

Radiative Transfer Studies in Support of Improvements to Radiometrics, Inc. Model TP/WVP-3000 Retrievals

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Introduction

This work was motivated by examining temperature retrievals from radiometer measurements in cloudy areas, and noting that they may have been perturbed by mixed-phase precipitation. Our subsequent model simulations suggested microwave brightness temperature measurements are sensitive to scattering due to precipitation-sized hydrometeors, generally those ice crystals and liquid droplets with diameters exceeding ~1 mm. In real clouds, mixed-phase conditions appear to be the norm rather the exception; the relevance of that observation is that ice crystals tend to be present in larger sizes than the accompanying water drops. Thus, in the case of a ground-based instrument, for a specified columnar liquid and vapor content, the brightness temperature is biased higher for these relatively common conditions.

The expected results of this study are: quantification of effects of scattering by ice crystals and raindrops on temperature retrievals by the TP/WVP-3000 and a recommendation as to whether to add an additional, higher-frequency channel to the instrument to improve ground-based remote sensing of atmospheric variables related to inflight icing. These represent improvements over the Level 1 icing remote detection system proposed by NASA GRC, a development needed prior to progression to Level 2.

The tasking under the subcontract is as follows:

1. Radiative transfer studies for single and mixed-phase clouds at 90, 150 and 220 GHz, using the NCAR software with modifications.
2. Analysis of simulation results for quantifying scattering effects on retrieval of liquid, vapor and temperature for the frequencies currently in use by the TP/WVP-3000, and for the potential higher-frequency add-on.
3. Joint analysis of radar, ATEK sonde, aircraft and TP/WVP-3000 datasets obtained during MWISP and the 2001 GRC flight season for estimating improvements to the retrieved TP/WVP-3000 temperature, relative humidity, and liquid water profiles

Radiative Transfer Simulation Results (Tasks 1 and 2)

A conference paper describing a multi-frequency polarization radiometry technique for estimating vapor, liquid water path and detecting mixed phase

cloud based on numerical simulation was presented at International Geoscience and Remote Sensing Symposium in July 2001 (Vivekanandan et al., 2001, attached to this report). This summarized our previous work (under FAA Aviation Weather Research Program funding) on effects of ice and large water droplets on brightness temperature (T_B) measurements. It was shown that differences in T_B at vertical and horizontal polarization may not be useful for detecting mixed-phase cloud. A physically-based method for detecting mixed-phase cloud that uses T_B measurements at 20, 30, and 90 or 150 GHz was described.

Our preliminary model calculations also suggested the T_B measurement at 150 GHz is more sensitive to mixed-phase cloud detection. In the following discussion, scattering effects due to ice particles on TP/WVP-3000 observation are investigated in more detail. Radiation transfer calculations for mixed-phase clouds with specified amounts of vapor, liquid and varying amounts of ice water content and particle size are modeled.

The Radiative Transfer Model: A Brief Description

The vector radiation transfer model determines the physical characteristics of radiation diffusely scattered, absorbed and emitted by the atmosphere. The atmosphere is assumed to be plane parallel, i.e., atmospheric properties are represented by a 1-D vertical profile and homogeneity in the horizontal plane is implied. Multi-frequency and polarized radiation can be used to infer properties of the atmosphere. The radiation transfer model considered in this study takes into account absorption and emission by gaseous water vapor and oxygen and scattering by liquid water and solid ice, the major constituents present in Earth's atmosphere affecting the microwave radiation. In a plane-parallel atmosphere, interaction of radiation with atmosphere can be described using the following first-order inhomogeneous differential equation:

$$\mu \frac{d\mathbf{I}(\tau, \mu)}{d\tau} = \mathbf{I}(\tau, \mu) - \frac{\omega}{2} \int_{-1}^1 \mathbf{P}(\tau, \mu, \mu') \mathbf{I}(\tau, \mu, \mu') d\mu' + (1 - \omega) \mathbf{B}(\tau)$$

where μ is the cosine of the zenith angle, τ is the optical depth, and ω_0 and \mathbf{P} are the single scattering albedo and phase matrix respectively. The vector \mathbf{I} represents the Stokes parameters describing the state of polarization of radiation and \mathbf{B} is the un-polarized thermal emission. The optical depth τ is the integrated total extinction in the medium, extinction being the sum of both absorption and scattering. The single scattering albedo ω_0 is the ratio of scattering to extinction. The phase matrix describes the angular scattering and the resultant polarization state. Mie scattering phase calculations are used for obtaining the phase matrix.

The above radiation transfer equation is solved using the invariant embedding method. 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.

Simulation Results for Quantifying Scattering Effects on TP/WVP-3000 Channels

A combination of brightness temperatures (T_B) at K (20 to 30 GHz) and V-band (50 to 60 GHz) is used to profile water vapor and temperature. A neural network-based profiler retrieval algorithm uses brightness temperatures at 12 discrete frequencies. A radiation model that includes emission and scattering of a cloud structure is used for simulating T_B at various frequencies. 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 or 0.1 g m^{-3} throughout a 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 lapse rate is $6.5^\circ \text{ km}^{-1}$ and temperature of the lower cloud boundary is 270 K. The shapes of liquid and ice particles are spherical and the density of ice 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 is 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.

Sensitivity to IWP

Figure 1 shows T_B as a function of IWP for K- and V-band frequencies, which are primarily sensitive to water vapor and oxygen, respectively. As the IWP increases, the downwelling radiation is biased high. The amount of bias varies between 0.5 and 1K. The bias at 30 GHz is twice as high as 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 T_B 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 effect on higher frequency V-band channels.

a. K-band

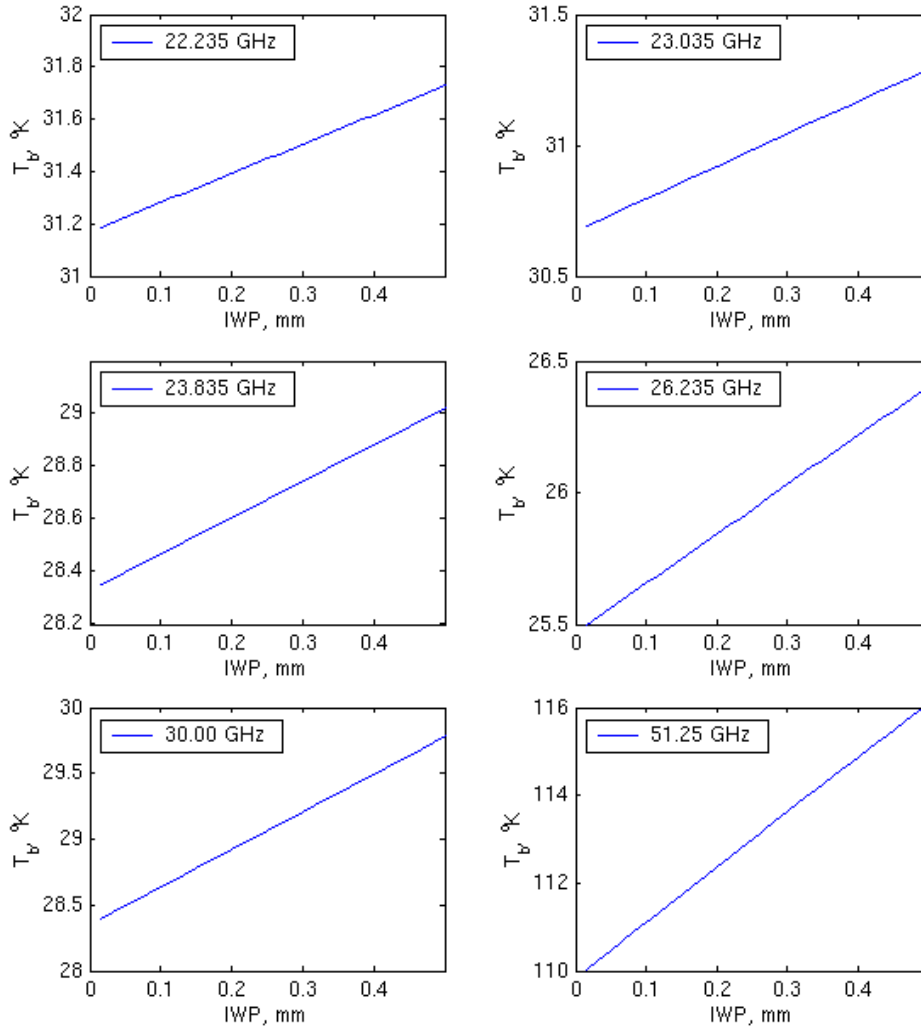


Figure 1a. Effect of scattering due to ice on downwelling brightness temperature at K- band frequencies. Brightness temperature emitted from a three-layer cloud (liquid, mixed phase, and ice) is calculated using a rigorous radiation transfer model that includes emission and scattering. Parameters used 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.

