7.7 MT. WASHINGTON ICING SENSORS PROJECT (MWISP) RESULTS

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1. INTRODUCTION

In April 1999, twenty organizations from the United States and Canada collaborated to conduct the Mt. Washington Icing Sensors Project (MWISP). Funded principally by the Federal Aviation Administration's Aviation Weather Research Program (FAA-AWRP) and the National Aeronautics and Space Administration's Glenn Research Center (NASA-GRC), MWISP resulted from requirements identified in the NASA, Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL), and FAA-sponsored *Inflight Remote Sensing Icing Avoidance Workshop* (Bond et al., 1998) and the FAA *International Conference on Aircraft Inflight Icing* (Riley and Horn, 1996). This paper highlights MWISP accomplishments.

2. SCIENCE AND FIELD PROGRAMS

The primary goal of MWISP was to *test and compare methods for remote sensing inflight icing [liquid water content (LWC)], droplet size, and presence of supercooled large drops (SLD) for reliability and accuracy* (Ryerson et al., 2000). This goal required verification of inversion algorithms for detecting and measuring these phenomena by collection of in situ data. Remote sensing methods included multi-wavelength radar differential attenuation LWC retrieval and neural net LWC and drop size retrieval, dual-polarization radar droplet and ice hydrometeor identification, multi-band microwave radiometer forward-looking (horizontal) icing characterization, and multiple-field-of-view lidar cloud characterization. A secondary goal was to *assess Mt. Washington as an aircraft icing research site*, which involved characterizing the mountain's climatology and determining the suitability of the mountain infrastructure for future icing research.

The Mt. Washington Observatory (MWO) operates a research station at the 1917-m MSL summit where in situ cloud microphysics equipment and a microwave radiometer were operated. Located 3.8 km west and 1063 m below the summit is the Mt. Washington Cog Railway Base (CRB), where most remote sensing systems were located. The field program operated for the entire month of April 1999. Daily operations started with a Cross-chain Loran Atmospheric Sounding System (CLASS) radiosonde flight, followed by an MWO-CRB weather briefing, resulting in a decision whether to initiate a coordinated MWO-CRB Intensive Operational Period (IOP). Though some instrumentation operated on at least 23 days, 13 coordinated IOPs occurred, with eight very successful "golden" days. During operations, CRB-based remote sensing devices either stared over the MWO or performed east–west scans. NASA-GRC's Twin Otter icing research aircraft conducted overflights. Participants included Mt. Washington Observatory, FAA-AWRP, FAA's Wm J. Hughes Technical Center, NASA-GRC, CRREL, National Oceanic and Atmospheric Administration's Environmental Technology Laboratory (NOAA-ETL), NCAR, National Weather Service (NWS) Forecast Office at Grey, ME, Defense Research Establishment at Valcartier, Quebec (DREV), University of Maine, University of Massachusetts (UMass), University of New Hampshire, University of Nevada's Desert Research Institute (DRI), Lyndon State College (LSC), Plymouth State College (PSC), Quadrant Engineering, ATEK, Inc., Stratton Park Engineering, Inc. (SPEC), Sensor Concepts and Applications, Inc. (SCA), and Radiometrics, Inc.

3. ICING DETECTION BY RADAR

A noteworthy achievement of MWISP was NOAA-ETL's proof of concept of a polarization radar technique for reliably differentiating ice crystals and supercooled large drops. As a result NOAA is building the Ground-based Remote Icing Detection System (GRIDS) with FAA funding for potential prototype fielding in two years (Reinking et al., 2001). GRIDS was designed primarily to distinguish SLD (supercooled liquid water droplet diameter > 50 µm) conditions, which can pose a particular hazard to aircraft. However, with a dual-channel microwave radiometer as part of the system, GRIDS should also be able to quantify cloud-droplet icing regions. The SLD detection is based on the shape of larger droplets, which distinguishes them from ice crystals with similar reflectivities. A 45° slantwise polarization state was found to be optimal for distinguishing drizzle from ice crystals through theoretical scattering calculations confirmed through the analysis of MWISP data collected in drizzle situations.

Techniques for using multiple wavelength radars for liquid water quantification were also tested. NCAR is developing K_a- and X-band retrieval methods for liquid water path (LWP) and range-differentiated liquid water

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content (Vivekanandan et al., 2000). When large water droplets or ice crystals are present (diameters >~500 μm), Mie-scattering effects are introduced that corrupt the retrieval. The MWISP data sets have proved useful in evaluating methods to alleviate this problem. Data were collected on 22 April in a shallow stratiform cloud that was determined (by K_a-band polarization and lidar measurements) to be dominated by cloud droplets and thus ideal for LWP calculations. Comparisons of dual-wavelength radar-retrieved LWP were excellent for this case. However, when the technique was applied to a different data set collected on 10 April in a cloud with significant ice crystal concentrations, LWP was overestimated by a factor of 2–3. Current research is being conducted at NCAR employing the MWISP data set to explore the use of polarization signals to recognize ice crystals, as well as to apply assumptions of the shapes of ice crystal and drizzle size distributions through correlation of Gamma-fit parameters.

