NOAA K_a-BAND CLOUD-SENSING RADAR MEASUREMENTS FROM WISPIT

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1. INTRODUCTION

The new NOAA 8.66-mm (K_a-band) cloud-sensing Doppler radar with multiple dual polarization (Martner and Kropfli 1993, Kropfli et al. 1993) was one of several state-of the-art atmospheric remote sensors deployed for the Federal Aviation Administration's Winter Icing and Storms Project Instrument Test (WISPIT, northeast Colorado, 16 February - 12 March 1993). WISPIT objectives requiring remote sensors are outlined in Table 1; the umbrella WISP project is outlined by Rasmussen et al. (1992). The ensemble of specialized instrumentation was tested for capabilities to detect key features of winter storms relevant to the formation and depletion of liquid water, which is necessary for forecasting aircraft icing conditions. Shallow upslope cloud systems (Reinking and Boatman 1986) served as the test bed. These winter storms occur where the High Plains meet the eastern slope of the Colorado Rockies. The K_a-band radar provides high resolution measurements of structures, motions, and certain microphysical features of non-precipitating, lightly precipitating, and snowing cloud systems. Thus, it is well suited for studies of winter cloud conditions that cause aircraft icing. The radar mapped the fine-scale features of upslope clouds that were simultaneously monitored with longer-wavelength radars, wind profilers, radio acoustic sounding systems (RASS), and a microwave radiometer, and sampled for ice nuclei and cloud particles with the aircraft. Examples of initial WISPIT results from the radar alone and in combination with associated instrument systems are presented.

Table 1. WISPIT objectives involving remote sensors.

Multi-parameter radar and aircraft studies of winter storms

- Combined remote sensor detection of storm features
- Measurements to test numerical models
- Remote characterization of ice crystals and detection of aggregation

Diagnosis of cloud layers and icing hazard altitude by remote measurements

- Detect cloud boundaries, temperature structure, and liquid and vapor profiles
- Distinguish wet snow from dry snow
- Large drop studies

2. POLARIZATION TO DETECT SNOW CRYSTAL AGGREGATION

Short wavelength radars with multiple polarization capabilities are theoretically capable of measuring ice mass content, particle size, shape, and concentration (Kropfli et al. 1993). In WISPIT, fixed horizontal and circular polarizations were used. Also, a new rotating quarter-wave plate (QWP), which cycles the polarization through horizontal, elliptical, and circular states, was tested for the first time. The QWP tests are very preliminary and are not presented here. Figure 1 shows some of the measurements with fixed circular polarization, between 2253 and 0002 UTC, 11-12 March 1993. At the radar, snow crystals from this upslope case were photographed on black velvet and their features noted in the radar's electronic log book.

In snowfall with predominantly unrimed or lightly rimed branched planar crystals (dendrites) and only minor aggregation, the circular depolarization ratio (CDR) varied in a well-defined pattern from approximately -17 dB at the 90°

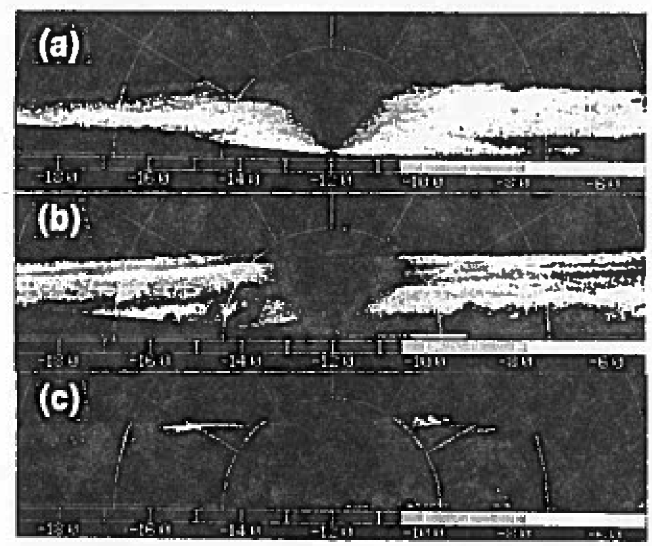

Fig. 1. Over-the-top range-height (RHI) scans of CDR (scale, -5 to -19 dB): (a) predominantly unaggregated dendritic snow crystals; (b) dendrites and aggregates mixed; (c) primarily aggregates of dendrites. Range rings are 3 km.

