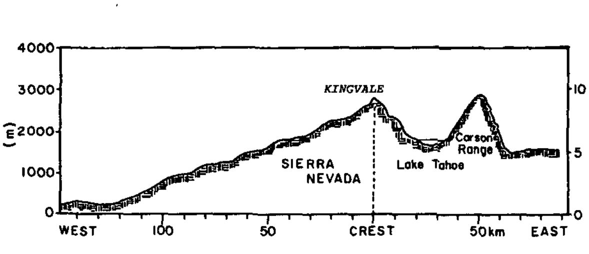

FIG. 1b. Elevation transect over the Sierra Nevada and Carson Ranges, which characterizes the continuous lift provided over 100 km of the Sierra Nevada.

3. Discussion: Case day 20–21 January 1984

a. Synoptic setting

After several weeks of dry weather in northern California, a weak short wave moved through the mean ridge position which had been established over the eastern Pacific Ocean along the coast of California. National Meteorological Center analyses depicted the short wave as losing synoptic support as it approached the project area. The surface low pressure center showed 12 mb of filling during the 12-h period preceding its arrival. A 35 m s^{-1} jet at 300 mb and a weak divergence field defined the upper level support while 14 s^{-1} vorticity was indicated from the 0000 GMT 21 Jan 500 mb analysis over the project area.

The system has been analyzed by the authors as a split front as it impacted the project area, though there was no evidence of a well-defined surface front. Split fronts have been studied by Browning and Monk (1982), and described as a situation where the upper cold front has overrun the surface cold front, leaving a moist shallow layer of air near the surface. The split front, characteristic of katafronts, is further described in Section 3c of this article.

The onset of precipitation observed at Kingvale was associated with the approach and passage of the upper front. The actual surface front was indistinguishable, but believed to trail the upper front by over 200 km (16 h), as indicated by the back edge of low-level cloud cover indicated by satellite pictures. The system brought precipitation to the upper elevations of the Sierra Nevada (above 1000 m elevation), while the upwind valley had no reports of measurable precipitation.

b. Analysis

Figure 2 shows the temporal variations in the parameters measured at Kingvale. The uppermost panel (Panel A) shows the Ka-radar shadow image which provides detail as to the cloud depth variations for the storm event. Panel B shows the radiometer derived integrated vapor and liquid amounts in centimeters and millimeters respectively. Panels C and D present temperature (°C) and precipitation rates (mm h^{-1}), respectively.

A gradual increase of water vapor shown in Fig. 2b was detected by the radiometer after 0000 GMT on 21 January, which was in response to the approaching storm. The cloud continued to thicken as the radiometer water vapor exceeded 1 cm. Light snow was observed by 0430 GMT with the temperature at −1.5°C. The cold temperature ensured that all the liquid water observed by the radiometer was supercooled. Precipitation was first observed at the surface by 0416 GMT. Ice crystal observations made at Kingvale between 0430 and 0500 GMT identified the crystals as being unrimed dendrites, which were expected from a deep cloud with tops near 8 km above mean sea level.

The structure of the cloud began to change by 0550 GMT, as indicated on the Ka shadow plot (Fig. 2, Panel A). The decrease of Ka-radar cloud tops signified the passage of the upper front. This transition of cloud character coincided with the first measurement of SLW by the radiometer. Cloud top temperatures decreased from −35°C to −10°C through the transition measured by Sheridan rawinsonde. Liquid water continued to increase as the upper cloud moved off. The highest integrated liquid water measurements were made between 0645 and 0815 GMT, with integrated liquid values exceeding 0.3 mm. The shallow cloud which persisted for the next 16 h had measurable amounts of SLW. Crystal habit change was observed with the loss