b. V-Band

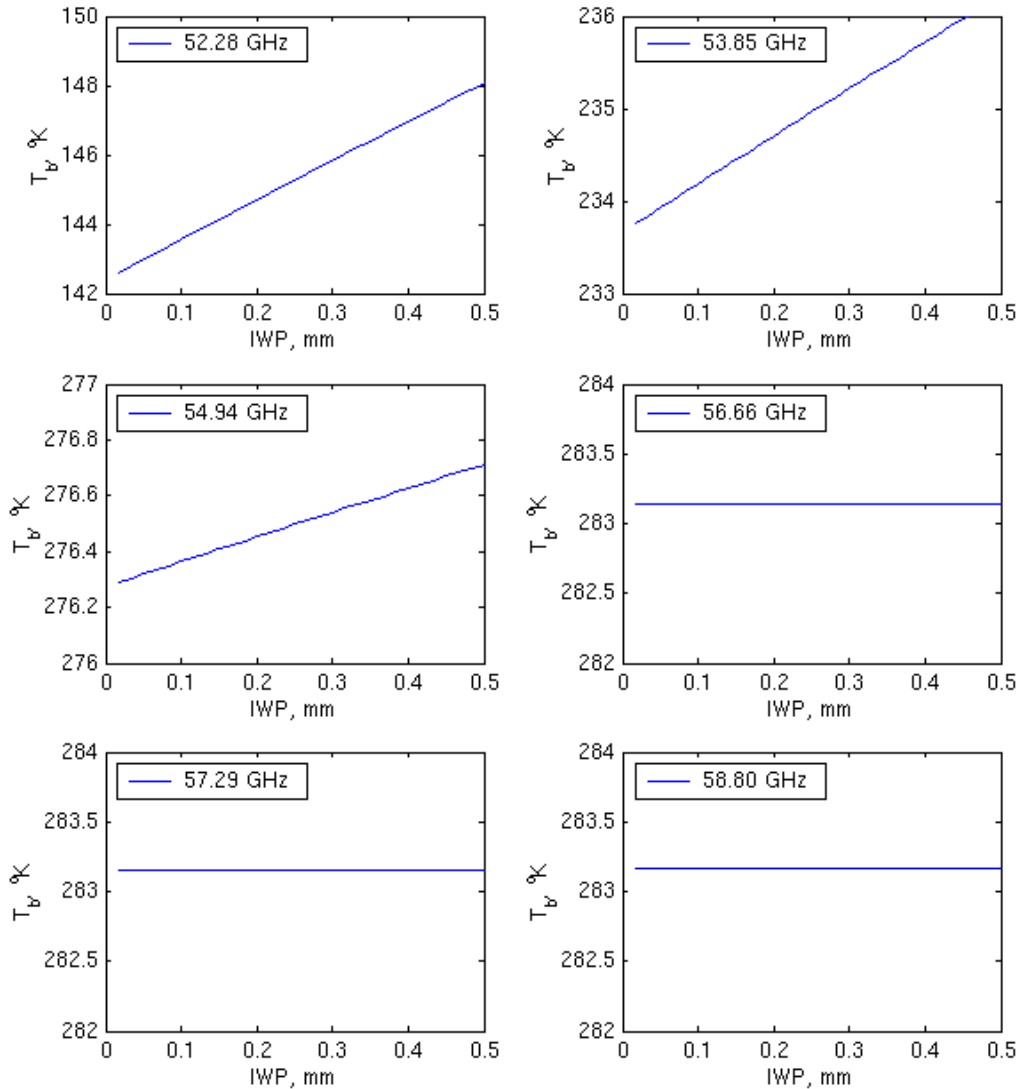


Figure 1B. As for Figure 1a, except at V-band frequencies.

Sensitivity to Particle 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 radar-estimated size (RES) is defined as the cube root of the 6th and 3rd moment size distribution ratio. 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- 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. In general, for a liquid cloud with maximum particle size smaller than the radar wavelength, RES is greater than or equal to the median volume diameter. The bias on T_B is sensitive to particle size at both bands only for RES exceeding ~ 1 mm. The scattering-induced T_B could increase by more than a factor of 2 at larger RES.

a. K-band

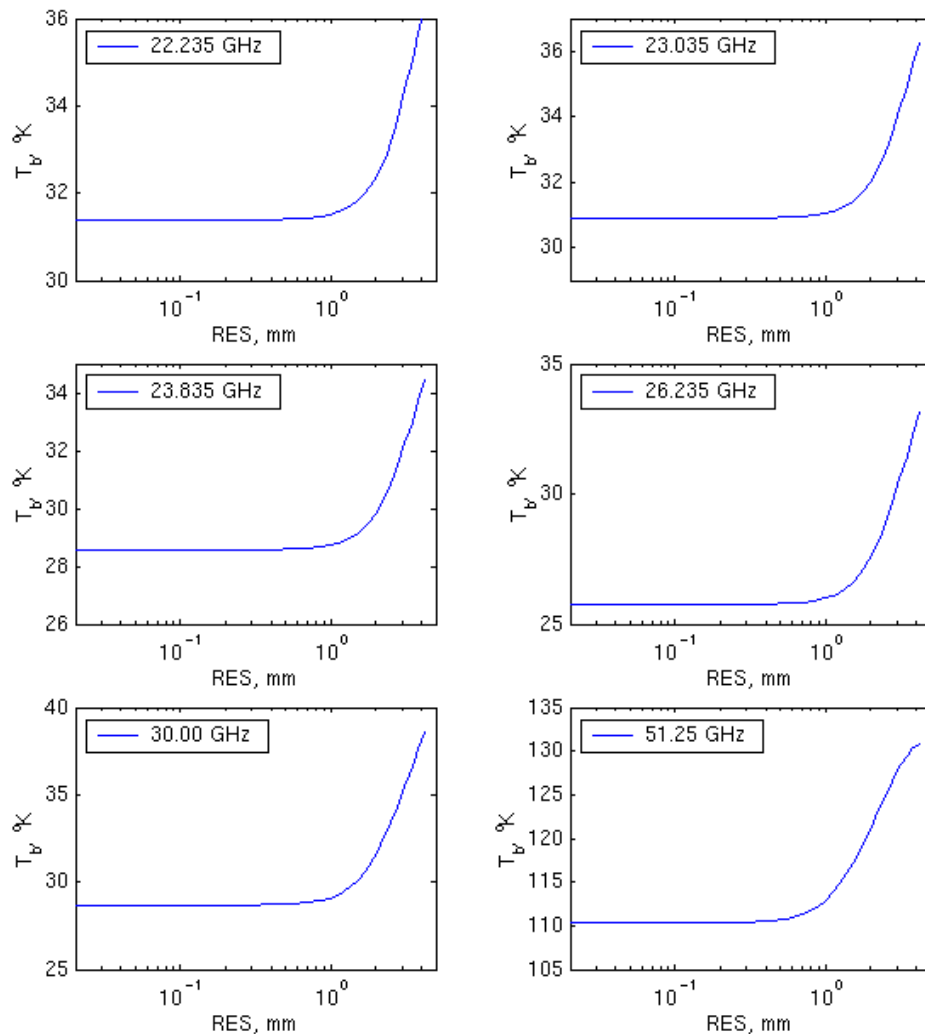


Figure 2a. Effect of scattering due to ice on downwelling brightness temperature at K-band frequencies. Parameters used in calculation are: LWP = 0.5mm, IWP = 0.5 mm, and drople RES = 0.14 mm. RES of ice is varied between 0.01 and 3 mm.

b. V-band

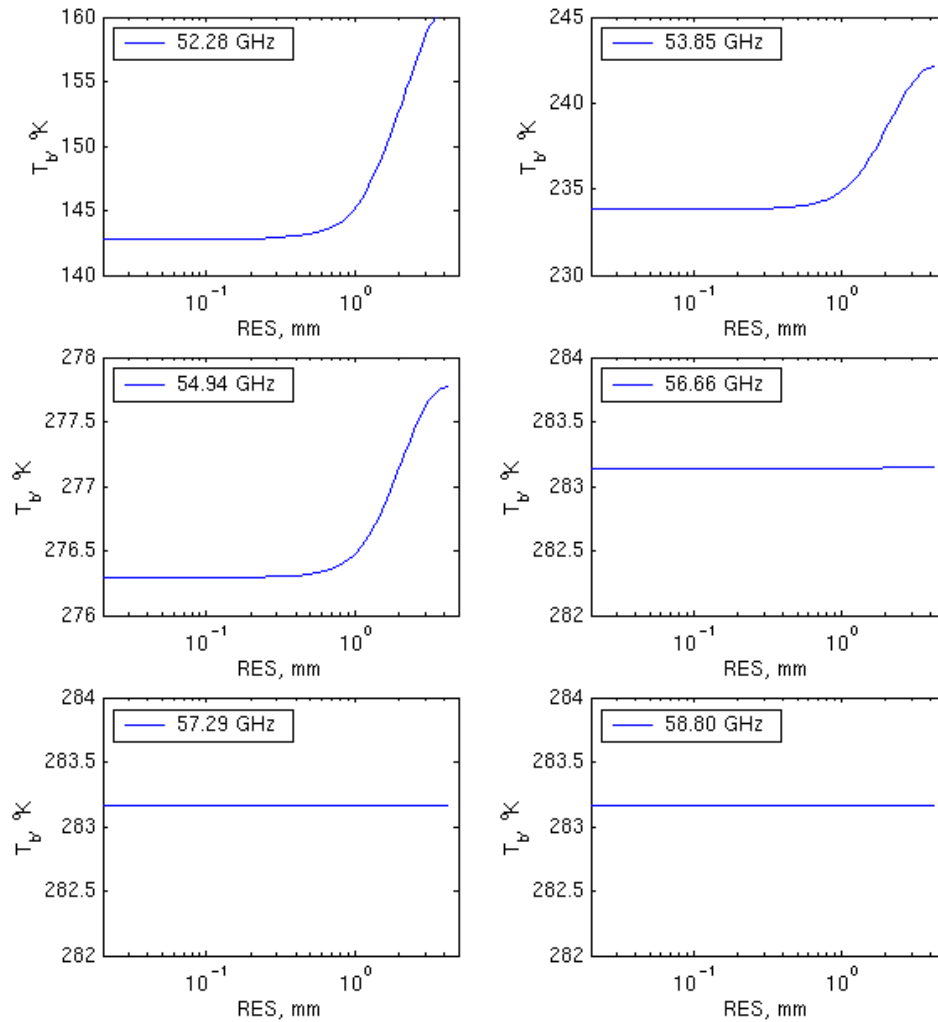


Figure 2b. As for Figure 2a, except for V-band frequencies.