radar elevation angle to -6 dB at 10 - 25° elevation (Fig. 1a, 2057 UTC, 11 March; and Table 2). Reflectivities in the core of this snowing layer cloud ranged from approximately -3 to +5 dBZ. Qualitatively, because the depolarization results from non-sphericity, the measured angle-dependent variation in CDR is expected. The symmetrical, quasi-circular outline of settling pristine crystals viewed overhead should produce the least depolarization. Thus, minimum CDR values could be expected at 90° at cloud top, where the crystals are in their most pristine growth stage, and the measurements show this. The thin rectangular outline of the edges of the crystals as viewed at low angles should produce the greatest depolarization. The measurements correspond. An advantage of circular polarization is that scattering of crystals viewed on edge is independent of the orientation of the edge, so no degradation should occur as a result of varied crystal orientation (oscillation or flutter), whereas it would with horizontal polarization.

Figure 1b shows a transitional case (0001 UTC, 12 March) with a combination of aggregates and single branched planar crystals (with light to moderate rime). CDR varied through a range narrowed by 3-5 dB or 27-50 % compared to the non-aggregation case, i.e., from about -16 dB overhead to mainly about -8 dB at the lower angles (Table 2). The angle-dependent pattern in CDR is still evident but degenerated, as it should be. The reflectivity ranged from -3 to +15 dBZ in the main body of this cloud.

In snowfall where aggregates of branched planar crystals predominanted (with moderate rime), the well-defined elevation angle dependency of CDR was washed out, and CDR values near -14 to -17 dB were evident for the bulk of the cloud volume (Fig. 1c, 2253 UTC, 11 March). This 2-3 dB range of CDR is about 8 dB (75 %) narrower than the range measured with pristine crystals (Table 2). In a very thin signature near cloud top, where the pristine crystals would begin their growth, the CDR does exhibit an angle dependency, with values of about -16 at 90° and -7 dB at 30° elevation.

In all, the variations in the measured CDR with elevation angle and degree of aggregation are qualitatively in accord with theory. However, there are ambiguities in the absolute values. Branched planar crystals are difficult to model theoretically, but they settle like hexagonal plates, with their c axes approximately horizontal. Theory (Matrosov 1991) dictates that for hexagonal plates with negligible deviation from horizontal settling ($\sigma = \pm 3°$), CDR would increase from -37 dB at 90° elevation to -28 dB at 75°, -12 dB at 30°, and -7.5 dB at 10°. The measured low-angle signatures (-6 to -7 dB) of the unaggregated crystals correspond well with the 10° value. However, measured depolarizations of less than -30 dB were expected above 75° elevation, and -17 dB was the minimum achieved. There are questions about the new antenna polarization calibrations and purity of the circular polarization. Also, significantly increased crystal flutter or oscillation that would vary settling orientations, e.g. by $\sigma = \pm 45°$, would dramatically narrow the theoretically expected range in CDR: *-14 dB* at 90° to *-10.5 dB* at 10° for hexagonal plates. This range is of the same order as the measurements, but conclusions should not be drawn without further radar calibrations.

Table 2. Measured CDR versus aggregation.

	CDR / Elevation angle	CDR Range
Planar crystals	-16,-17 dB/90°; -6,-7 dB/10°-30°	10-11 dB
Planars and aggregates	-16,-17 dB/90°; -7,-10 dB/10°-30°	6-9 dB
Aggregates	-15,-17 dB/90°, -14,-17 dB/10°-30°	2-3 dB

3. COLD SURGE IN AN UPSLOPE CLOUD SYSTEM

A series of cold surges (minor cold fronts) within a prevailing upslope cloud system were predicted for the experimental area on 24 February 1993 using the Penn-State/NCAR MM5 (mesoscale model version 5). WISPIT observations of one of these surges demonstrate the capability of the millimeter wave radar to detect important fine scale features of very weak but organized cloud systems, structures that were not detected by the longer-wavelength radars. Early stages of this event did produce large cloud droplets of sizes considered conducive to underwing icing.

