8.5 EFFECTS OF SCATTERING DUE TO ICE PARTICLES ON MEASUREMENT OF DOWN-WELLING RADIATION OBSERVATION OF K AND V-BAND RADIOMETERS

J. Vivekanandan and Guifu Zhang
NCAR/RAP, P.O.Box 3000
Boulder, CO 80307

1. INTRODUCTION

Studies have shown that a combination of supercooled liquid water (SLW) content and droplet size contributes to the amount of ice accretion on an aircraft surface, which is related to the icing severity. Remote measurement of liquid water content (LWC) and mean droplet size are essential for quantifying icing severity in a detection system. Icing severity of a single-phase cloud consisting of small cloud droplets can be quantified easier than in the case of a mixed phase cloud containing liquid droplets and ice particles. Recent in situ aircraft observations suggest that ~ 60% of icing clouds are mixed phase (Cober et al., 2001). In most of the mixed phase clouds, mean ice particle size is an order of magnitude larger than droplet size and hence ice particles enhance radiation measured by the ground-based radiometer through scattering of the emission from vapor, liquid, and atmospheric gases (Li et al., 1997).

Microwave radiometer observations around 60 GHz oxygen absorption lines are used for temperature profile estimation. The temperature estimation technique is based on a forward radiation model of various radiosonde profiles and a neural network inversion method. A thorough review of various statistical methods to retrieve the atmospheric variables using ground-based measurements can be found in Westwater (1993).

This paper describes the scattering effects by ice crystals on temperature retrievals by the TP/W VP-3000, a profiling microwave radiometer that uses K- and V-band channels (Solheim et al., 1998). The goal of this study is to determine whether the addition of a higher-frequency channel to the instrument will improve ground-based remote sensing of atmospheric variables related to inflight icing. A radiative transfer model for calculating brightness temperature of a mixed-phase cloud is developed. The brightness temperature is calculated by applying this model to clouds of liquid water droplets with and without ice particles present. The enhancement of the radiation due to ice particles is studied as a function of ice water path (IWP) and ice particle size. It is found that enhancement in downwelling radiation is a sensitive function of mean particle size. The temperature and vapor profiling as well as liquid water retrieval are affected by enhanced scattering of ice particles. An approach for quantifying enhanced radiation due to ice scattering is proposed using the brightness temperature measurements at higher frequencies, namely 90, 150, and 220 GHz.

2. RADIATIVE TRANSFER MODEL

For this study we invoked the assumption of a plane-parallel atmosphere. This assumption, usually made in atmospheric radiative transfer modeling, has limitations. It was generally shown that radiative transfer in media dominated by scattering suffers most from an assumption of plane parallelism and that those dominated by absorption (emission), such as in the microwave regime, are less influenced by geometry. The radiative transfer model determines the intensity of radiation, diffusely scattered, absorbed and emitted by the atmosphere. Basically,

$$\mu \frac{dT_B(\tau,\mu)}{d\tau} = -T_B(\tau,\mu) + \frac{1}{2}\int_{-1}^{1} p(\mu,\mu')T_B(\tau,\mu')d\mu' + (1-\omega)B(\tau) \quad (1)$$

where μ is the cosine of the polar angle, τ is the optical depth, and ω and p are the single scattering albedo and phase function, respectively. The variable T_B represents the brightness temperature and B is the unpolarized thermal emission.

The radiation transfer equation is solved using the invariant embedding method (Stephens, 1976). This method is based on the linear interaction of radiation with the medium through reflection and transmission matrices. The atmosphere is divided into a number of layers and the reflection and transmission matrices for each layer are calculated. Cumulative reflection and transmission matrices for the entire medium are computed using the interaction principle. Boundary conditions are used to specify the input radiation impinging on the medium from outside.

The modeled cloud structure consists of liquid and ice layers of 2 km thickness. The amount of liquid water path (LWP) is fixed at 0.2 mm (0.1 g m^{-3} throughout the 2 km layer), and the ice water path (IWP) is varied between 0 and 0.5 mm. The vapor column is assumed to be 1 cm. Temperature is assumed to linearly decrease with height starting at 283 K on the ground with lapse rate of 6.50^{o} km^{-1}. The shapes of liquid and ice particles are spherical and the ice density is assumed 0.92 g cm^{-3} (the density of bulk ice). The liquid and ice can be combined in various proportions to form a mixed-phase layer.