Summary

The model calculation shows that both K- and V-band channels of TP/WVP-3000 are sensitive to IWP and ice particle size. It is assumed that the size of cloud drops is much smaller than the wavelength and do not scatter the radiation significantly. Ice scattering introduces 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 in-cloud temperature and vapor profiles would be biased higher as a result of ice scattering. The effect of scattering on retrieved vapor and temperature profiles will be considered for future work.

Comparisons of Radiometrics 3000 Retrievals to Other Data Sets (Task 3)

A total of 13 radiometer – ATEK sonde or aircraft comparisons are available from Lorain County Airport (LPR) in late February and early March 2001. Table 1 lists the dates and times for which there are comparison data sets. This is not a very good comparison data set for liquid water profiles. Most of the clouds are thin and have very low LWC (and ILW) values. However, even with these cases we feel we can come to some conclusions and put forth recommendations for future work. (Note that data from case 2 were not used; the ATEK data look suspect.)

Table 1: Dates and Times of Data Sets Used in the Analyses

Case	Date	Radiometer	Time (UTC)			METARs
			ATEK	Aircraft	RUC/IIDA	
1	16 Feb	2209:13	2200			2153
2	22 Feb	1406:25	1406			1353
3	22 Feb	1635:46	1634			1553
4	22 Feb	2117:02	2114			2053
5	23 Feb	1358:04	1402			--
6	26 Feb	1450:40	1501			1453
7	1 Mar	2204:45	2204			2153
8	2 Mar	1549:18	1552			1553
A	22 Feb	1456:44		1455 -1509	1500	1453
B	23 Feb	1338:15		1330 -1335	1300	--
C	26 Feb	1500:33		1453 -1457	1500	1453
D	2 Mar	1340:32		1333 -1346	1400	1353
E	2 Mar	1539:22		1522 -1530	1500	1453

Data sources include:

- Radiometrics TP/WVP-3000, recently purchased by NASA GRC
- ATEK liquid water measurement devices which provide high-resolution measurements of supercooled (only) liquid water content
- NASA Glenn Research Center Instrumented Twin Otter research aircraft (a reverse-flow temperature probe was used for temperature measurements, and a forward-scattering spectrometer probe was used for liquid water content measurements corrected for airspeed, etc., measurements were recorded every second)
- 40-km RUC2, which has hourly output
- Integrated Icing Diagnosis Algorithm (IIDA) icing potential field (from 0 to 1, where 0 is no icing potential, 1 is certain icing) to indicate where icing and thus supercooled liquid water -- is expected
- Surface weather reports (METARS) from the ASOS at Lorain County Airport (LPR) reported at 53 min after the hour

Surface T and RH and ILW Comparisons

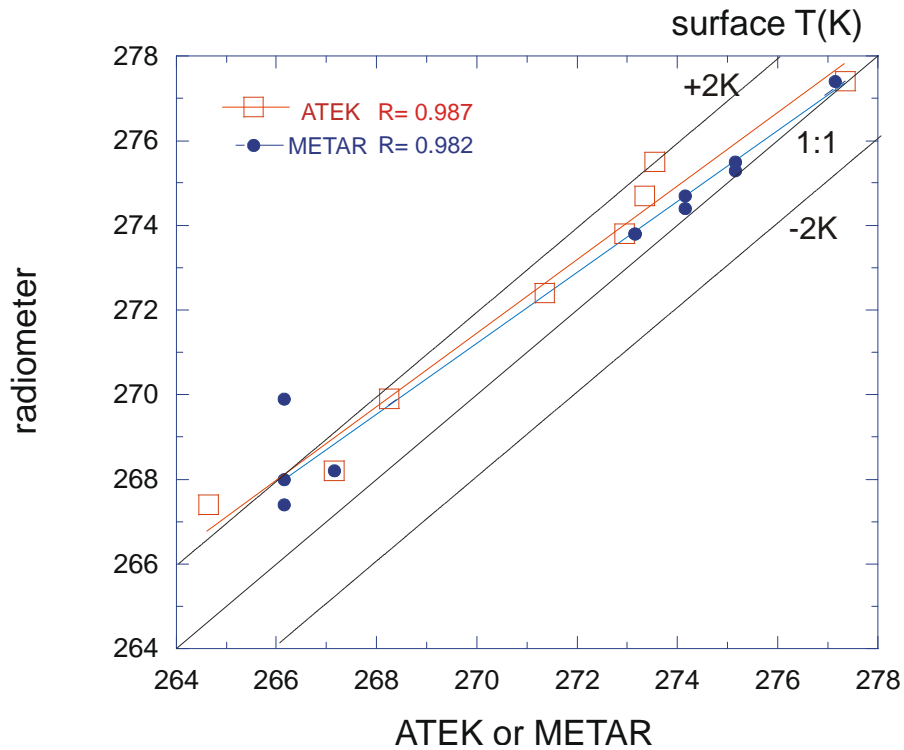


Figure 3: Surface temperature (T_{sfc}) comparison for the radiometer, ATEK sondes and METARs. Best-fit lines and correlation coefficients between the radiometer and ATEK or METARs are as indicated. The solid black line is the 1:1 correspondence; the dashed lines are $\pm 2K$.

Temperature: (Note that this is a direct measurement, not a radiometer retrieval.) The surface values are in fairly good agreement (Figure 3) although there seems to be a warm bias of 1-2K at the lower temperatures. All but two of the comparisons are within 2K of each other. Three of the surface temperature points were at $T > 273K$ (above freezing), the warmest was just over 277K. Thus, ILW from all the soundings should be below freezing assuming temperatures were consistently decreasing with height and cloud base was high enough to reach 273K. The surface temperatures appear reasonable; if assumptions about temperature aloft are made using lapse rates, etc. starting at the surface, it looks like the surface values should not produce significant errors.

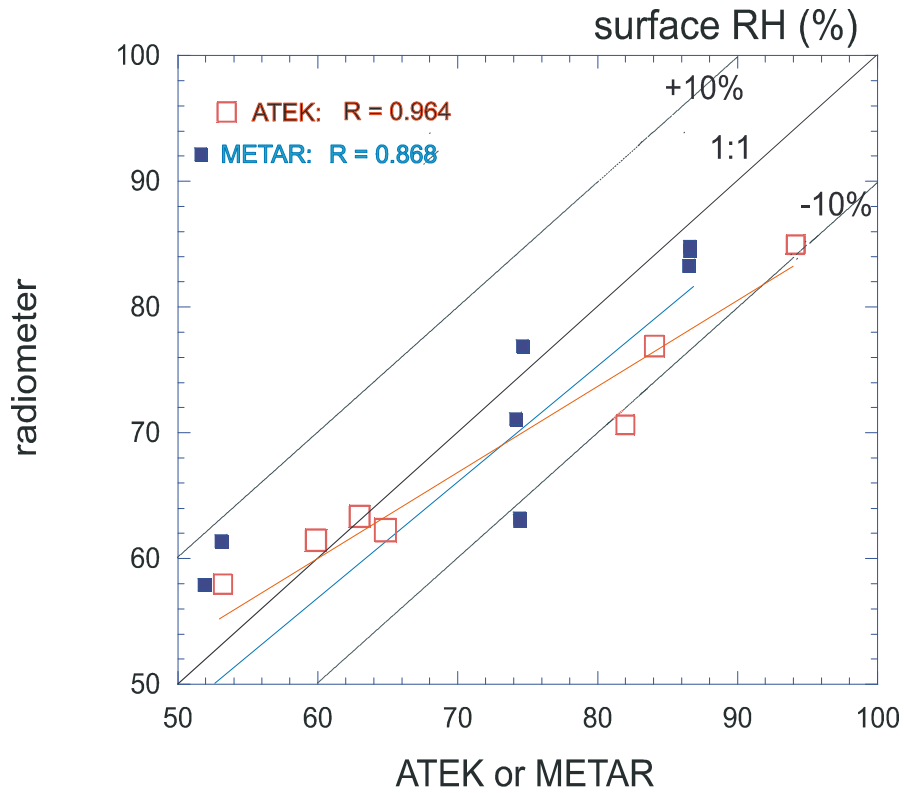


Figure 4: Surface relative humidity (RH_{sfc}) comparison from the radiometer, ATEK sondes and METARs. Best-fit lines and correlation coefficients are as indicated. The solid black line is the 1:1 correspondence; the dashed lines are $\pm 10\%$.