Surface streamline and temperature analyses from the northeastern Colorado mesonet for 1715 UTC showed evidence of the encroaching cold surge. The flow up the slopes of the High Plains was from the east at the eastern edge of the network. The streamlines converged within the area of Platteville (PTL), where the K-band radar, RASS, radiometer, and four wind profilers were sited. A "Denver cyclone" formed, with PTL at the center. Temperatures along the foothills and east as far as PTL were -4 to +2 °C; however, cooling to about -7 C° in the encroaching surge was evident. A MM5 18-h forecast for 2100 UTC predicted the cyclonic circulation and called for temperatures between -2 and -8 °C in the upslope flow within the experimental area.

Figure 2 shows the radial velocity and reflectivity structures of the cold surge as it arrived at PTL. The entire upslope cloud was only about 750 m thick. The flow delivering the colder air was only 200 m thick. In the plane of this RHI, near-surface upslope winds were only 0-1 m s^{-1}, i.e., nearly calm in the pre-frontal air to the west (left) of the radar. East of the radar, within 600 m, and within the frontal zone, velocities increased to 5 m s^{-1} toward the southeast (Fig. 2a). The shift occurred in less than 300 m producing convergence in excess of 1.7×10^{-2} s^{-1} at the front. Speeds of the overriding westerly winds in the cloud layer just above the front reached 3-4 m s^{-1} in the plane of this RHI, suggesting a Bernoulli acceleration between an inversion capping the cloud and the underlying frontal surface. A shear of 8 m s^{-1} across a 100-m depth was induced between the opposing flows. A wave structure at the interface of the counter-currents, with wavelengths of about 0.8 km, is suggested.

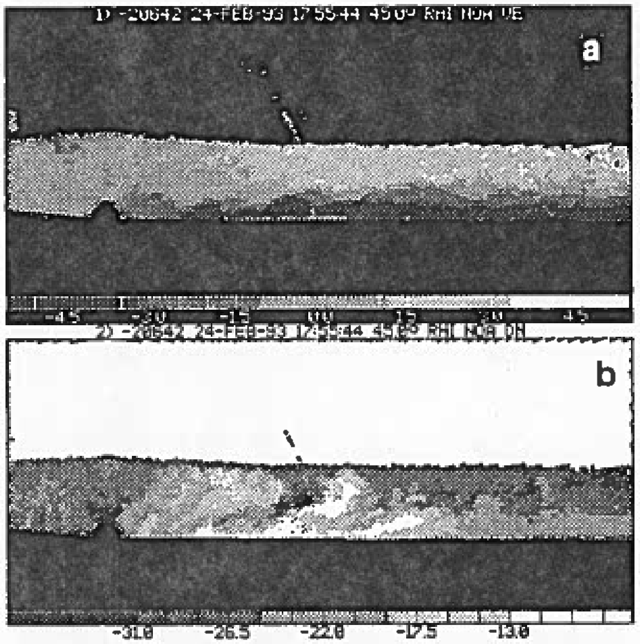

Fig. 2. K_a-band radar RHI at 1755 UTC, 24 February 1993; (a) radial velocity, m s^{-1}, (b) reflectivity (dBZ). Radar is at 0 range; 45° azimuth is to the right. Grid mark (+) spacing is 1 km.

