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Overview of Mt. Washington Icing Sensors Project

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OVERVIEW OF MT. WASHINGTON ICING SENSORS PROJECT

Charles C. Ryerson, Marcia K. Politovich, Kenneth L. Rancourt, George G. Koenig,
Roger F. Reinking, and Dean R. Miller

Abstract

NASA, the FAA, the Department of Defense, the National Center for Atmospheric Research and NOAA are developing techniques for retrieving cloud microphysical properties from a variety of remote sensing technologies. The intent is to predict aircraft icing conditions ahead of aircraft. The Mount Washington Icing Sensors Project (MWISP), conducted in April, 1999 at Mt. Washington, NH, was organized to evaluate technologies for the prediction of icing conditions ahead of aircraft in a natural environment, and to characterize icing cloud and drizzle environments. April was selected for operations because the Summit is typically in cloud, generally has frequent freezing precipitation in spring, and the clouds have high liquid water contents. Remote sensing equipment, consisting of radars, radiometers and a lidar, was placed at the base of the mountain, and probes measuring cloud particles, and a radiometer, were operated from the Summit. NASA's Twin Otter research aircraft also conducted six missions over the site. Operations spanned the entire month of April, which was dominated by wrap-around moisture from a low pressure center stalled off the coast of Labrador providing persistent upslope clouds with relatively high liquid water contents and mixed phase conditions. Preliminary assessments indicate excellent results from the lidar, radar polarimetry, radiosondes and summit and aircraft measurements.

Introduction and Problem

MWISP is the first field program conducted since NASA, the FAA, and DoD dedicated themselves in 1997 to developing ground-based and onboard technologies and procedures for detecting icing conditions ahead of aircraft for avoidance and escape. Several documents[1,2,3] outline plans for research and development of these technologies. The field program was funded largely by NASA and the FAA, directed by the National Center for Atmospheric Research (NCAR), and co-directed by the Mt. Washington Observatory Center for Wind, Ice and Fog Research (MWO-CWIFR) and the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC/CRREL). Overall, MWISP consisted of 19 government, university, and industry participants (Table 1).

The principal goal of the project was to field evaluate technologies for predicting icing conditions ahead of aircraft in a realistic icing environment. The technologies were multiple-band radars (X, K_a, and W), multiple-band microwave radiometers, and multiple field of view lidar. Secondary goals were to characterize icing cloud and drizzle environments, and to assess Mt. Washington as an aviation icing test bed, a role that the Observatory had in the late 1940s and early 1950s.

Background

Research dedicated to remotely detecting cloud properties for the express purpose of measuring conditions conducive to inflight icing started in the early 1980s.[4,5,6] WISP, the Winter Icing and Storms Program,[5] was a large field program dedicated to aircraft icing and winter storms

Table 1. MWISP participants.

MWO CWIFR
FAA Aviation Weather Research Program
NASA Glenn Research Center
FAA Wm. J. Hughes Technical Center
ERDC/CRREL
NOAA/ETL Radar and Ocean Remote Sensing Groups
NCAR
National Weather Service (NWS) Forecast Office at Grey, ME
Defense Research Establishment at Valcartier, Quebec, Canada (DREV)
Lyndon State College
Plymouth State College
University of Maine
University of Massachusetts
University of Nevada Reno Desert Research Institute (DRI)
University of New Hampshire
Quadrant Engineering
ATEK, Inc.Stratton Park Engineering, Inc.
Radiometrics, Inc.

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forecasting that had four successful field seasons in northeastern Colorado between 1990 and 1994. Remote sensing concepts for inflight icing conditions, based on radar and passive microwave radiometers, saw substantial development during WISP. MWISP continued this work, but with a broader array of remote sensing and in situ technologies for actual field testing.

The principal problem of developing remote sensing systems for detecting icing conditions is the unambiguous retrieval of cloud microphysical properties, liquid water content, particle size, and temperature, from the remotely detected signals. Development of retrieval methods for liquid water content, cloud, and precipitation droplet size spectra, and identification of the presence of drizzle and rain drops, using ground-based and airborne radar and passive microwave radiometers, has been the focus of government investment to date.

Radar retrieval methods have focused principally upon two methods: differential attenuation of two radar frequencies to retrieve cloud liquid water content alone,[7,8,9] and neural network techniques to retrieve liquid water content and droplet size from multiple frequencies.[10,11] In addition, work is in progress to retrieve droplet temperature from multiple-frequency radar.