There are three primary cloud layer configurations to consider: the ice layer just above the liquid layer with minimal overlap; 50% overlap between liquid and ice; and complete overlap of liquid and ice layers. It has been shown (Zhang and Vivekanandan, 1999) that for a specified vapor, LWP and IWP, the enhancement in downwelling brightness temperature is maximized when liquid and ice layers completely overlap, is intermediate for partially mixed configuration and minimized for the non-overlapping configuration. Thus, for this study, we have considered the intermediate case: a mixed-phase layer with 50% overlap between liquid and ice.

3. RESULTS OF RADIATION CALCULATION

Figure 1 shows T_B as a function of IWP for K- ,V-band and higher frequency channels that are more sensitive to scattering. As the IWP increases, the down-welling radiation is biased high. The bias at 30 GHz is twice that at 20 GHz for the specified IWP. In an atmosphere dominated by emission, T_B at 20 GHz increases by 9K for every 1-cm increase in vapor path. Thus, the presence of an ice cloud would positively bias the retrieved vapor.

The V-band frequencies are used primarily for profiling temperature. Lower frequency (i.e. < 55 GHz) channels in V-band are much more sensitive to IWP. For a specified ice cloud structure, scattering increases at higher frequencies and hence V-band TB are more sensitive to IWP than K-band channels. However, higher frequency (> 55 GHz) channels in V-band are sensitive only to lower portions of the atmosphere and are nearly insensitive to the atmosphere above 2.0 km AGL. Thus, the assumed cloud structure has no affect on the absorption lines of V-band channels.

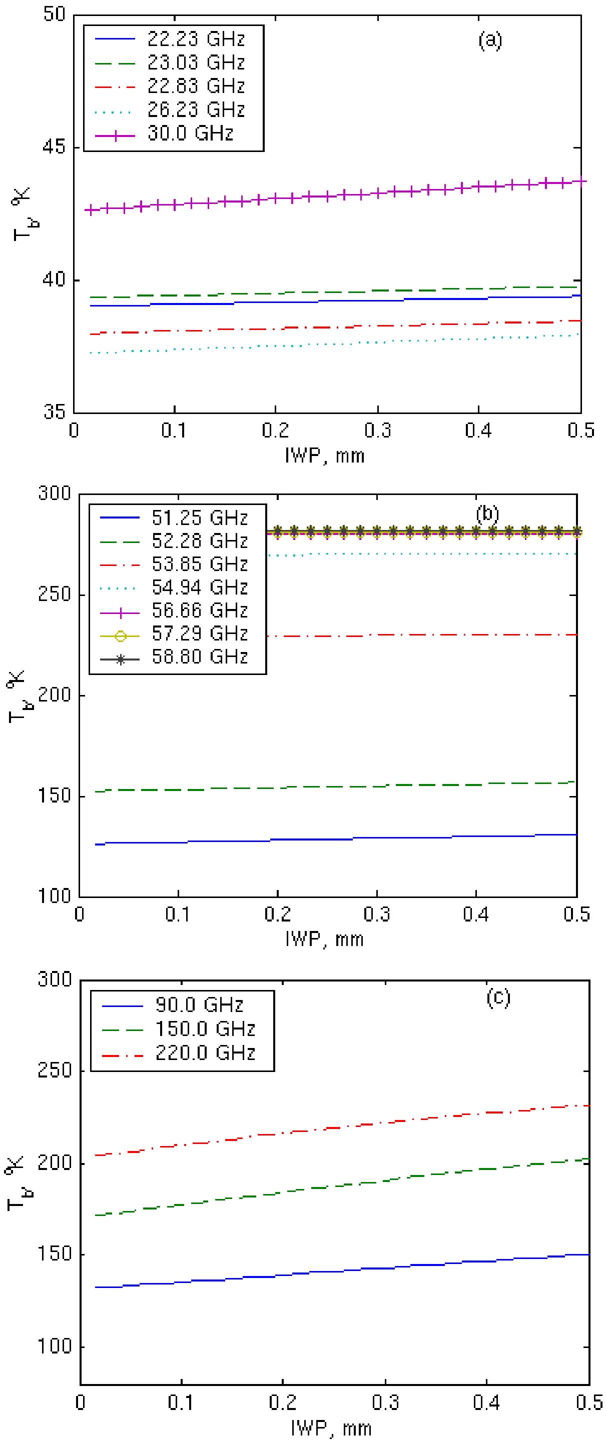

Figure 1. Downwelling brightness temperature as a function of IWP at: a) K-, b) V-band and c) higher frequency channels. Parameters used in calculation are: LWP = 0.5mm, RES_L = 0.14 mm, RES_I = 1.4 mm. IWP is varied between 0.01 and 0.5 mm.