The MWISP data have also yielded information used for design requirements for a new K_a-band antenna to augment the existing National Science Foundation S-Pol (S-band polarized) radar. This will be used both in the development of a future operational system to be paired with NEXRAD and for detailed cloud physics research.

UMass had varying success retrieving LWC values with multi-band radar. Utilizing data from their K_a/W-band radar and the NOAA-ETL X-band radar, UMass was able to retrieve LWC and droplet size information with neural net post-processing (Pazmany, 2001). For 14 April the resultant retrievals agreed well with an ATEK LWC-measuring radiosonde. Results for other days were not as promising, perhaps because of the mixed-phase cloud conditions at MWO.

4. MICROWAVE RADIOMETRY

Radiometrics, Inc. was able to use MWISP to verify measurements from their newly developed profiling radiometer (Solheim and Godwin, 1998). This instrument uses twelve channels to provide temperature and humidity profiles through the troposphere. Additionally an algorithm was tested that provided liquid water profiles in cloud.

Comparisons with ATEK sonde (Hill, 1992) LWC profiles (see below) were generally good, but differences in the measurements have led to research into improvements in the retrieval algorithms. Temperature profiles were often too warm, which theoretical radiative transfer studies suggested were due to the presence of ice crystals in clouds above the site. As a result, Radiometrics is building a higher-frequency receiver for the unit that should indicate the presence of ice above a certain threshold value. The liquid water algorithm did not perform well, and adjustments were subsequently implemented to make better use of infrared cloud base temperature information available from the instrument, and an improved profile shape.

NOAA-ETL operated their five-channel (10.7, 18.7, 21.5, 37.0, and 89.0 GHz) polarized scanning radiometer (PSR) at the summit, with the highest two frequencies having the first three Stokes vectors. PSR brightness temperatures will be 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. When calibrated data are released, they will validate a neural network-based LWP inversion algorithm being developed by CRREL for scanning horizontally ahead of an aircraft.

5. LIDAR

DREV has developed a multiple-field-of-view (MFOV) lidar system to determine cloud microphysical properties (Bissonnette et al., 2000). Using the range-resolved effective droplet diameter and the Mie calculation and assuming a drop size distribution function, DREV calculated the range-resolved extinction and liquid water content in clouds at MWISP. The precisions of the retrieved LWC and effective droplet diameter are on the order of 30% and 10%, respectively, based on comparison with in situ measurements (Bissonnette et al., 2002). The in situ measurements did not coincide with the lidar measurement volume for safety reasons, raising the question if some of the observed differences may be due to differences in the spatial distribution of cloud microphysical properties. The lidar backscatter and depolarization measurements can be used to determine the cloud and, if present, precipitation phase (Bissonnette and Roy, 2001). For example, horizontally oriented crystals will exhibit low depolarization at the zenith, while raindrops that have some degree of deformation will have large backscatter values near the zenith. The main disadvantage of lidar is the limited cloud penetration depth (100–150 m during MWISP). The cloud penetration depth may be greater for clouds containing hazardous drizzle drops, which decrease the number of smaller cloud drops and thus may offset the increase in the cross-sectional area of drizzle drops.

6. CLOUD MICROPHYSICS

CRREL operated a Rosemount ice detector, from which cloud supercooled LWC was computed and compared against 27 rotating multicylinder runs made by MWO. A Particle Measuring Systems (PMS) forward scattering spectrometer probe (FSSP) and two PMS 2-D gray optical array probes (OAP) covering particles 2–6400 μm in diameter were also operated for 159 hours at MWO (Ryerson et al., 2002). Probe operations were compromised by icing and fluctuating winds. The inability to compute accurate particle concentrations from the FSSP required corrections using the derived Rosemount LWCs. Approximately 3600 5-min particle and drop size distributions have been derived from the PMS measurements, with identification of dominant particle types. SLD were observed for 10 of the 159 hours. In addition, PSC used software to extract percentages of drop, column, dendrite, and irregular-shaped particles from CRREL's PMS OAP data (Schmitz et al., 2002).

SPEC operated its high-resolution cloud particle imager (CPI) at MWO. Measurements from eight days have been summarized at 5-min intervals, providing water and ice particle size distributions and concentrations and histograms of particle type frequency. Particle size distributions are computed only for sizes ≥150 μm because the CPI is least sensitive to small particles. LWC and drop concentration computations were adjusted against the MWO rotating multicylinder measurements.

ATEK flew 32 radiosondes designed to measure supercooled LWC through clouds on 12 days of MWISP from the CRB, with 23 flights providing LWC measurements (Hill, 1992). The sondes provided direct indication of the depth of cloud supercooled LWC. ATEK also attempted to measure particle size during several flights, but data noise was a serious obstacle.