Vertical, or near vertical, passive radiometer retrieval methods use microwave brightness temperatures to profile temperature and water vapor, and retrieve integrated liquid water.[12,13] However, liquid water profiles are more useful than integrated values for assessing aircraft icing conditions, and are available from a radiometer recently developed by Solheim et al.[14] In addition, Savage et al.[15] have demonstrated, via a computer model, that estimates of cloud liquid water content, range to liquid water, temperature, and the presence of drizzle using polarization, can be retrieved in the horizontal from an aircraft using a dual-wavelength microwave radiometer.

The Canadian Department of National Defense (DND) has developed a Multiple Field Of View (MFOV) lidar for measurement of cloud liquid water content and mean volume diameter.[16,17] Though suffering rapid extinction in optically thick clouds, its proven capability makes it a useful tool for verifying the accuracy of other remote sensing devices.

A secondary problem is to develop a better understanding of icing cloud and precipitation liquid water content, drop size spectra, and temperature. Typically, research aircraft accomplish this, but they are expensive, and are in the air for only a small portion of an entire field program. In addition, it is difficult to obtain a full time series of cloud conditions with an aircraft because it is not stationary. Though NASA, the Canadian Atmospheric Environment Service (AES), NCAR, and the University of Wyoming have demonstrated the value of aircraft-based in situ measurements,[5] a sampling system that provides continuous and long-term measurements at a fixed measurement site, such as the summit of Mt. Washington, is attractive. Unfortunately, such a site cannot provide information on the spatial variations in the remotely sensed sample volume, nor can it travel to the weather as can an aircraft.

Science Goals

The overall scientific goal of MWISP was to test methods for remote sensing of inflight icing conditions. Within this goal were the following specific objectives:

1. *Test and compare methods for remote sensing of inflight icing (liquid water content, droplet size, presence of freezing drizzle, or rain) for reliability and accuracy:* Little testing of remote sensing equipment for detecting icing conditions has been done in locations with more than a few tenths of a gram per cubic centimeter of liquid water. Few studies have had the opportunity for continuous verification because of limited hours of research aircraft availability. Ideally, accurate retrievals of the entire droplet size distribution are desired to determine total water mass and its distribution over size. It is likely that only total water mass (perhaps range-gated) and moments of the size distribution can be retrieved. Accuracy of retrievals in environmental conditions has not been fully examined.

2. *Collect in situ data for verification and environmental characterization:* SLD (supercooled large droplet) conditions, being relatively rare, are not well represented in the FAA inflight icing conditions database. Changes in certification regulations for flights into known icing are being considered, thus the range of typical sizes, concentrations, and liquid water in SLD conditions are needed. In addition, verification information was needed for the remote sensing work.

3. *Collect comprehensive remote and in situ data in an early spring/late winter environment:* Previously, only data on shallow upslope clouds with low liquid water contents, and few SLD cases, were collected during WISP in northeastern Colorado in winter and early spring. Mt. Washington promised reliable clouds with higher liquid water contents and freezing precipitation.

4. *Determine the horizontal and vertical uniformity of the cloudy environment near Mt. Washington:* MWO is a

convenient location for instrument placement. However, differences between the remote and in-situ-sensed sample volumes are a problem. If clouds are uniform, in situ measurements of cloud characteristics at the Summit should represent cloud characteristics remotely sensed a few kilometers away. However, if clouds are non-uniform, Summit sample usefulness decreases unless a systematic difference is found between cloud properties at and away from the Summit.

5. *Make remotely sensed and in situ data sets available for development of new methods:* Since this is a relatively recent area of research, it is likely that new methods may be available after MWISP is completed. The comprehensive remote and in situ data will be available to evaluate additional methods.

Specific tasks designed to accomplish these objectives, include:

- *Retrieve dual band differential attenuation liquid water content.*
- *Retrieve multiple band radar neural net liquid water content and drop size retrieval.*
- *Identify dual-polarization radar drizzle and ice hydrometeors.*
- *Characterize microwave radiometer forward-looking (horizontal) icing.*
- *Characterize clouds with multiple-field-of-view lidar.*
- *Profile liquid water content and drop size via radiosondes.*
- *Verify icing forecasts.*
- *Obtain continuous, high resolution spatial and temporal icing environment characterization.*
- *Develop integrated sensor algorithms.*
- *Investigate freezing drizzle formation processes.*

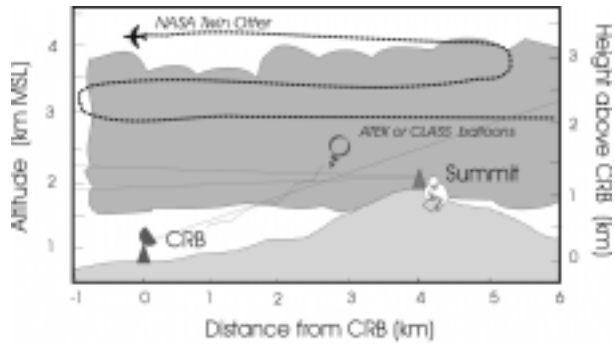

Figure 1. MWISP sampling plan.