The brightness temperatures at higher frequency channels such as 90, 150, and 220 GHz are also calculated and shown in Fig. 1c. They are more sensitive to IWP than those at K- or V-band. Enhancement in T_B due to scattering at 150 and 220 GHz is almost factor of two larger compared to at 90 GHz for a specified IWP. It should be noted the results shown in Fig. 1 assume that the radar estimated size of ice particles (RES_I) is 1.4 mm and of water droplets (RES_L) is 0.14 mm. Radar estimated size (RES) is the cube root of the sixth divided by the third moment of the size distribution and is the same as median volume diameter (MVD) for a narrow distribution. It is larger than MVD for a broad size distribution. The calculations in the next section describes the effect of ice particle size on T_B for a specified IWP.

4. SENSITIVITY TO PARTCLE SIZE

The scattering component in radiation transfer depends on both ice water path and characteristic particle size. Various statistics can be used to characterize particle size in a distribution. The RES has been shown to be useful in characterizing icing environments through simulations using modified Gamma droplet size distributions with realistic bounds based on several sets of in situ measurements (Vivekanandan et al., 1999). In the case of liquid-only cloud, the RES is also relatively easy to retrieve using dual wavelength (e.g., K_a- and X- or S-band) radar measurements. In a size distribution with both small and large particles (i.e. broad spectrum) the RES value is primarily biased towards large particle size. Thus in a mixed-phase cloud with a few large ice particles, those ice particles will dominate the reflectivity measurement and the calculated RES might not characterize the size distribution well, especially for the liquid component.

Figure 2 shows the downwelling brightness temperature as a function of RES. At K-and V-band, T_B increases as RES is larger than 1 mm as shown in Figure 2a and 2b. However, at higher frequencies such as 150 and 220 GHz, T_B first increases and then decreases with respect to RES. This is because when ice particle size is large compared with the wavelength, the scattering is mainly in a forward direction and hence energy scattered toward the ground is reduced. In general, the presence of large ice particles causes positive bias in measured brightness temperature. As expected for a specified LWP, the brightness temperature varies as a function of RES. These calculations assume a constant ice