RH: (This is a also direct measurement, not a radiometer retrieval.) There is a good range of RH from just over 50% to 94% and all but two of the points have RH within 10% of each other (Figure 4). There is a slight low (dry) bias from the surface measurement from the radiometer at the higher RH.

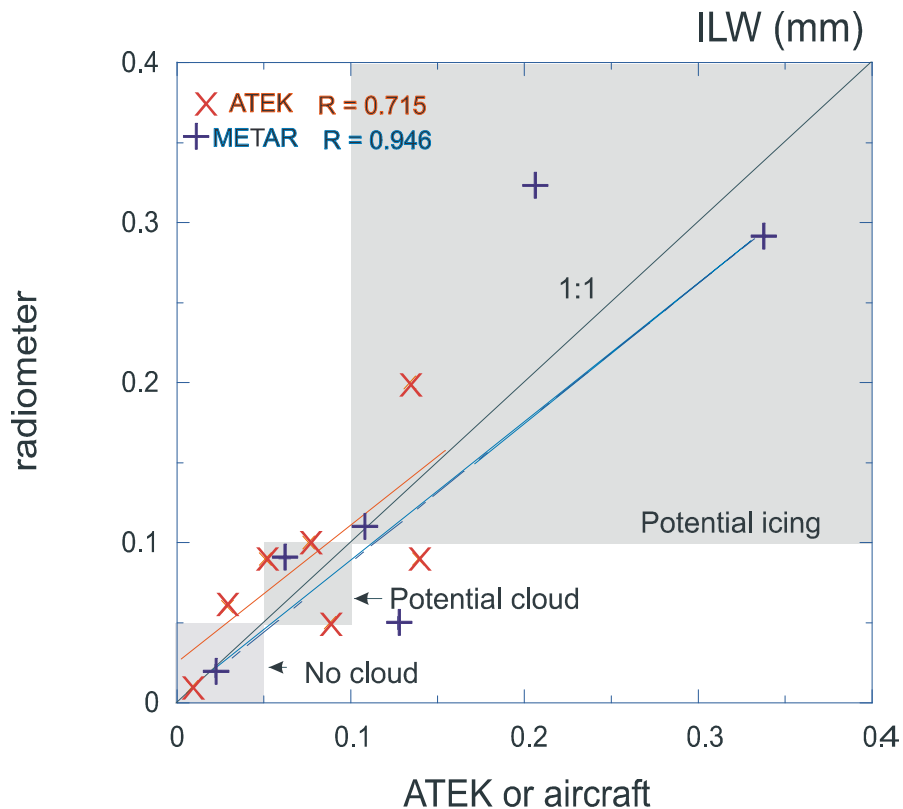


Figure 5: ILW from the radiometer and ATEK sondes. The radiometer ILW is retrieved from the K-band T_B ; the ATEK ILW is integrated from the LWC measurements during ascent. Best-fit linear relations and correlation coefficients are as indicated. The solid black line is the 1:1 correspondence.

ILW: This is obtained from the K-band radiometer retrieval or from integration of the measured liquid from the ATEK sonde. Most of the aircraft measurements were within ~10 km of LPR; the sonde positions are dependent on wind speeds aloft. There is considerable scatter in the ATEK comparison ($R = .72$, see Figure 5), but no real bias. The aircraft measurements have better agreement which is surprising since they don't include possible higher clouds. Two data points have both measurements <0.05 mm, which ETL considers the noise floor of their radiometer (labeled "no cloud"). Four points has both measurements >0.1 mm (labeled "potential icing"), which based on [Popa Fotino et al. \(1986\)](#) could be considered an "icing threshold". Four points lie between 0.05 and 0.1 mm, which suggests cloud but perhaps not an icing situation aloft ("potential cloud").

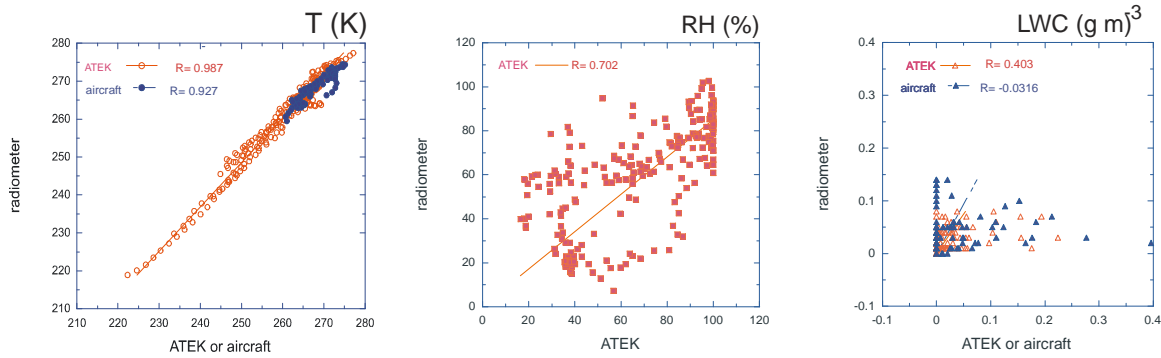


Figure 6: Temperature, RH and LWC comparisons between the radiometer retrievals and the *in situ* ATEK and aircraft measurements. ATEK and aircraft measurements were averaged on vertical scales matching those of the radiometer retrievals. Best-fit lines are shown with their correlation coefficients. The two diagonal black lines on the temperature plot are ± 1 K.

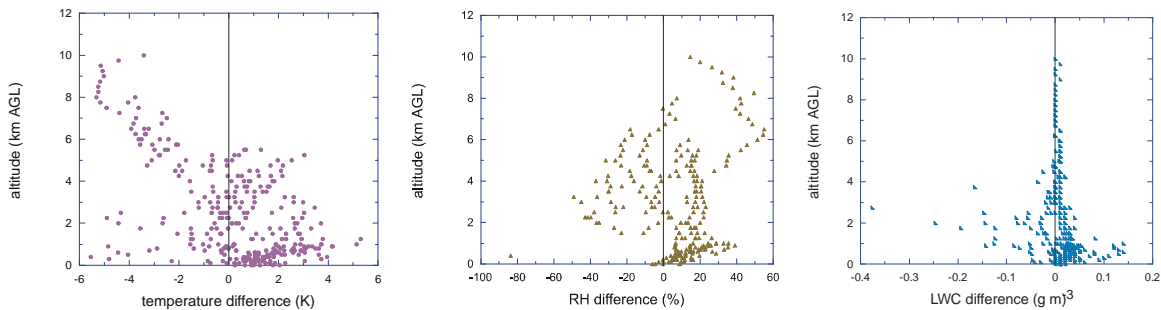


Figure 7: Differences in temperature, RH and LWC as a function of height agl. The difference is defined as the radiometer retrieved value minus the *in situ* value. Aircraft and ATEK data are not differentiated in these plots.

Temperature measurements show generally good agreement; 115 out of the 310 data points are within 2K of one another. The retrieved temperatures tend to be higher than the *in situ* measurements at lower (<~5 km AGL) altitudes and lower at higher altitudes. There is no evidence of a warm temperature bias that might be due to ice in clouds. RH shows poor agreement between sonde and retrieved values. There is no real trend with altitude; one sounding has the retrieval very moist compared to the sonde measurements; and several are too dry at mid-levels (~2-6 km AGL). ILW has also poor agreement between the retrievals and values from sondes or aircraft. The most extreme differences are negative; the radiometer is not catching peaks in the liquid water in clouds, even at the 100- or 250-m resolution shown here.

Comparisons With Aircraft Data

For these comparisons the aircraft performed missed approaches to Lorain County Airport then climbed to a predetermined altitude (based either on knowledge of cloud top or air traffic directions). Data are 1-s values, which at an airspeed of $\sim 80 \text{ ms}^{-1}$, gives about 80-m horizontal resolution. Climb rates are variable, and some data were available during descent. Most of the data are

within 10 km of the radiometer (Figure 7). Values of RH versus height from the radiometer were not available for these cases so the comparisons are limited to temperature and liquid water content.