NASA's Twin Otter icing research aircraft was staged in Portland, ME, and flew five in situ measurement flights over MWO and the CRB along east–west transects. Flights were restricted to altitudes above 2440 m for terrain clearance. A total of 25 transects with durations of ~4-min each were flown on 13, 15, 26, and 27 April, all but one resulting in cloud liquid water and particle type measurements between altitudes of 2470 and 3506 m MSL.

7. AIRFLOW STUDIES

MWISP remote sensing research focused on upslope flow, which promotes the development of cloud liquid water and aircraft icing conditions that the project was designed to study. But the presence of mountains can also disrupt ambient winds in other ways that may affect aviation and human activity in the vicinity.

NOAA-ETL analyzed an MWISP traveling gravity-wave case with a boundary-layer jet (Reinking et al., 2002) on 3 April. Two radars (K_a-band and X-band), a microwave radiometer, and a lidar revealed the propagating waves, with wavelengths of 0.8–1.2 km from 0.5 to 1 km AGL. The Doppler velocity variance field from the K_a-band radar showed that the strongest turbulence was detached from the surface and generated by shear associated with a jet.

The synoptic flow created an environment with vertical wind shear and a low-level jet (LLJ) at the top of a temperature inversion, which is the classic situation for the generation of gravity-shear waves. However, the waves, which formed below the nose of the 10- to 12-m s^{-1} LLJ, were not triggered spontaneously but were formed only when the mountain induced them. Air below about 0.5 km AGL was nearly stagnant, indicating either complete blocking or simply a calm boundary layer. The laminar flow near the mountain was compressed, converged under the trapping inversion, and buckled to form the waves. The wave amplitudes were consistently greatest near the barrier and tapered up to 4–8 km upstream (relative to the LLJ).

The ETL radars at the CRB also documented a well-defined downslope flow case on 16-17 April (Martner et al., 2002). Continuous, high-resolution (37.5 m) radar observations provided flow field measurements throughout the event. MWO was embedded in SE flow several hundred meters beneath a strong inversion and SW flow that gradually lowered to eventually end the event after 8 hours. During the event, low-level air from the SE poured over the ridges and down the western side of the mountains toward the CRB. Wind speeds at MWO were <5 m s^{-1}, while Doppler radar velocity patterns showed that the air accelerated in a laminar layer down the west side of the mountain and reached a maximum speed of 12 m s^{-1} at ~2.5 km downslope from MWO. At that location the laminar flow abruptly broke into a hydraulic jump. At times the air directly above the CRB exhibited sustained updrafts and downdrafts of ~3 m s^{-1}, suggesting the formation of a strong wave. The laminar layer was initially 1 km deep and became steadily shallower as the lowering inversion approached the mountaintops.

8. WEATHER STUDIES

Weather conditions encountered during the month did not live up to the expectations of many on the MWISP team. Most had expected a greater frequency of icing conditions in deep clouds, but no one knew for sure how anomalous the month really was, if at all. As a result, PSC students (Markle et al., 2001) developed a detailed 45-year synoptic climatology for the Mt. Washington area to determine whether April 1999 differed from normal.

The results indicated that April 1999 was warmer and more humid than normal. April synoptic weather features show that northern New England is usually dominated by both a northwesterly flow from Canada and an easterly flow bringing moisture into the region. April 1999 had synoptic features more frequently associated with warm air advection into the region, i.e., less favorable for icing. The 850-mb climatological temperature analyses reinforced the surface synoptic results, showing the area normally situated either in the trough axis or on the upstream side of the trough, thus providing cold air advection and instabilities suitable for producing icing situations. The average April temperature is usually below 0°C for MWO, and relative humidity levels indicated that sufficient moisture is usually available for icing to occur on many days. However, April 1999 was dominated by warm air advection over the region and thus was not a "normal" April for the production of frequent icing situations at MWO.

9. CONCLUSIONS

MWISP taught us that radars to be used for icing detection must be properly designed for the task. They need to be extremely sensitive (easily detecting –10 to –20 dBZ) and, in the case of multiple wavelength analyses, beam-matched. MWISP also showed that MFOV lidar is an effective tool for assessing icing cloud microphysics and, along with radar, assessing airflow regimes in extreme terrain. The terrain and extreme weather provided conditions needed to distinguish SLD from ice crystals using radar but hindered measurements at the summit, even with careful planning. While MWO dependably provides cloudy situations for such studies, weather can vary substantially from climatological averages. CRB and MWO facilities, including excellent transportation to the summit, allowed MWISP to uniquely assess icing where research aircraft have limited access for in situ measurements. MWISP, along with the Alliance Icing Research Study (AIRS) during the winter of 1999-2000, has allowed the development of inflight icing remote sensing techniques to progress to the point where prototypes can be field tested within the next few years.

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