- *Determine the suitability of the MWO-CWIFR facility for future icing research.*

Operations

The geography of the Mt. Washington area presented opportunities to locate equipment and develop a sampling plan that suited the scientific objectives. It also presented some limitations. Figure 1 shows the general layout of the MWISP field site, with most remote sensing equipment located at the base of the mountain at the CRB (Cog Railroad Base), and most in situ equipment located at the mountain summit (Summit) approximately 1.1 km above and 4 km east of the CRB. Line of site distance from the CRB to the Summit was about 4.1 km.

Except for the NOAA Polarimetric Scanning Radiometer (PSR), all remote sensing equipment operated from the CRB (Table 2). Except for a snow gauge, the two radiosonde systems, and the aircraft, all in situ instrumentation operated from the Summit (Table 3).

The overall sampling strategy was simple. Each day began with an early morning CLASS sonde launch, a

Table 2. Remote sensors.

Instrument	*Site*	*Operator*	*Sponsor*
X and Ka radars	CRB	NOAA ETL	FAA (AWRP)
Ka and W radars	CRB	UMass, Quadrant	NASA
Lidar	CRB	DREV	NASA
Profiling radiometer	CRB	Radiometrics	Radiometrics
Dual-channel radiometer	CRB	MWO, FAA	FAA (AWRP)
Ceilometer	CRB	FAA WJHTC	MWO (FAA)
Dual-channel tippable microwave radiometer	CRB	NOAA ETL	FAA (AWRP)
Polarimetric scanning radiometer (PSR)	Summit	NOAA ETL	NASA

Table 3. In situ sensors.

Instrument	*Site*	*Operator*	*Sponsor*
Particle measuring probes	Summit	CRREL	FAA (AWRP), CRREL, NASA
Cloud and drizzle scopes	Summit	DRI/FAA	FAA WJHTC
King probe, multicylinder	Summit	MWO	FAA (AWRP)
Rosmount ice detector	Summit	CRREL	CRREL
Cloud particle imager	Summit	SPEC	NASA, FAA
Snowgages	Summit CRB	NCAR	FAA (AWRP)
CLASS soundings	CRB	NCAR	FAA (AWRP)
LWC soundings	CRB	ATEK	CRREL, FAA
Twin Otter aircraft	Aloft	NASA	NASA

weather forecast, and an operations brief. If appropriate weather conditions were present, the CRB remote sensors were pointed in staring mode a few degrees above the Summit during odd hours (UT). During even hours, various other scans were performed as appropriate, including PPI (Plan Position Indicator) mode for surveillance (favorable elevations were limited by nearby high terrain), and VAD (velocity-azimuth display) scans for wind analysis and RHI (Range-Height Indicator) scans. When the NASA Twin Otter research aircraft flew, RHI scans were performed along an east-west transect.

Predominantly westerly winds usually placed the CRB upwind of the Summit, and CLASS and ATEK liquid water sondes flew toward the Summit. However, a few days of pronounced easterly winds carried the sondes away from the Summit sampling site. Whereas all CRB equipment did not operate continuously and simultaneously, such as the lidar because of eye safety concerns when the aircraft was in the area, Summit instrumentation always operated whenever any remote sensing system was operating. Conditions at the Summit were often severe, with high winds and frequent clouds, which produced icing and vibration of instruments. Instrumentation was protected from icing, and rotated hourly into the prevailing wind direction to ensure proper sampling.

Weather at the Summit during April 1999 can be categorized as cool, dry, and relatively calm. The April climatological averages and the departures from these values in 1999 are listed in Table 4. There were only three rain events in 1999, including one freezing rain event of 95 minutes duration. Of two drizzle events, neither was freezing drizzle. However, during these above-freezing rain and drizzle events, Summit temperatures ranged from 1–2°C, suggesting that these events were either melting snow or indications of freezing rain or drizzle not far aloft. A climatology performed for the years 1986–1996 shows an average of 2.9 freezing rain events of average duration of 260 minutes, and 1.1 freezing drizzle events with average duration of 270 minutes. Thus, 1999 did not provide as many opportunities for sampling freezing precipitation as expected.