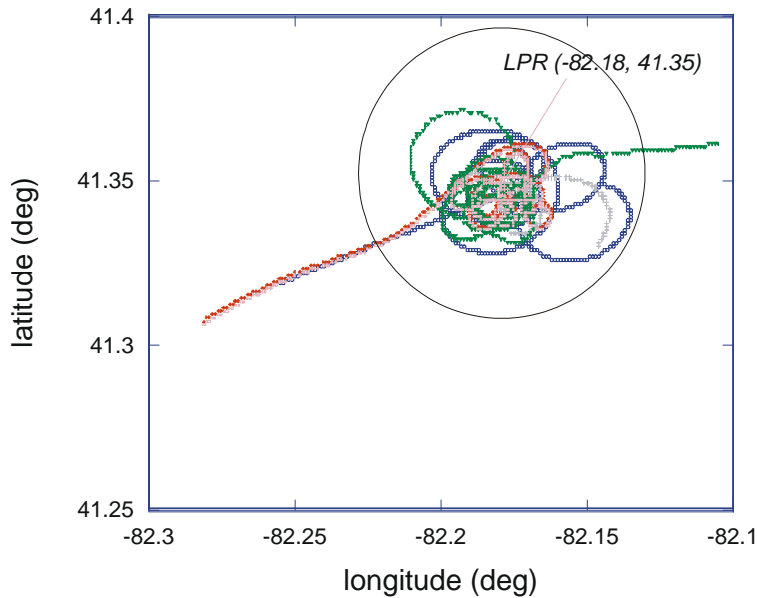


Figure 8: Locations of measurements from the Twin Otter used in these comparisons. The circle is a radius of ~5 nmi or ~10 km around LPR. Colors indicate cases: A, B, C, D, E.

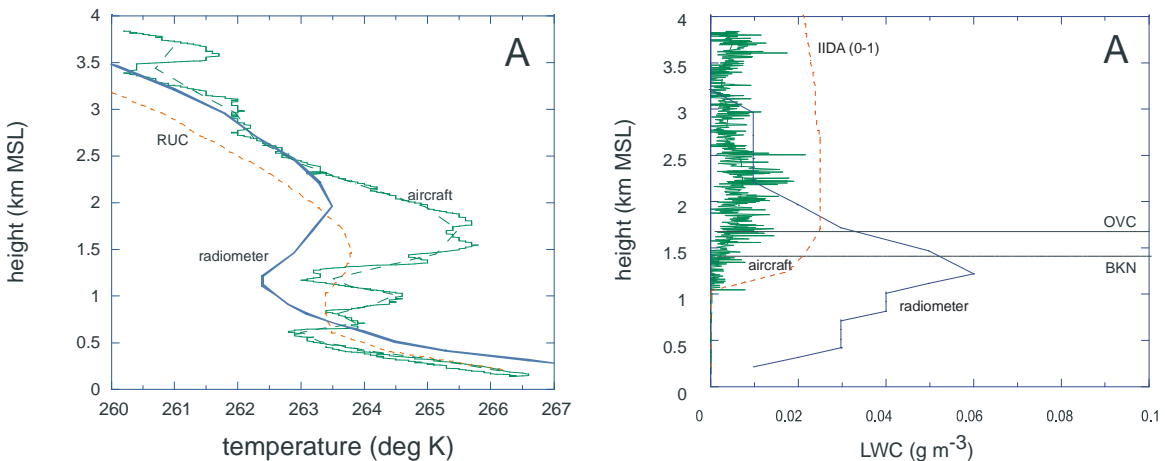


Figure 9: Temperature and LWC profiles from the aircraft, radiometer, and RUC model output or IIDA for Case A (Table 1). Note that the IIDA is a 0-1 scale of icing likelihood, with 0=no icing, 1=icing present. LPR METAR ceiling (BKN = broken, OVC = overcast) is also shown. Both the “raw” (solid line) and averaged (dashed line) aircraft data are shown.

Case A: The Twin Otter ascended to just above 2 km MSL after its missed approach to Lorain County Airport. The temperature structure was somewhat complex with multiple inversions (Figure 9), the largest of which was 2.7°C from

1171 to 1762 m MSL. Temperature began decreasing with height again at 1840 m MSL. The radiometer correctly places the base of the inversion, and gives a reasonable top location, but the retrieved inversion magnitude was not as large, only 0.9°C. Lapse rates above and below the inversion match those from the aircraft fairly well. The RUC model temperature profile, shown as a comparison, places the inversion too low, but does have good lapse rate agreement. The radiometer cloud profile does not match the data well at all; but the cloud was fairly thick with very low liquid water amounts (suggesting noise from the instrument). The IR temperature sensed from the radiometer is 264.4K. Using the retrieved temperature profile this puts the cloud base near 500 m MSL as opposed to the measured cloud base at ~1 km. The IIDA locates the cloud well but only gives an icing potential of ~0.2, which indicates low likelihood of icing conditions. The METAR broken (BKN) and overcast (OVC) ceilings match the aircraft and IIDA clouds reasonably well.

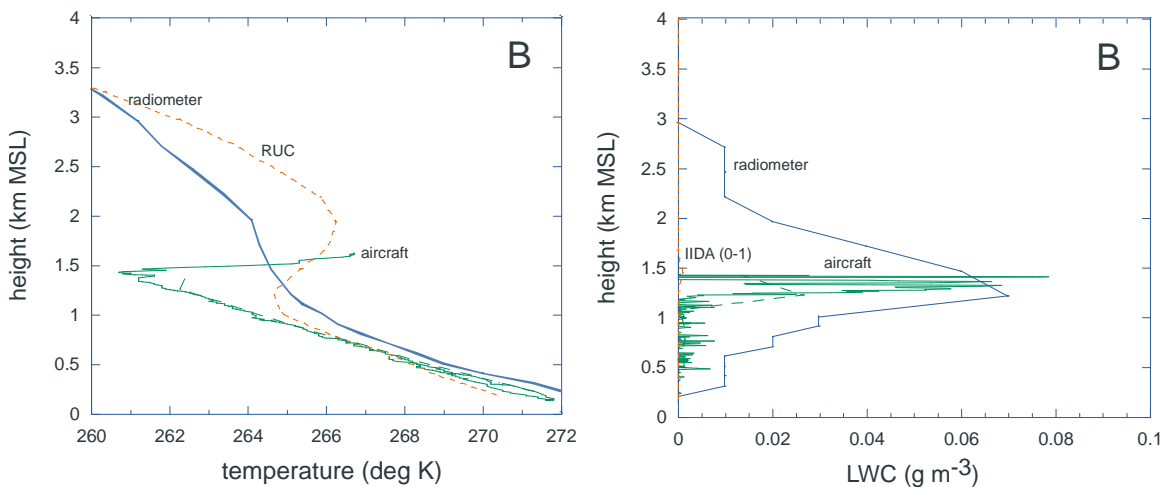


Figure 10: As for Figure 9, for Case B (Table 1).

Case B: The aircraft only climbed to 1.4 km MSL in this case, but did measure a 5.5°C inversion near the top of the ascent (Figure 10). The retrieval shows an inflection at this inversion location, and the retrieved temperature is about 1°C warmer than the aircraft measurements below that. The RUC catches the inversion but smooths it in magnitude and probably in vertical extent.

The cloud was very thin and again had low (maximum <0.1 g m⁻³) liquid water content. The location and value of the maximum LWC are well placed by the radiometer, but again, the prescribed shape is too deep. The IIDA places the icing likelihood as extremely low (just above zero) but in good location. This cloud was not an icing hazard --- it's very thin (< 1000 ft) and has low LWC.

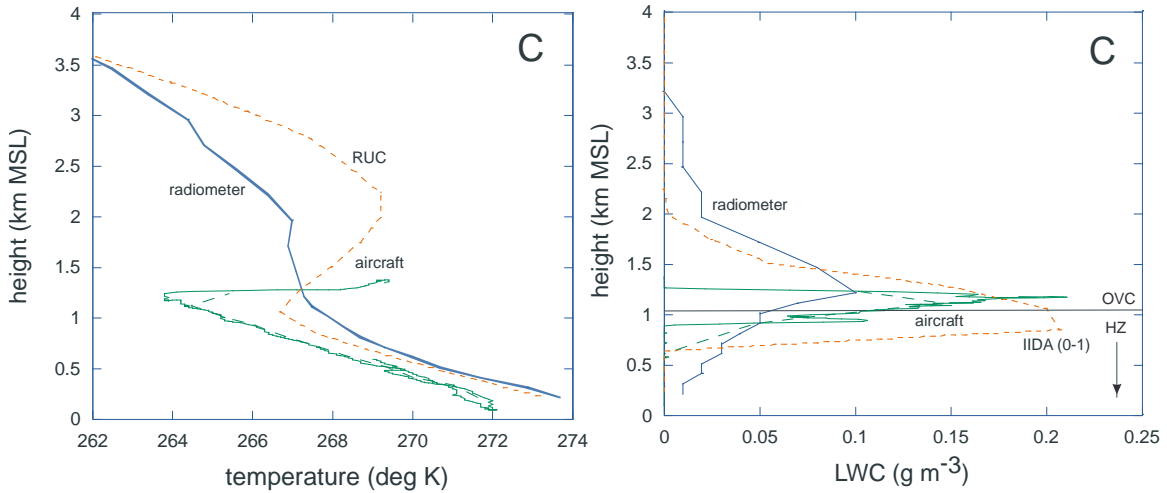


Figure 11: As for Figure 9, for Case C (Table 1).