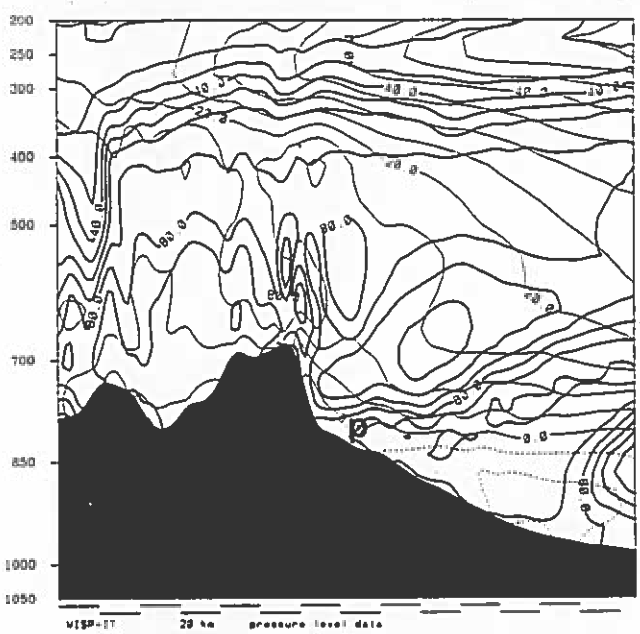

Fig. 3. MM5 forecast issued at 12 UTC for 18 UTC, 24 February 1993; relative humidity (heavy solid lines), west wind component (light solid lines), east wind component (dashed lines), in east-west plane. Cross section is through Denver, CO, located where mountains rise steeply from sloping plains. Bars at bottom equal 20 km. PTL is near "p".

The high-angle radial winds above the front, along with their transition from near-calm ahead of the front, also suggest lifting 2 m s^{-1} or more above the insurgent cold air. Convection was set off throughout the depth of the cloud layer (Fig. 2b). Cloud reflectivity was in the -22 to -32 dBZ range ahead of the front, but reached -6 dBZ in the weak yet distinctive frontal cells. The weak-echo cloud boundaries are well defined with these measurements from the radar's linear receiver. A 135° azimuth RHI, nearly perpendicular to the arriving front, indicated divergent flow around the nose of the cold air.

The MM5 18-h forecast for 1800 UTC, the time of the radar observations in Fig. 2., called for shallow upslope (westward) flow overridden by eastward flow (Fig. 3). The predicted cloud boundaries estimated by the 80% relative humidity (RH) contour (arrow in Fig. 3) indicate a shallow cloud in a layer lifted by the upslope forcing, and orographic clouds forming from forcing in the westerlies over the mountains. Over the plains near the mountains the 80% RH contour is near 770 mb; the PTL pressure elevation is approximately 860 mb. Thus, the predicted cloud depth over PTL, about 400 m, is comparable, within model resolution, to that observed at PTL at 1800 UTC.

4. BLIZZARD DRIVEN BY A PBL JET

For 11-12 March 1993, MM5 predicted upslope conditions with north-northeasterly flow, and forecasters noted the possibility of a PBL jet in the study area along the front range of the Rocky Mountains. A jet did develop, creating a blizzard that closed all of the airports in the locale. After 2300 UTC/11 March, the K-band radar began to detect increasing winds in the clouds and precipitation in the PBL. By 0030 UTC, the bullet signature typical of a jet was evident in plan-position indicator (PPI) scans (Fig. 4). RHI's showed an upslope cloud 3 km deep. The northeasterly winds reached 14-16 m s^{-1} in the kilometer nearest the ground, but decreased upward to a minimum of 3-4 m s^{-1} between 1.5 and 2 km AGL. The PPI shows the dramatic backing of the wind to westerly above 2.5 km; here, the vector shear within the cloud was severe.

A profile of the *15-min average* vector speed, from a continuous radar vertical azimuth display (VAD) scan three hours later, shows that the jet was sustained for several hours (Fig. 5). The gradual downward increase of radar-measured negative vertical velocities (Fig. 5) from zero at cloud top (4 km at this time) to 75 cm s^{-1} at the 2.5- km AGL level suggest growth and increasing fallspeeds of snow crystals; 50-100 cm s^{-1} is the norm for large crystals. Below this level, vertical motion was evidently influenced by the wind structure. Within the horizontal wind minimum in the profile, the downward motion is decelerated, suggesting lifting against crystal settling above the jet. The downward motion is then accelerated within the jet, forcing the blizzard.