Participants and Tasks

Cog Railway Base (CRB)

Radars. NOAA/ETL utilized its K_a-band and X-band radars to test the dual-wavelength differential attenuation technique. In principle, the K_a-band signal is attenuated more than an X-band signal with increasing distance as both pass through a liquid water cloud. For Rayleigh scattering, the range derivative of the X–K_a reflectivity difference is linearly related to the liquid water content (LWC). Thus, the greater the liquid water content and the longer the path length through the liquid are, the larger and more readily detectable the attenuation difference will be. At MWISP both radars stared at identical elevations and azimuths slightly above the MWO Summit, where in

Table 4. April 1999 weather at the summit.

Value	*April 1999 average*	*1999 departure from climatology (1961-1990)*
Temperature	–6.0°C	–0.6°C
Snowfall	64.3 cm	–14.2 cm
Melted-equivalent Precipitation	10.7 cm	–10.0 cm
Wind speed	12.9 m s^{-1}	–3.2 m s^{-1}

situ measurements of liquid and the features of cloud ice were gathered. However, clouds during MWISP were generally quite shallow, thus, the 18–20° tilted-beam path length through the clouds was very short and minimized attenuation differences, which will limit tests of the method.

The University of Massachusetts Cloud Profiling Radar System (CPRS) worked in coordination with the NOAA/ETL X-band radar to retrieve cloud liquid water using the neural network technique.[10] Range-resolved liquid water content and median particle size will be compared with in situ aircraft measurements, and integrated radar-derived liquid water content will be compared with microwave radiometer measurements of path integrated liquid water content.

The adjustable-polarization NOAA/ETL K_a-band radar used the depolarization ratio (DR) to isolate clouds of drizzle-sized drops (50–500 μm diameters) from ice particles.[18] A 45° slant, quasi-linear (very slightly elliptical) polarization state was tested to achieve a greater cross-polar return than the commonly-used horizontal linear polarization. This allows surveillance of lower-reflectivity clouds, and greater dynamic range enhances separation of the signatures of various hydrometeors. The 45° slant, quasi-linear polarization state is one of a few polarization states that may offer drizzle-drop isolation in clouds that is superior to that obtained with standard linear or considerably elliptical states. Examination of the MWISP data, especially incorporating samples measured at the summit, and estimates of cloud phase, cloud liquid water content, and drop size near cloud base from the DREV lidar, will assist in identifying drizzle versus ice signatures.

Radiometers. Three passive microwave radiometers, from NOAA/ETL and Radiometrics, located at the CRB were tasked to 1) verify icing forecasts, 2) obtain continuous, high resolution temporal icing environment characterization, 3) develop information needed for integrated sensor algorithms, and 4) provide information required for analysis of freezing drizzle formation processes. CRB radiometers operated near 20, 30, 60, and 90 GHz to retrieve integrated and profiled water vapor, and liquid. In addition, the NOAA dual-channel tippable radiometer had RHI scanning capability.

Lidar. The DREV lidar was tasked to provide MFOV cloud characterization in the vicinity of Mt. Washington to verify other remote sensing devices, and to establish the representativeness of Summit in situ measurements to remotely sensed information taken some distance away. DREV's goals were to provide additional field validation of the MFOV retrieval technique, and to test and characterize the MFOV lidar as a possible remote sensing tool for retrieving cloud parameters leading to in-flight icing. Additionally, DREV investigated the precision of water phase identification, the accuracy of the liquid water content and droplet size retrievals, whether MFOV techniques work in rain and drizzle, and the limitations of the method. The MFOV lidar obtained measurements at various elevation angles between zenith and line of sight up the mountain slope, and westward away from the mountain. Measurements were made at discrete elevation angles with a lidar repetition frequency of 100 Hz, while the eight fields of view of the receiver were continuously scanned.

Sondes. The scientific tasks of the two radiosonde systems, the NCAR CLASS sondes and the ATEK supercooled liquid water sondes, were to provide information for forecasters, to profile supercooled liquid water content profiles with height, and to test an experimental drop size measurement system. The CLASS sonde uses LORAN to determine wind direction with height. CLASS sondes were launched on mission days to determine cloud vertical extent, the altitude of the freezing level when it was above the surface, and wind fields. CLASS measured winds can be used to plot the flight of the ATEK sondes, which did not have onboard LORAN, assuming the winds do not change significantly from the time of the launch of the CLASS sonde. A total of 24 CLASS launches were made.