Case C: The sounding is very much like that for Case B and the radiometer retrieval and RUC behaved similarly as well, placing the inversion base at a reasonable location but smoothing the magnitude and deepening the inversion (Figure 11). Also again, both the radiometer and RUC are warmer than the aircraft measurements. The cloud was in a similar location, with the top just below the inversion, but thicker and with higher liquid water content. The radiometer LWC maximum is in a good location, but is less than the actual LWC maximum (~ 0.1 compared to $\sim 0.2 \text{ g m}^{-3}$). The IIDA has good icing placement with a likelihood value of 0.8, showing high probability of icing conditions. Both the IIDA and radiometer suggest clouds that are too deep, with tops at 2 and 3.2 km MSL, respectively. The METAR ceiling is slightly different than the aircraft-sensed cloud, but the cloud was thin and perhaps variable in height as well. The IIDA cloud base was just below the METAR base, and haze (HZ) was reported at the surface.

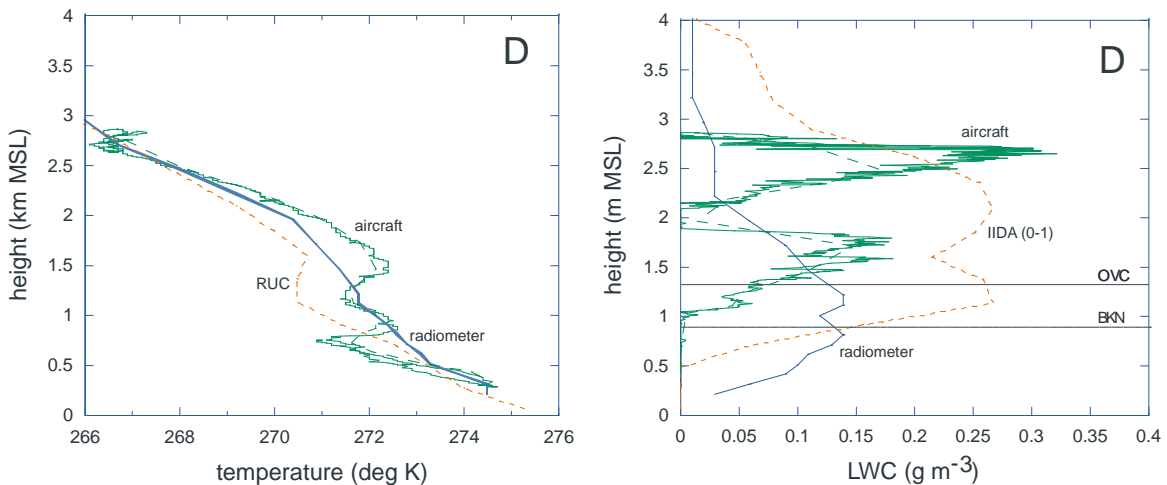


Figure 12: As for Figure 9, for Case D (Table 1).

Case D: For such a complex temperature profile this is probably the best retrieval of the cases involving the Twin Otter. Given the smoothing from both the radiometer and the RUC, the agreement is good. There were two layers of cloud each nearly 1 km thick, with liquid maxima of the lower and upper cloud of $\sim 0.15 \text{ g m}^{-3}$ at 1.5-1.9 km MSL and 0.3 g m^{-3} at 2.6-2.7 km MSL, respectively (Figure 12). The radiometer does a poor job with this two-layer structure; it was apparently trained to produce a single-layer cloud. The IIDA indicates two maxima in icing potential, and both have high values (~ 0.6). However, they are not well placed, with the lower at 1.1 km and the upper at 2.1 km. Still, the overall icing potential covered both layers. The METAR broken ceiling agrees with that from the lowest aircraft-measured layer; the overcast is 400 ft higher.

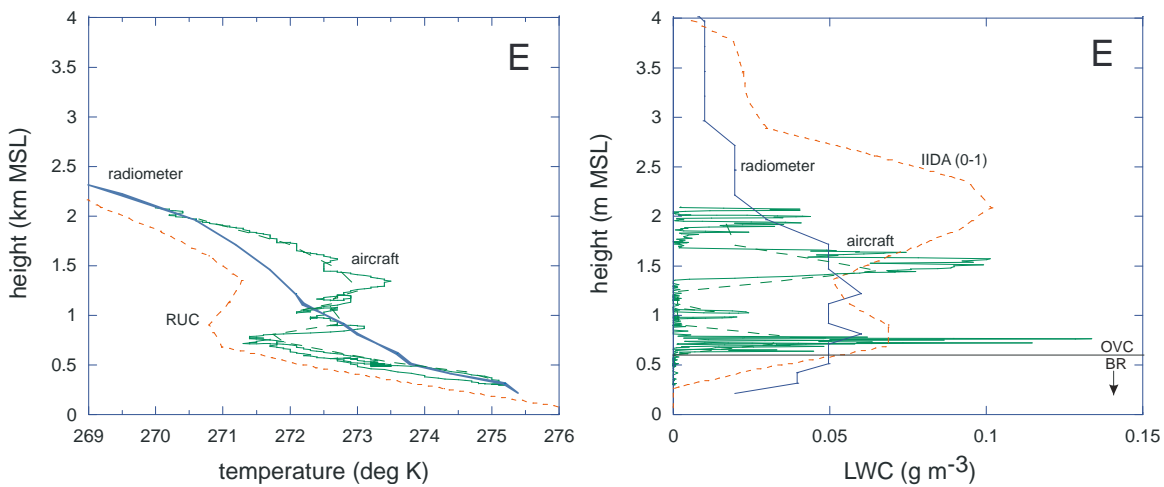


Figure 13: As for Figure 8, for Case E (Table 1).

Case E: This is several hours after Case D and the complex cloud and temperature structures remained, although the clouds have thinned and decreased in LWC considerably (Figure 13). Again, the radiometer and RUC performed reasonably well given the complexity of the temperature structure. The radiometer retrieval covers the measured cloud locations fairly well; the magnitude of the LWC is in fairly good agreement given the smoothing. The IIDA again has a double maximum and those are not well placed --- the upper layer is too high and deep. The METAR cloud base and that from the aircraft are the same. Mist (BR) was observed at the surface. IIDA and the radiometer locate this cloud base fairly well.

Note that an assumption of the inversion marking the cloud top is not always a good one. It works for the lowest, thin cloud layer but not for the more significant layer centered at $\sim 1.5 \text{ km}$. In most of the clouds sampled during WISP in northeastern Colorado, the inversion was at the top of the cloud. However, most of those clouds were upslope stratus, formed in moist westerly flow up the front

range of the Rocky Mountains. They were capped by drier, warmer westerlies. The Cleveland clouds, even these few cases, represent more varied conditions.

Comparison with ATEK Soundings

These comparisons are very similar to those for the aircraft, with the exception of RH being available from the radiometer. Rather than cover every case, we will look in detail at two of the soundings from 22 February (cases 3 and 4, [Table 1](#)). However, observations on the overall collection of retrieved and ATEK soundings are summarized as follows:

- Most of the ATEK soundings included one or more inversions of 1-4K, with some dry layers where dewpoint depression was significant. The significance of the inversions either brightness temperature retrieval or relevance to identifying icing conditions has not yet been investigated. The dry layers, however, are important for determining where icing does not reside.
- Above ~4 km AGL there is generally good agreement between the sonde and the retrieved radiometer temperature lapse rates. Retrieved temperatures tended to be several degrees K cooler than the sonde measurements. The RH retrieval, even at these higher altitudes, is not as good and it's easy to see where the climatological "shape" comes in.
- It looks like the effect of changing the algorithm from the Oct-Dec (10-12 NN) to Jan-Mar (1-3NN) version is to warm and dry the lower levels, and cool and dry the upper levels. The dividing point is around 4-5 km AGL.
- The LWC profiles don't fare as well, although as stated above, this isn't the best data set for comparison. There shouldn't be liquid, even tiny amounts, indicated above ~5 km. Although the amounts there are low, they are deep layers, and in the integration they add up and decrease the amount available for distribution in the lower cloud.

The lowest 5 km of two of the soundings for 22 February were examined in more detail since is where we expect icing to be more prevalent. These were plotted as T, RH, and LWC. The relevant model outputs were also included in the comparison: the T and RH are from the NCEP operational 40-km RUC, and the "ice potential" is from the IIDA. The latter is a number from 0 (no icing) to 1 (certain icing). The scale for ice potential is shown at the tops of the diagrams, Heights in these diagrams are MSL.