The PBL jet developed immediately behind a front that passed PTL at 2330 UTC. The frontal structure was clearly defined in a potential temperature time-height analysis from the RASS. The front and the jet are also evident in the winds from the 915- and 50-MHZ PTL profilers (Fig. 6a).

The wind profile *forecast* for PTL, derived from interpolation of the MM5 winds (Fig. 6b), predicted the north to north-northeasterly wind shift below 2.5 km AGL that occurred at 1900 UTC (29 h in Fig. 6b). It also predicted the observed low-level northerly flow after 1200 UTC/11 March (24 h in the figure), and hinted at the observed PBL jet development at 0000 UTC/12 March (36 h). The model forecast, issued during actual WISPIT operations, did not correctly predict the front or the winds aloft within this time period. Analysis of the forecast started at 1200 UTC/11 March is pending.

The simultaneous wind and temperature profiling from the RASS provides a means for calculating the Richardson number, the ratio of work done against gravitational stability to energy transferred from mean to turbulent motion ($Ri = [g\delta\Theta/\Theta\delta z]/[\delta u/\delta z]^2$), where Θ is potential temperature, u is wind speed, and z is height. Figure 7 is a time-height section of Ri for this case. In

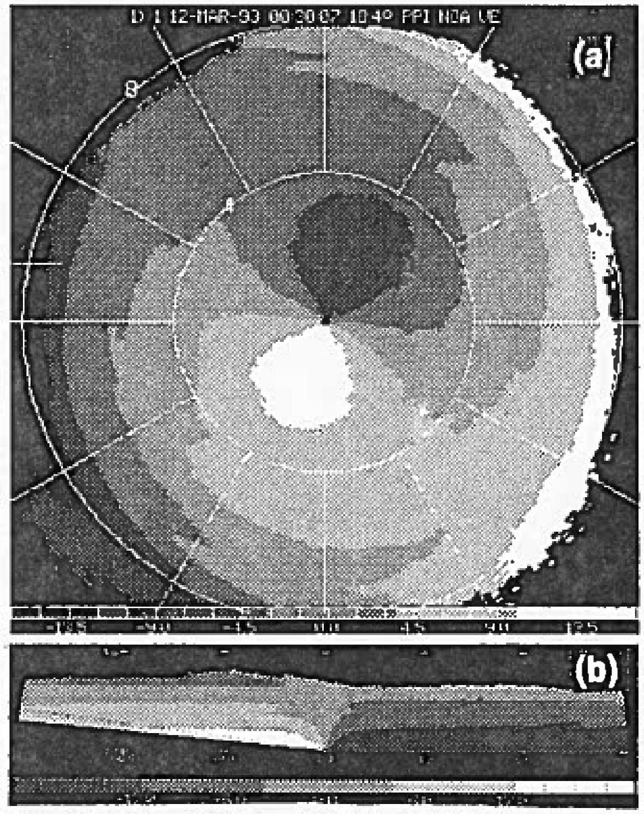

Fig. 4. (a) Radar PPI at 18.4° elevation, 0031 UTC and (b) 14.5° azimuth RHI (into the PBL jet) at 0025 UTC, of radial velocity (m s^{-1}), 12 Mar 93. Grid mark (+) spacing is 4 km.

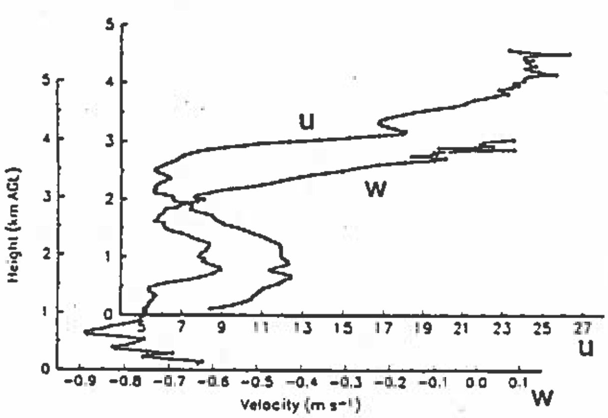

Fig. 5. A 15- min average VAD of wind speed, u, and vertical velocity, w (0330-0345 UTC, 12 March 1993).