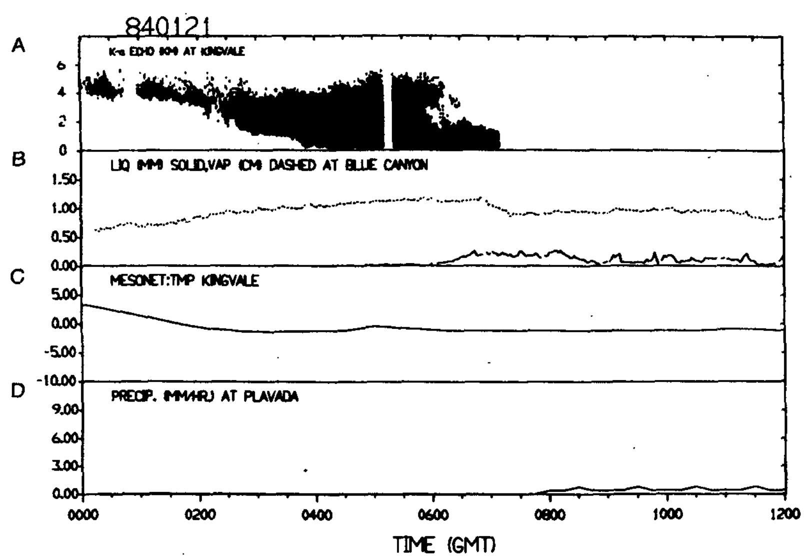

FIG. 2. The evolution of the split front as observed from Kingvale for 21 January 1984 from 0000 to 1200 GMT. Panel A shows a shadow plot of Ka-band radar reflectivities with elements shadowed with returns greater than −98 dB (−30 dBZ at 0.25 km and −2 dBZ at 8 km). Panel B presents integrated quantities of vapor (dotted) and liquid (solid) retrieved from the dual channel radiometer. Panel C provides the temperature at Kingvale. Panel D displays the precipitation record from Pla Vada, which was the closest operating gage to Kingvale (3.5 km to the west).

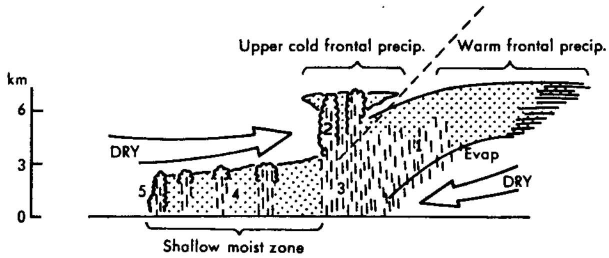

FIG. 3. Schematic portrayal of the saturated flow (stippled) and precipitation distribution (hatched) (from Browning and Monk, 1982).

of the cold cloud top temperatures, as the unrimed dendrites vanished giving way to moderate rimed needles and plates. By 0800 GMT, Ka radar observations were terminated, though satellite images indicated the presence of warm topped cloud (−10°C or warmer) in the vicinity of Kingvale through 2200 GMT.

c. Implications of the katafront to weather modification operations

Browning and Monk (1982) describe the katafront as a common feature which effects the British Isles. A split cold front model developed by Browning and Monk provides a useful representation of the principal characteristics of many katafronts. The split front model adapted to the storm of 20–21 January 1984 is shown in Fig. 3. A primary point of interest is the transition from a deep saturated air mass to an air mass comprised of a 2 km shallow moist zone which is found to occur with the passage of the upper cold front. It is the existence and duration of this shallow moist layer which is of great interest to weather modification.

A cause for the sharp break in cloud aloft as shown in Fig. 3 is associated with the core of the upper tropospheric jet and upper cold front. The ascent of air on the anticyclonic shear side supports the presence of high clouds and the descent of air on the cyclonic shear side contributes to evaporation and absence of higher cloud. Precipitation from the system is generated as a result of weak synoptic scale ascent. The shallow moist zone, described by Harrold (1973) as part of the conveyor belt, is the subject of great interest to the field of precipitation enhancement operations. It is within this area that SLW has been identified. Mountainous barriers like the Sierra Nevada accentuate vertical motions and production of SLW through the condensation process. If the necessary ice crystal production mechanisms are absent an excess of SLW is measured near the summit.

4. Summary

Precipitation enhancement opportunity within wintertime storms effecting the Sierra Nevada may well lie in the character of the synoptic situation. This case study presented evidence of a storm which provided a 16-h period of SLW observed near the Sierra Nevada crest by a passive microwave radiometer. The frontal analysis was evaluated as being a katafront where the upper cold front became detached from the surface feature and moved ahead of the surface front. The ensuing low-level moisture field appears to be amenable to precipitation enhancement efforts.

The decrease of cloud top and the presence of a shallow low-level moisture field appears to be synonymous with conditions leading to the greatest potential for cloud seeding. This is in agreement with studies by Heggli *et al.* (1983), which show a tendency for airborne measurements of SLW to be in shallow clouds with weak radar echo returns. The echoes would often appear convective in nature, but were usually embedded in a nonechoing cloud field.

Future studies will attempt to assess the amount of SLW that constitutes a seedable situation and the seeding strategy to be used to extract this water effectively in order to increase the region's water supply.

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