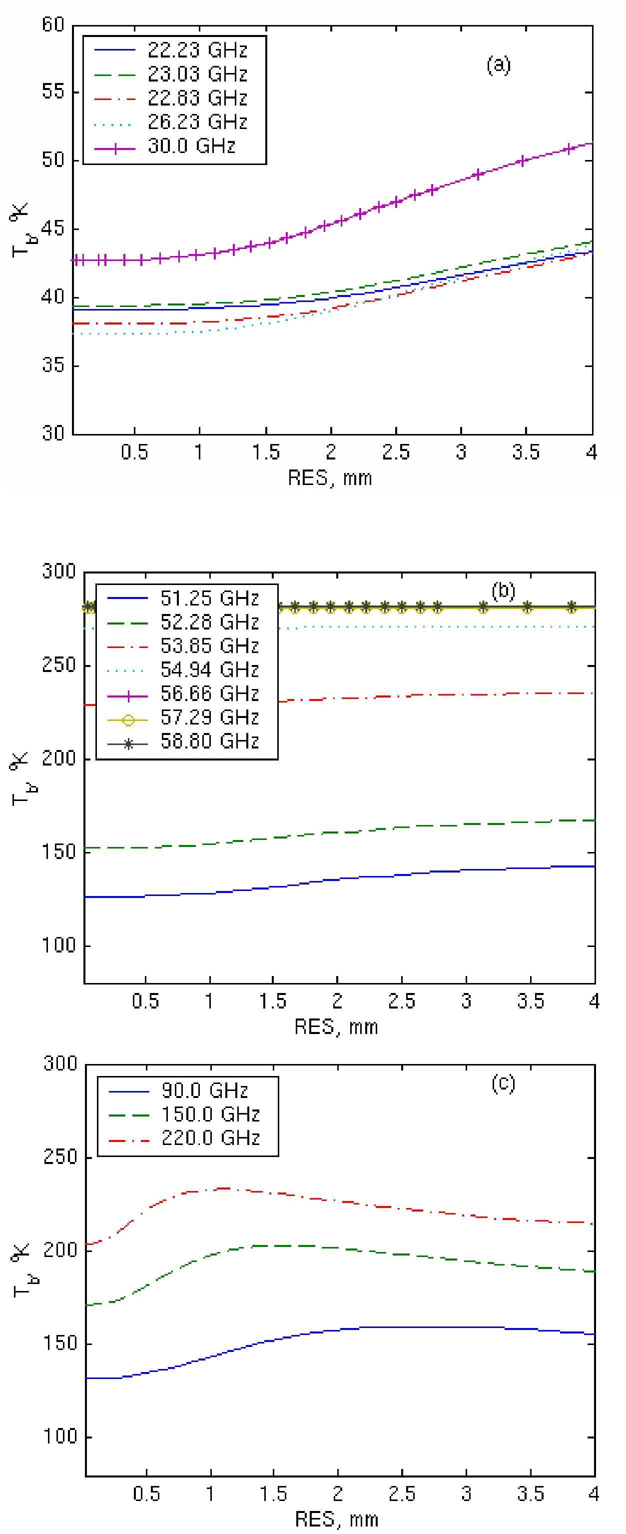

Figure 2. Downwelling brightness temperature as a function of RES. Parameters used in calculation are: LWP = 0.5mm, IWP = 0.5 mm, and droplet RES = 0.14 mm. RES of ice is varied between 0.01 and 3 mm. a) K-, b) V-band and c) higher frequency channels.

particle density. For a specified IWP, mean density of particles is inversely proportional to size (Vivekanandan et al., 1991). Thus it might be sufficient to retrieve mean size or density of the ice particles when IWP is estimated.

5. SUMMARY AND DISCUSSIONS

The model calculation shows that both K- and V-band channels of the TP/WVP-3000 radiometer are sensitive to IWP and ice particle size. A parameterized radiation transfer model is used to calculate the downwelling microwave radiation. It is assumed that the size of liquid cloud drops is much smaller than the wavelength and do not scatter the radiation significantly. Ice scattering introduces a positive bias on T_B that increases with frequency; ice particle sizes larger than 1 mm might increase the bias by a factor of two or higher. Model calculations suggest that the retrieved in-cloud temperature and vapor profiles would be biased higher as a result of ice scattering. To identify a scattering effect due to ice particles on retrieval of vapor and temperature profiles, additional brightness temperature measurements at higher frequencies such as 90, 150 or 220 GHz would be useful. The quantitative effect of scattering on retrieved vapor and temperature profiles will be considered for future work, as well as algorithms based on the higher frequency channels to minimize the effect.

ACKNOWLEDGEMENT

This paper is produced under the NASA SBIR contract 99-01.03 (NAS3-01005). Portions of this research were sponsored by the National Science Foundation through an interagency agreement in response to requirements and funding by the Federal Aviation Administration's Aviation Weather Research Program. The views expressed are those of the authors and do not necessarily represent the official policy or position of the U.S. Government.

REFERENCES

Cober, S.C., G.A. Isaac, A.V. Korolev and J.W. Strapp, 2001: Assessing cloud phase conditions. *J. Appl. Meteor.,* **40**, 1967-1983.

Li, L., J. Vivekanandan, C. Chan, and L. Tsang, 1997: Radiometric technique to retrieve vapor, liquid and ice, Part I - Development of a neural network-based inversion method. *IEEE Trans on GRS*, **35**, No. 2, pp. 224-236.

Solheim, F., Godwin, J., Westwater, E., Han, Y., Keihm, S., Marsh, K., and Ware, R., 1998: Radiometric profiling of temperature, water vapor and liquid water using various inversion methods. *Radio Sci*, **33**, 393-404.

Stephens, G. L., 1976: The transfer of radiation through vertically non-uniform stratocumulus water clouds. *Contrib. Atmos. Phys*., **49**, pp. 237-253.

Vivekanandan, J., J. Turk, and V.N. Bringi, 1991: Ice water path estimation and characterization using passive microwave radiometry. *Applied Meteor*., **30**, No. 10, pp. 1047-1421.

Vivekanandan, J., G. Zhang, M.K. Politovich, 2001: Estimates of droplet size and liquid water content using dual-frequency radar measurements for aircraft icing detection. *J. Atmos. Ocean. Tech*., **18**, No. 11, pp. 1787-1798.

Westwater, E.R., 1993: Ground based microwave remote sensing of meteorological variables. *Atmospheric remote sensing by microwave radiometry*, M. A. Janssen, ed., 145-213.

Zhang, G., and J. Vivekanandan, 1999: Microwave radiation from mixed phase cloud and parameter retrieval. *Proc. IGARSS'99*, Hamburg, Germany. June 28-July 2.