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Supercooled liquid water content profiling case studies with a new vibrating wire sonde compared to a ground-based microwave radiometer

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ABSTRACT

An improved version of the vibrating wire sensor, used to measure supercooled cloud liquid water content, was developed by Anasphere Inc. and tested during early 2012. The sensor works on the principle that supercooled liquid will freeze to the vibrating wire and reduce the frequency at a known rate proportional to the liquid water content as the sensor rises through the cloud attached to a weather balloon and radiosonde. The disposable Anasphere sensor interfaces with an InterMet Systems iMet radiosonde. This updated sensor reduces the weight of the instrument while updating the technology when compared to the preceding balloon-borne sensor that was developed in the 1980's by Hill and Woffinden.

Balloon-borne test flights were performed from Boulder, Colorado during February and March of 2012. These flights provided comparisons to integrated liquid water and profiles of liquid water content derived from a collocated multichannel microwave radiometer, built and operated by Radiometrics Corporation. Inter-comparison data such as these are invaluable for calibration, verification and validation of remote-sensing instruments. The data gathered from this sensor are potentially important to detection of icing hazards to aircraft, validation of microphysical output from numerical models, and calibrating remote sensors measuring supercooled liquid water.

1. Introduction

Liquid water existing within subfreezing temperature profiles is said to be 'supercooled liquid water' (SLW). When an aircraft encounters SLW, the SLW freezes quickly onto the leading edges, which acts to increase drag and reduce lift. SLW drops above 50 μm in diameter, termed 'supercooled large drops', can be even more dangerous to flight as they tend to splash and roll back beyond the aircraft's leading edges where icing defenses such as heaters or boots are located. For these

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reasons, in-flight icing can be a significant hazard to all forms of aircraft (Politovich, 1996; Fernández-González et al., 2014) and its detection is a high priority for the Federal Aviation Administration as well as the commercial and general aviation community.

Multi-channel microwave radiometers have been developed and utilized over the last few decades to provide continuous measurements of liquid profiles and other variables of state (Heggli et al., 1987; Solheim et al., 1998; Ware et al., 2013). Another method of detecting liquid profiles involved a balloon-borne instrument based on vibrating wire technology (Hill and Woffinden, 1980) to derive profiles of SLW, which was developed by the ATEK Corporation. Previous work by Ware et al. (2003) showed that over 24 cases where vibrating wire sondes were launched near a profiling radiometer that on average the height of the liquid layers matched 50% of the time between sonde and radiometer even though significant differences existed between the liquid measuring techniques of each instrument. This SLW sonde technology never gained widespread adoption as the developer did not make the technology available for large-scale production and commercialization. A prototype SLW sonde has recently been developed by Anasphere Inc. with support by The National Aeronautical and Space Administration (Bognar et al., 2011) that uses the same vibrating wire principles and vibrational sensing technology as the ATEK Corp. sondes while incorporating other technical improvements. The purpose of this effort was to launch sondes into cold-season stratiform cloud which contained SLW and compare the resulting supercooled liquid water content (SLWC) profiles to liquid water path (LWP) and SLWC derived from ground-based radiometers. Section 2 is a description of the data sources utilized by this study for atmospheric observations. Section 3 is a methods used section. Section 4 describes the theory and design of the SLWC sondes. Section 5 details two SLWC sonde balloon launches conducted on March 7th, 2012. Section 6 is a discussion on sources of error in the SLWC sonde/radiometer comparison and Section 7 are conclusions based on this study's findings.

2. Observations

2.1. Supercooled liquid sonde

SLWC sondes were launched near a radiometer in cases with known SLWC, whose presence was verified with Pilot Reports of in-flight icing. The theory and practice of profiling SLWC with vibrating wire sondes attached to balloon-borne radiosondes are discussed in detail in Section 4.

2.2. Radiometer

A Radiometrics MP-3000A Series 35-channel microwave radiometer was located on the roof of Radiometrics Corporation's two-story office building located in North Boulder, CO. The passive microwave radiometer, the derived LWP, SLWC, humidity and temperature profiles are described by Solheim et al. (1998), Ware et al. (2003), Knupp et al. (2009), Cimini et al. (2011), Gultepe et al. (2012) and Friedrich et al. (2012). LWP can be calculated using closed retrieval algorithms and SLWC profiles are computed by building a training set of 10,000 historical radiosonde profiles from Denver and inverting the meteorological fields by computing the associated brightness temperatures with a radiative transfer model. Previous studies found that the radiometer LWP retrieval accuracy was better than 15% for a broad range of cloudy conditions (Westwater, 1978) and that there was no dependency on the sampled drop size (Westwater, 1978; Snider et al., 1980). Sampling volume considerations between the radiometer and the SLWC sonde are addressed in the Section 6 Discussion.

For this field study, the radiometer was programmed to collect brightness temperatures from zenith and off-zenith (15 degree elevation) north and south observations. Retrievals only from the northerly observation direction were used in the analysis, as that was the approximate mean direction of travel of the sondes. At 15 degrees elevation, the radiometer is viewing along an optical path that is equivalent to the depth of four atmospheres, as opposed to one atmosphere at zenith. At this low viewing angle, the radiometer's individual channel weighting functions become maximized in the lowest few kilometers and do so much closer in altitude to each other, which acts to increase the sensor's resolution in the lowest atmospheric levels (Xu et al., 2014). The low elevation viewing angle also means the sensor is viewing through the nearly vertical sides of the hydrophobic radome, which further mitigates the effects of precipitation on the detected brightness temperatures.

2.3. Pilot reports

When pilots visually detect icing on their aircraft, they can choose to voluntarily call in a Pilot Report to an air traffic controller that specifies a subjective icing severity ('null', 'trace', 'light', 'light–moderate', 'moderate', 'moderate–severe' and 'severe'), icing type ('rime', 'clear' or 'mixed'), reported altitude, air temperature, hazard location coordinates and other meteorologically relevant fields. Known deficiencies in the quality of these data such as occasional locational misreporting, decoding errors, subjective severity categorization, and severity dependence on aircraft type and size are detailed in Kelsch and Wharton (1996).

3. Method

In order to make a direct comparison between sonde and radiometer SLWC, several physically realistic constraints were applied to the raw neural network liquid profile retrieval derived from the radiometer. First, the radiometer temperature profile is adjusted to saturate the relative humidity with respect to liquid inside cloud. Second, cloud-top infrared temperature values from the Geostationary Earth-Orbiting Satellite infrared channel values are used to constrain the vertical extent of liquid detected by the radiometer. Third, liquid densities less than 0.03 g m^{-3} were considered to fall within the neural network noise level and therefore were adjusted to zero. Finally, the radiometer SLWC profile was normalized so that the integral of the profile was equal to the radiometer retrieved LWP value.