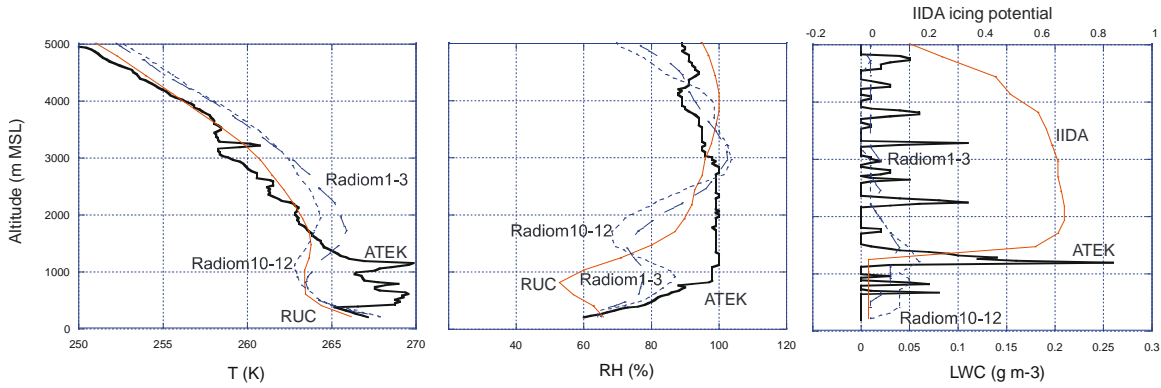


Figure 14: Temperature (T), relative humidity (RH) and liquid water content (LWC) profiles from the radiometer, ATEK sonde, and RUC model output for Case 3 (see Table 1).

At 1634 UTC (Figure 14), the RUC and radiometer miss the warm layer just above the surface, and place it about 1000 m higher. The RUC temperature matches the observation fairly well above 1800 m. The radiometer follows the lapse rate well above that height, but values are 4-5 K too warm.

RH is also confused, RUC handled it better with a shallow dry layer near the surface, but smoothed out the possible cloud area ($RH > \sim 90\%$). The RUC RH was below 90% at 5.8 km; the IIDA icing potential identified icing conditions up to 5.1 km (not on the figure). The sonde RH was $>90\%$ to 4.9 km. The radiometer retrievals placed a dry area right in the middle of the RH-defined cloud. Liquid is again a poor case for comparison. The ATEK sonde had low ILW (0.088 mm). There appears to be patchy clouds through a significant depth, with peaks $0.05 - 0.1 \text{ g m}^{-3}$, and one brief peak at just over 0.25 g m^{-3} . IIDA indicated a deep layer of icing potential but only a maximum of 0.63. The radiometer retrievals are difficult to decipher, mainly because of the lack of a good comparison data set here.

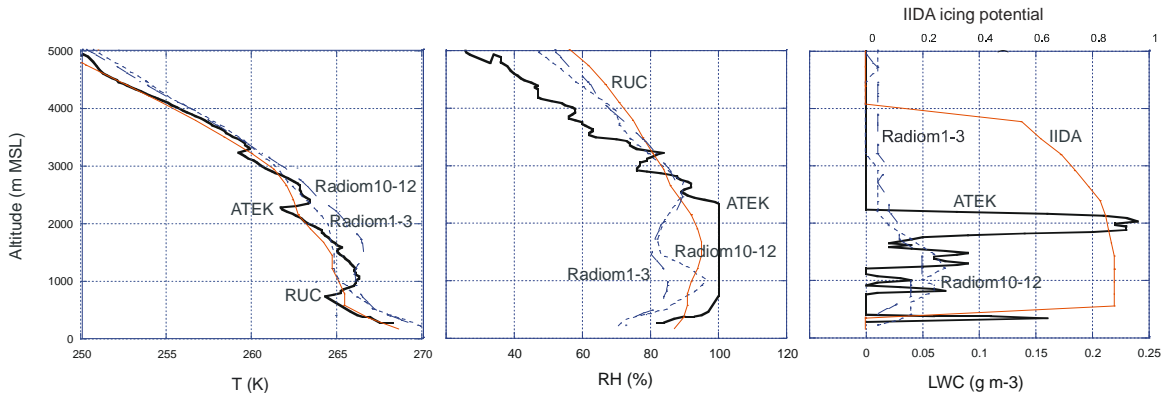


Figure 15: Temperature (T), relative humidity (RH) and liquid water content (LWC) profiles from the radiometer, ATEK sonde, and RUC model output for Case 4 (see Table 1).

The 2114 case ([Figure 15](#)) is the best of the day. Temperature retrievals and model output match the sonde profile well. There are slight differences in shape, and placement of inversions, but for icing these are probably not significant. The RUC RH is smoothed, of course, but handled the high RH from 700 – 2400 m MSL fairly well. It's too moist farther up as are the radiometer retrievals. The radiometer does not well depict the dry layer below cloud. Liquid retrieval from the radiometer is still not a good match to the sonde data, the top and bottom pretty well but that shape is just not very good. The IIDA indicates some icing potential cloud potential higher than the sonde-detected cloud. The actual cloud top would probably reside between ~3200 -- 3800 m, to match the sharp drop in icing potential. With a patchy/scattered cloud situation, it's a difficult comparison case.

Improved Cloud Definition: RH

The neural net approach for producing liquid water profiles has some rather serious shortcomings, which are largely responsible for the poor agreement with observations. The biggest problem is the lack of a training set; soundings of temperature and RH were used and parcels were raised 100 m to produce clouds. That there are no NWS sounding sites at Cleveland (the nearest are Detroit, MI and Buffalo, NY) is another problem. A better method might be to estimate the cloud boundaries -- base and top -- and distribute cloud water vertically according to some rules or observations.

Cloud may be inferred using RH; [Wang and Rossow \(1995\)](#) describe a method that looks for gradients and or high RH layers. If this is applied to the radiometer data, a set of estimated cloud bases and tops is obtained. The ATEK sonde LWC, Lorain County Airport (LPR) hourly METARS and IIDA ice potential can be used as a comparison. We use the IIDA icing potential rather than the RUC RH for this comparison. The IIDA is our best guess at where cloud base resides and includes local METARS and precipitation information from the nearest NEXRAD to obtain this estimate. All cloud bases had temperatures <273K, so the IIDA icing potential-based cloud is an appropriate comparison. This method was applied to cases 1-8 for which we have RH soundings.

The comparisons show considerable variation ([Figure 16](#)). Cloud base heights show the weakest comparisons; with most radiometer RH-based values vastly overestimating the base height. Cloud base temperatures are in good agreement, however, with correlation coefficients nearly unity. Cloud tops fare somewhat better. IIDA probably overestimates cloud top height (and thus underestimates temperature) as it uses a rather conservative approach to determining the cloud top in order to safely warn of possible icing conditions. The ATEK agreement is very good both for height and temperature.

Not all of these clouds are overcast layers, in fact, on 22 February a lower broken cloud layer was present. This brings up the question of how to treat scattered or

broken clouds in a RH-based cloud analysis. There have been comparisons done between observations and soundings to determine what RH levels should be used as threshold definitions for broken and even scattered clouds, and perhaps these should be tried. Also, bear in mind that for the ATEK data, what appears to be vertical layers may just be the result of the sonde going in and out of broken clouds that actually extend through the entire lowest base to highest top altitudes. It may also be possible to use other clues to determine how widespread the cloud deck is, such as the variability in the radiometer IR temperature.