ATEK launched 29 liquid water and experimental drop size measurement sondes from the CBR MWISP field site, with 23 flights yielding high resolution liquid water profiles. The sonde operates by exposing a vibrating wire to supercooled drops, causing ice to accumulate on the wire. The resulting decrease in frequency of the wire is proportional to the supercooled liquid water content, which provides a profile of LWC since the ascent rate of the balloon is nearly constant.[19] ATEK data generated a log for each flight that included the integrated liquid water content, which can be compared to integrated radiometer water retrievals and profiles. Unfortunately, noise plagued the droplet size experiment, which yielded little useful information.

Summit

Both remote sensing and in situ measurements were taken on the Summit. The only remote sensor there was the NOAA-ETL Polarized Scanning Radiometer (PSR). The PSR operates at five frequencies (10.7, 18.7, 21.5, 37.0 and 89.0 GHz), with the lowest two frequencies having full Stokes vectors (I, Q, U, V), and the highest two frequencies having the first three Stokes vectors (I, Q, U). The system was used to assess techniques of forward-

looking (horizontal) inflight detection of icing, and to determine, using the Stokes vectors, whether a polarimetric discriminant exists between supercooled liquid water droplets and ice particles. One technique to be evaluated for detecting aircraft icing conditions with the PSR[15] utilizes 37- and 89-GHz brightness temperatures at 2° above and below the horizon to detect liquid water content, its range from outside cloud, temperature, and, theoretically, the presence of drizzle drops. Discrimination between liquid water and ice crystals may be possible when scanning horizontally or slightly upward, where there should be similar orthogonal polarization brightness temperatures in supercooled liquid clouds, and polarization differences in ice clouds. Polarization differences depend upon the observation wavelength and particle alignment, expected to be greatest for small ice plates of less than ~1 mm at higher frequencies.

Summit in situ measurements support all of MWISP's scientific goals because they provide information that can be used for comparison with remote sensing and many other analyses. Summit in situ equipment included Particle Measuring Systems (PMS) Forward Scattering Spectronometer Probe (FSSP) (2–47μm), 2-D Gray cloud (12.5-μm channels), and precipitation (100 μm channels) probes operated from an SEA 200 data system, a SPEC Cloud Particle Imager (CPI), several Rosemount ice detectors, a DRI cloud scope and drizzle scope, a King liquid water probe, and rotating multicylinders. In addition, the Mt. Washington Observatory recorded standard weather information at 15-minute and hourly intervals. The PMS probes, the CPI, the King probe, and an anemometer were located about 2–3 m above the top and on the west side of the Observatory's 12-m concrete instrument tower. Other equipment was placed at other locations on the tower, and on the observation deck about 10-m below. Summit winds varied from calm to about 49 m s^{-1}, with frequent icing and temperatures ranging from 3 to –15°C. The PMS probes made 156 hours of observations through the project, though all three instruments were not always operating together, at least at the beginning of the project. The CPI operated throughout the project, acquiring particle imagery with a 2.5-μm resolution. The PMS and CPI probes characterize particle types at the Summit, and will be used to create drop size spectra and compute cloud liquid water content for periods of interest. The Rosemount ice detectors and King probe will allow liquid water estimates to be acquired as a time-series through the project. The rotating multicylinders will provide spot measurements of supercooled liquid water. The DRI instruments were experimental, but may also provide measures of cloud and drizzle water content.

NASA Glenn Research Center's Twin Otter research aircraft, based in Portland, Maine, for the project, flew six missions over the CRB on four days, measuring temperature, particle type and size with PMS probes, and liquid and ice water content with Nevzorev and King probes. FAA regulations required a minimum altitude of about 2500 m to clear the summit, thus preventing strong comparisons between Summit and aircraft measurements. However, the aircraft measurements may be the most valid verification of remote sensing measurements because of their distance from the Summit with its turbulence effects, and because its probes operated in a less harsh environment than instruments located on the Summit. Constant communication between the aircraft and CRB remote sensor operators allowed flights to be tailored to the interests of the research teams.

Initial Results

Several of the research teams have released initial data inventories and analyses, while others are in the early stages of analysis (Table 5).

ATEK has released its sonde-based supercooled liquid water profiles, and interpolation of liquid water content to summit elevation has provided liquid water contents as high as 0.48 g m^{-3} (Figure 2). Liquid water profiles from the Radiometrics profiling radiometer have not yet been released.

Table 5. MWISP principal investigators.