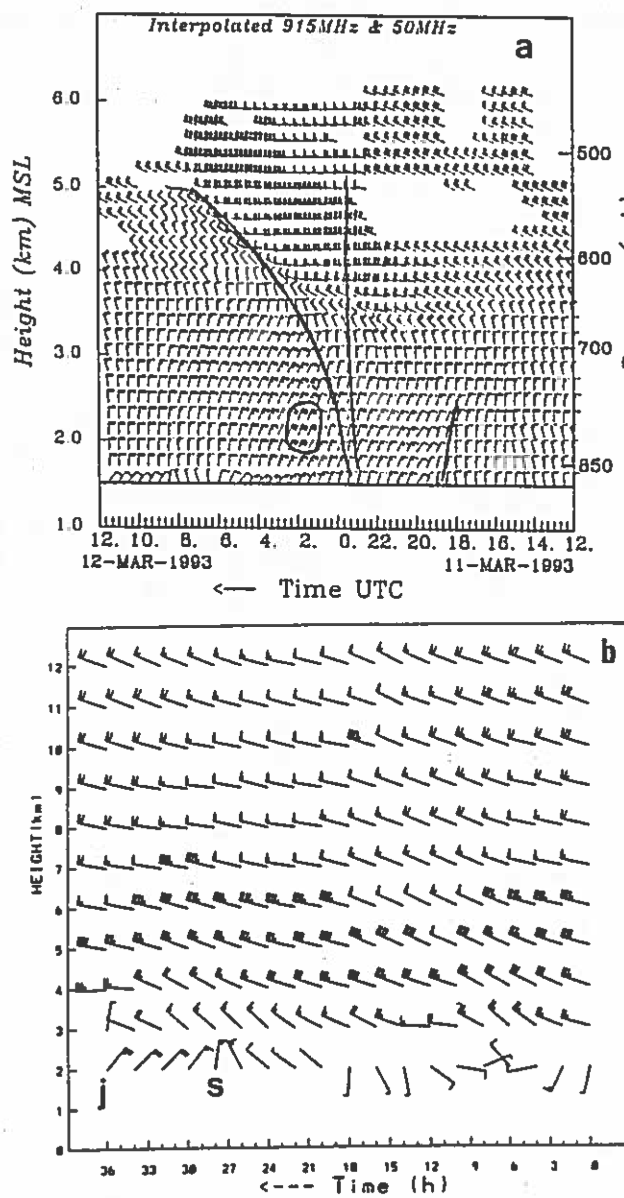

Fig. 6. Wind profiles over PTL, in knots: (a) combined measurement from 915 MHz and 50 MHz profilers, with core of PBL jet circled, frontal zone outlined, and pre-frontal wind shift marked; (b) MM5 forecast issued on 10 March 1993 at 1200 UTC (0 h in graph) for the ensuing 36 h. Actual pre-frontal wind shift (s) occurred at 29 h. The jet (j) was first established at 35 h.

practice, a value greater than 2 generally indicates stability for the vertical resolution of the profilers. Ri = 2 corresponds to the uppermost continuous contour across Fig. 7. Thus, a stable boundary layer is indicated for both the pre-frontal and post-frontal (jet) periods. The greatest stability occurred just before frontal passage, between 2000 UTC/11 March and 0000 UTC/12 March; here Ri reaches a peak value of 24 due to both thermodynamic stability and the minimal PBL shears in the light pre-frontal winds. The post-frontal PBL Ri dropped to a range range of 2-6 with the increased shears, but stability still persisted when the jet formed and continued (0000-0500 UTC).