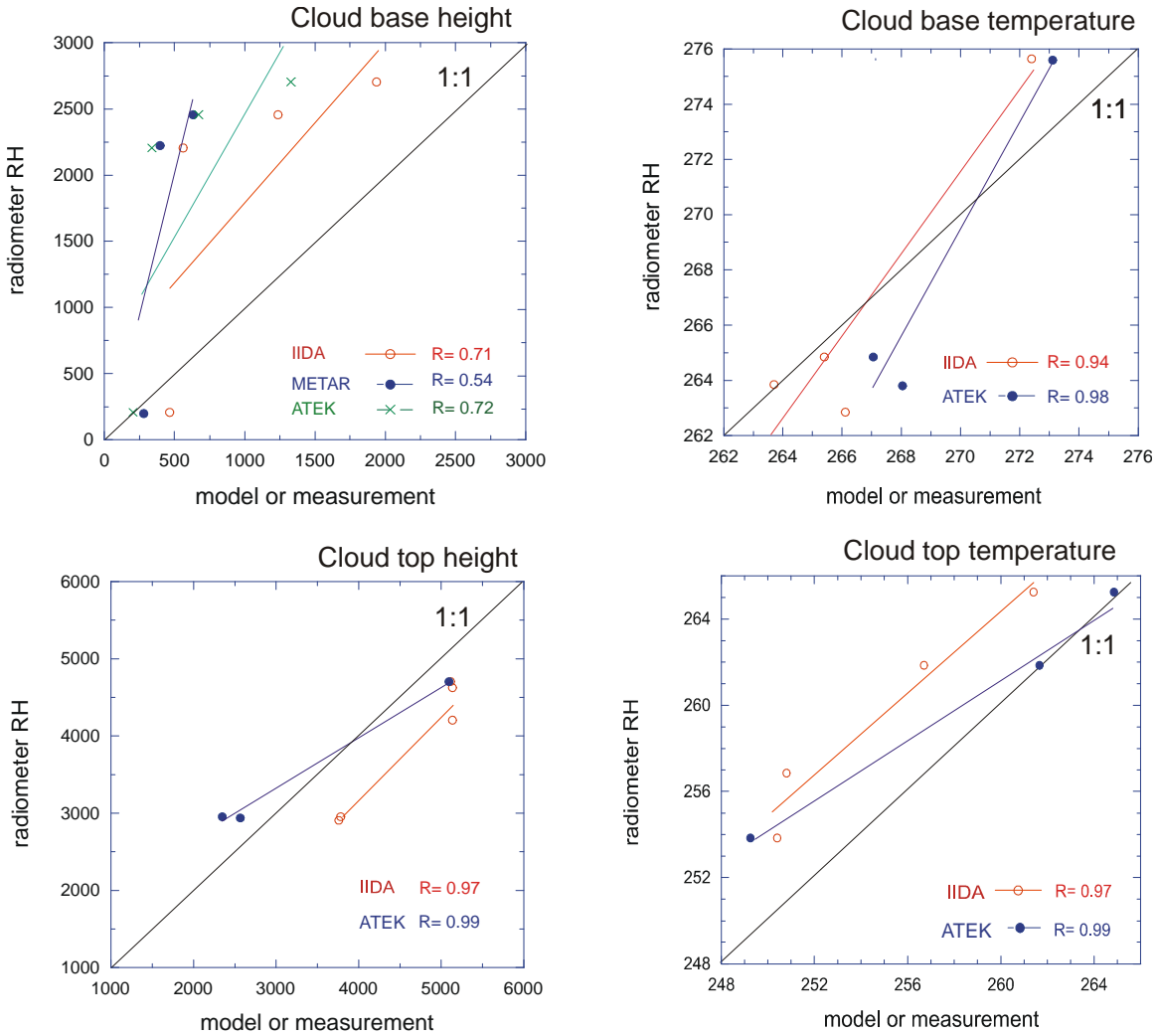


Figure 16: Cloud parameters from the radiometer (using RH estimate for cloud boundaries) ATEK sondes (LWC), and METARS for cases listed in Table 1.

Improved Cloud Definition: IR Temperature

The radiometer has an upward-looking IR temperature sensor that could alternatively be used to determine the temperature of cloud base. This is subsequently converted to height by comparing to the retrieved temperature sounding and using the level just below where the retrieved temperature falls below the IR temperature. Comparisons were made to the IIDA icing potential, the ATEK sonde LWC-determined cloud boundaries (values $> 0 \text{ g m}^{-3}$), and the aircraft data (FSSP $> 0.01 \text{ g m}^{-3}$; case A had very low LWC and was thus not included in this comparison). The height estimation is generally not good; the temperature estimation agrees reasonably well with the measurements and IIDA icing potential-determined cloud (Figure 17). For this set of cases, this technique performs similarly to the RH-based cloud estimation, but, that estimation provides a cloud top. Heights are still a problem but will see improvement as the temperature profile retrievals improve.

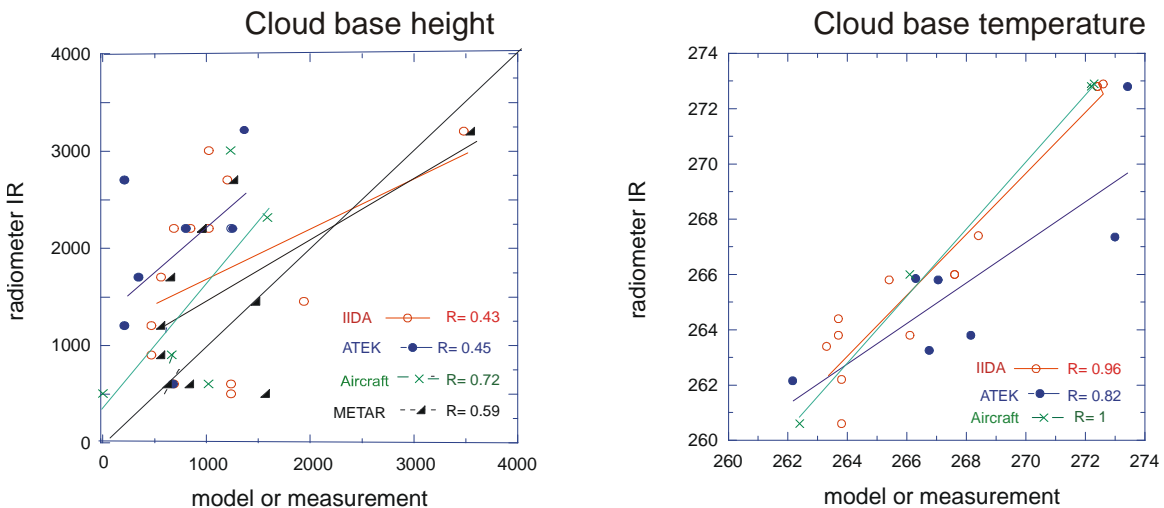


Figure 17: Comparison of cloud base heights and temperatures from the IR measurement on the radiometer and IIDA, ATEK sondes, the aircraft and METARS.

Summary

The retrieved temperature profiles are generally good; most values are within The clouds in these comparisons were generally shallow with low liquid water contents. They do not appear to have enough ice to produce the increases in brightness temperatures discussed in the earlier part of this report.

It should be possible to test various means to define cloud boundaries without using a neural-net approach. The training set for the neural net is poor; NWS soundings from Detroit or Buffalo were used and LWC was estimated by raising each point in the sounding 100 mb to condense a cloud. An alternate method would be to define the cloud by RH. The IR temperature could be used to find

cloud base, but the cloud top must be retrieved by a different means. There are several possibilities. One would be to obtain the satellite IR-sensed cloud top temperature and match that to the radiometer-retrieved temperature sounding much in the same manner as the cloud base is derived from the radiometer IR temperature measurement. However, if higher cloud layers are present these will obscure the lower cloud layer, making one solid cloud through a larger than necessary depth.

Measurements in northeastern Colorado obtained during the Winter Icing and Storms Projects (WISP, see [Rasmussen et al., 1996](#)) suggested that either a temperature inversion or wind shear (change in speed or direction) was a good indicator of cloud top. Those were generally upslope clouds formed in easterly winds, topped by dry westerlies so this concept worked much of the time. However, as is evident in the soundings shown earlier in this report, this is not a good assumption for the clouds sampled over LPR: cloud tops are near, above or below the inversions. A more robust method is needed.

Another possibility is to incorporate model or IIDA input to define the cloud top and base.

These boundaries can then be used to distribute liquid, either in a prescribed shape, or evenly throughout the RH-cloud depth. Or, a probabilistic approach could be employed for icing, by which the probability of encountering a severity category could be assigned to each level. Nearly 100 cloud water vertical profiles have been isolated from the NASA Supercooled Large Drop Research Program and WISP aircraft data sets. These can be used to build statistics on the shape of the cloud profile and the maximum liquid water content given such information as cloud depth, cloud base and top height, cloud base temperature, and liquid water content. These, incorporated perhaps with additional aircraft measurements, could be incorporated into a cloud climatology for liquid water estimation.

Recommendations

Results shown in this report might be the first systematic and independent verification of the radiometer-based retrieval of temperature, humidity, and liquid water profiles. From these studies, we can make the following recommendations for further work:

- These clouds do not appear to contain sufficient ice to cause the warming in temperature retrievals suggested by the radiative transfer simulations of brightness temperatures. Further work is needed to quantify the effects on the soundings, and to define how much ice is needed for this effect to be observed.

- In the best case (see [Figure 15](#)), the temperature profiles are in good agreement with observations. Humidity and LWC profiles are in reasonable agreement with ATEK or aircraft measurements, considering the inherent differences in spatial resolution of ATEK and aircraft point measurements and radiometer volumetric remote sensing. Better retrieval results might be obtained if the training sets were local to the observation site. Cloud vertical boundaries could be defined either by IR temperature, RH, or by importing information from RUC or IIDA. Then cloud liquid water could be assigned in several ways: as a uniform quantity throughout the depth; according to some pre-established profile (which may be altered according to cloud depth, temperature, or other measurable quantity); or, for aircraft icing applications, as a probability of exceeding certain severity thresholds (light, moderate, severe) based on statistics gathered from *in situ* measurements in similar clouds.
- Neural networks have little difficulty to learn forward problem, i.e., obtaining a set of brightness temperatures for a specific temperature, vapor, liquid and ice profile. The neural network used by Radiometrics Inc. is based on simple inversion of the forward model and it is called *explicit* inversion where the roles of inputs and outputs are reversed. The explicit inversion method suffers from one-to-many mapping. As a result, the inverted profile might be an average of many possible solutions ([Li et al., 1997](#)). An iterative inversion method might reduce the above-mentioned ambiguity by converging to a particular solution in the input (atmospheric profile) space, rather than an average over many possible solutions.
- V-band frequencies are less sensitive to temperature changes in the atmosphere layer above 5 km. Thus radiometer-based profiling is applicable only to lower atmosphere.
- TP/WVP-3000 beam widths range between 2 and 5° and hence the instrument may have inherent limitation in resolving finer details of the atmospheric profile.
- Except for three cases, most of the observations analyzed in this report don't correspond to a potentially hazardous icing condition. Clouds are shallow and liquid water contents are quite low ($<0.1 \text{ g m}^{-3}$). Additional data in cases with higher liquid water contents and thicker clouds are needed for a more robust comparison.

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