MWO CWIFR—King probe, rotating multicylinders: Kenneth Rancourt
NCAR—CLASS sondes, MWISP Program Director: Marcia Politovich
NASA Glenn Research Center—Twin Otter aircraft: Dean Miller
ERDC/CRREL—PMS probes: Charles Ryerson
NOAA/ETL Radar and Ocean Remote Sensing Groups—X and Ka band radars: Roger Reinking, Brooks Martner; PSR radiometer: Al Gasiewski
DREV—lidar: Luc Bissonnette
DRI and FAA Technical Center—cloud and drizzle scopes: John Hallett, Richard Jeck
University of Massachusetts and Quadrant Engineering—CPRS Ka and W band radar: Steve Sekelsky, Andrew Pazmany
ATEK, Inc.—icing radiosonde: Geoffrey Hill
Stratton Park Engineering, Inc—cloud particle imager: R. Paul Lawson
Radiometrics, Inc.—profiling radiometer: Fred Solheim

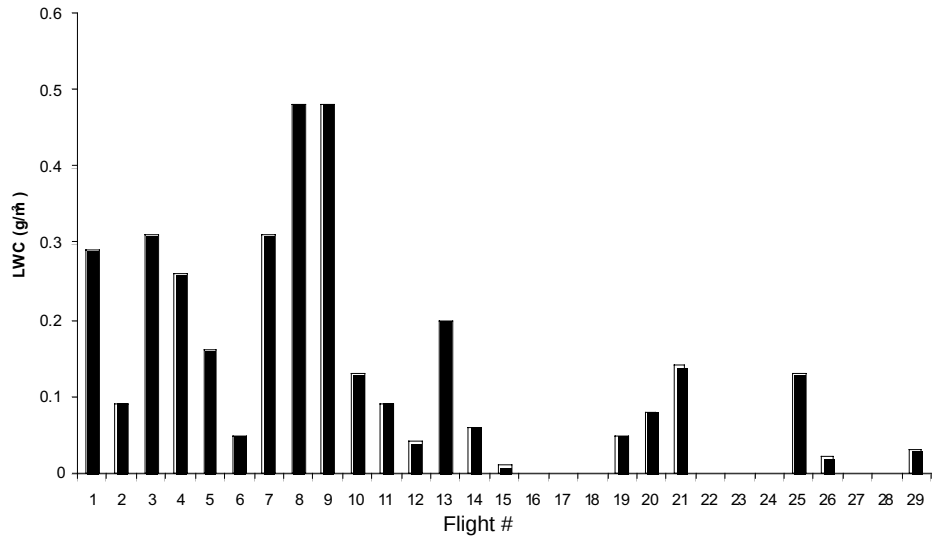

Figure 2. ATEK sonde liquid water content at Summit altitude

DREV has released an initial analysis of MWISP measurements with the MFOV lidar demonstrating time-series of polarization returns, liquid water content, and effective drop diameter. In one case, representing two hours on 10 April, mean effective cloud drop diameters ranged from 8–24 µm, with greatest frequency occurring near 12 µm, and liquid water contents ranged from 0.05 to 0.45 g m^{-3} (Figure 3). The largest droplet size the retrieval method can achieve is about 100 µm, and overall accuracy of retrievals is estimated to be about ± 30 to 40%.

DREV and NOAA-ETL are collaborating to compare polarized returns of cloud droplets, drizzle drops, and ice crystals of various habits using the lidar and K_a-band radar returns. Analyses are complicated by the inability of lidar to penetrate cloud more than a few hundred meters, and the often large distance between cloud base lidar observations and Summit in situ measurements, making the verification process difficult. However, combining polarization tools from both the lidar and radar appears to be a powerful tool for the analysis of cloud properties. Figure 4 shows measurements of planar ice crystals, columnar ice crystals, and drizzle drops obtained from scans in vertical planes from horizon through zenith to the opposite horizon with the K_a-band radar. Drizzle drops are spherical, so they do not depolarize the transmitted signal. Planar crystals settle with their major dimension approximately horizontal, so they also depolarize the transmitted radar radiation more when observed at their edges near the horizon than when observed at zenith where they appear more spherical. Columns settle with their major axis horizontal, so they also depolarize the signal substantially and show offset from the non-depolarizing drops, although columns, like drops, show little variation in the depolarization with antenna elevation angle. NCAR is working with NOAA to develop retrieval techniques for identifying regions of liquid, ice and mixed phase precipitation, to estimate droplet size and LWC using dual-frequency radar, to compare the radar-based retrievals with radiometer and in situ microphysical observations, and to pro-