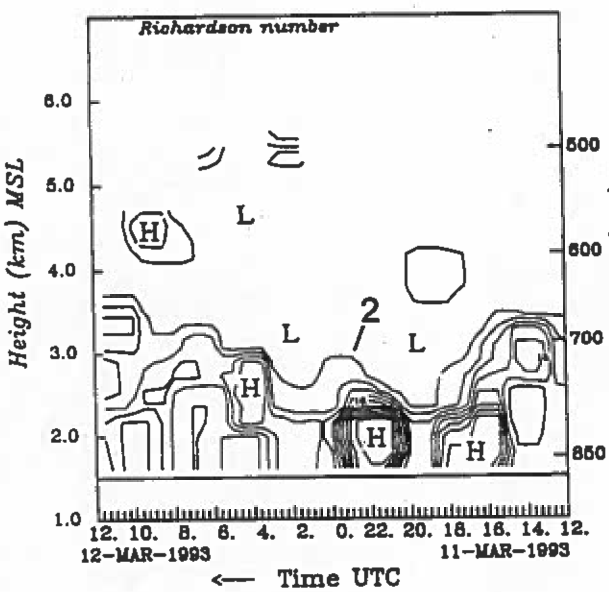

Fig. 7. Time-height evolution of the Richardson number, obtained from RASS data.

While aircraft traffic was impeded by post-frontal wind-driven snow, any icing hazard occurred before frontal passage. Supercooled liquid water persisted in the pre-frontal upslope cloud (Fig. 8), peaked at the encroaching frontal zone at 2320 UTC, and was then rapidly consumed by the post-frontal snowfall.

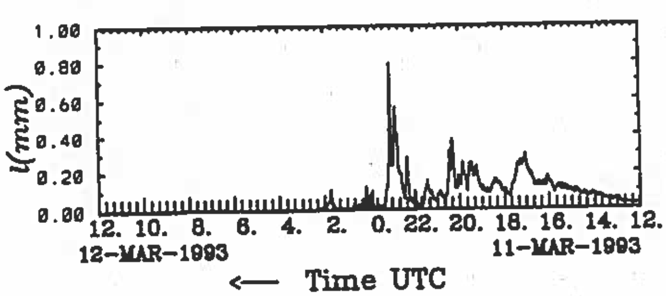

Fig. 8. Vertically integrated cloud liquid water content from the PTL microwave radiometer.

5. SUMMARY

The preliminary data indicate that K-band dual-polarization radar can do well in distinguishing pristine dendritic crystals from aggregates in winter storms. This kind of information will help to define the consumption of liquid water in aircraft icing conditions. The K-band radar's sensitivity to cloud particles (~ -30 dBZ at 10 km), velocity precision (~ 5 cm s^{-1}), fine spatial resolution (pulse width, 37.5 m, 0.5° beam width), and relative insensitivity to ground clutter (Martner and Kropfli 1993) are further illustrated in the case studies from WISPIT. Our preliminary analyses show the high-resolution definition of features of cold surge in a shallow upslope cloud system, including the cloud top boundary, narrow shear zones, waves, and cloud internal structures at very low reflectivity.

Comparisons to features of the MM5 with 20 km grid spacing show aspects of strengths and weaknesses in the model. The upslope blizzard driven by a PBL jet has provided an excellent opportunity for the WISPIT combined remote sensor tests. The combination of the radar with two RASS-equipped wind profilers and the microwave radiometer show how thoroughly the fine-scale measurements can map winter storm features that would affect aircraft operations.

6. ACKNOWLEDGEMENTS

This work was funded by the Federal Aviation Administration through a subcontract with the National Center for Atmospheric Research (NCAR). NCAR is primarily supported by the National Science Foundation. Bruce Bartram, Bob Kropfli, Brooks Martner, Sergey Matrosov, Scott Shaver, and Darren Pastore of NOAA/ERL's Radar Meteorology Group were instrumental in procuring, processing, and/or interpreting the data.

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