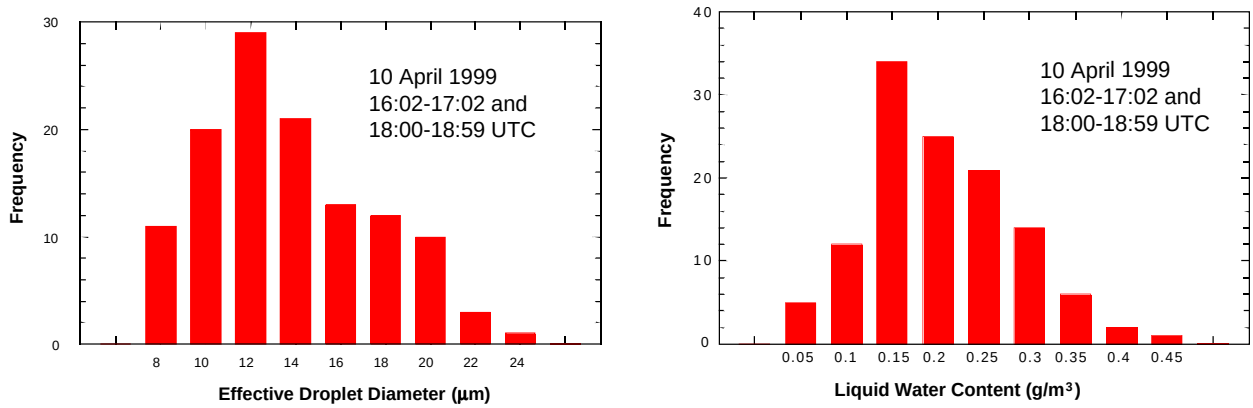

Figure 3. Cloud-averaged drop diameter (left) and liquid water content from DREV MFOV lidar (right).

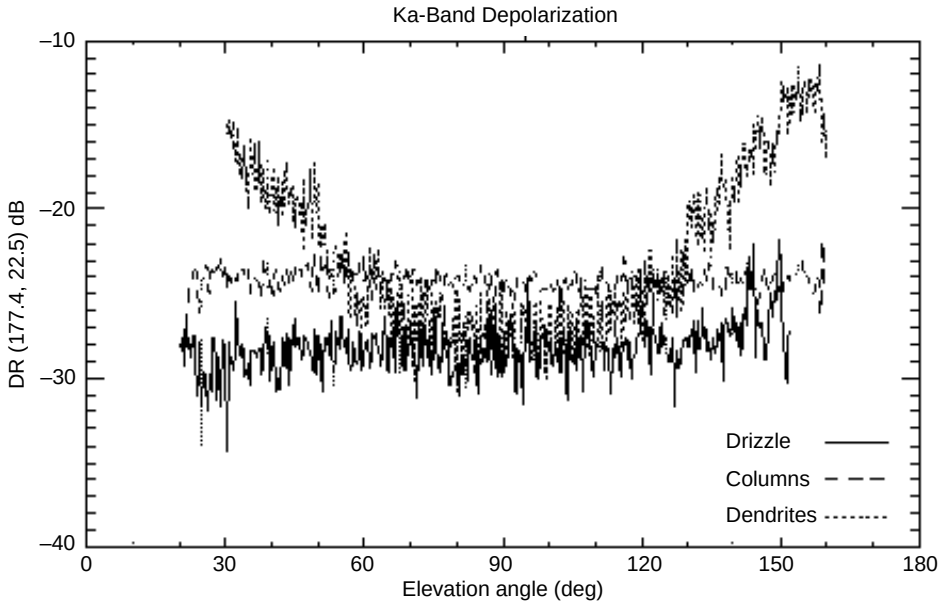

Figure 4. NOAA K_a band polarization signatures of drizzle, columns and dendrites at MWISP.

pose an operational method for detecting icing in and around aircraft terminal areas.

The University of Massachusetts/Quadrant Engineering team will use the neural net approach to retrieve liquid water and drop size. However, until all radar bands are available, liquid water and drop size are being retrieved using the CPRS K_a- and W-band radars. As an example, Figure 5 displays estimates of median droplet diameter calculated using attenuation-corrected radar reflectivity measurements and liquid water content estimates along the side of Mt. Washington. These were derived from dual-wavelength radar measurements, using an assumed drop-size distribution.

PSR radiometer data have been extracted, but not fully analyzed, to identify forward-looking detection of icing capabilities, and discrimination of ice from water. However, as with lidar and radar returns, the radiometer also provides imagery for assessing the complexity of cloud structure in the vicinity of Mt. Washington by obtaining the relative brightness for each channel and each polarization as a time-series. Evaluation of the multi-view, multi-frequency returns for determining cloud microphysical parameters, however, requires calibrated brightness temperatures rather than relative brightness values.

In situ measurements of cloud properties were made by SPEC, CRREL, DRI, Mt. Washington Observatory, and NASA's Twin Otter research aircraft. SPEC has created histograms of particle sizes, including both ice and

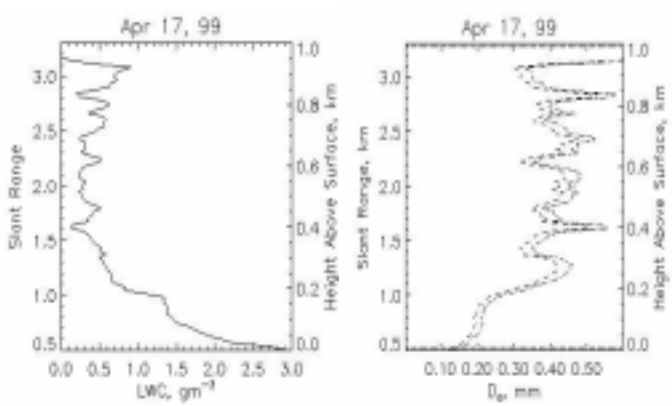

Figure 5. CPRS range resolved liquid water, left, and median volume diameter (MVD) using two gamma distributions, right, alongside of Mt. Washington.

water, for most of the project, and has released particle images. Liquid and ice water contents will be computed during the winter of 1999–2000, and some analyses of crystal habit will be done. CRREL has completed post-project PMS probe calibrations, and is extracting particle images for selected periods. Initial liquid water contents will be computed from the FSSP, ice and liquid estimates will made from the 2-D Gray probes, and crystal habits will be classified. It is not yet clear what information will be available from the DRI drizzle or cloud scopes, or the Mt. Washington King probe. Liquid water estimates will also be extracted from the Rosemount ice detectors and the rotating multicylinder. Liquid water contents and particle size and shape information will be available from NASA's Twin Otter overflights in early 2000.

In situ measurements from the NASA Twin Otter appear to be of high quality. A few short periods of supercooled liquid water were encountered on these flights, but no freezing drizzle was observed.

All instruments providing similar information will be compared for physical consistency to assess which instruments are performing best, and to establish consistent values for the record. These analyses are expected to be performed during the remainder of FY00.

Summary

The primary goal of MWISP was to evaluate the ability of remote sensors to retrieve cloud information relevant to assessing aircraft icing conditions, with a secondary goal to characterize icing microphysical conditions. Initial results suggest that MWISP will be successful for many of the remote sensing evaluations, especially lidar and radar polarization studies, and the microwave radiometer analyses both at CRB and at the Summit. One goal of polarization studies was to assess capabilities for detecting drizzle size drops. Several drizzle events were recorded with the NOAA/ETL K-band radar. Although these events were not supercooled, the measured depolarizations are the same as would be measured in cold clouds. The drizzle commonly occurred below the summit. Good comparisons of drizzle with ice crystal depolarizations were obtained. Inventories of the Summit probe data also suggest that several hours of drizzle occurred at various times at the Summit. A full analysis of summit measurements will confirm this. It is also not yet clear how successful differential attenuation and neural network retrieval of liquid water contents will be. Both techniques require information from up to five sequential radar range gates. There is concern that a predominance of thin clouds may prevent sufficient gates to be retrieved for useful analyses.

The mountain environment provides opportunities and limitations for icing characterization. Though using Summit in situ observations may be challenging because of the complexity of alpine boundary layer effects, areas of rough terrain are often also where more intense aircraft icing occurs because of lifting caused by the terrain. In addition to the Summit measurements, the CRB radars and lidars are providing valuable information about wave structures and small-scale circulations that were previously unobserved at Mt. Washington. This information should allow an assessment of the representativeness of Summit observations to conditions observed by the remote sensors.

Though MWISP did not experience as many freezing drizzle events as desired, it will provide valuable information for further development of methods for detecting inflight icing conditions remotely. The Alliance Icing Research Study (AIRS), being conducted at Ottawa, Ontario, and Mirabel, Quebec, between November 1999 and February 2000, is the follow-on field project to MWISP, and may deliver weather conditions not available during MWISP.

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