Comparisons of Cloud Ice Mass Content Retrieved from the Radar-Infrared Radiometer Method with Aircraft Data During the Second International Satellite Cloud Climatology Project Regional Experiment (FIRE-II)

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Introduction

Comparisons of remotely sensed meteorological parameters with in situ direct measurements always present a challenge. Matching sampling volumes is one of the main problems for such comparisons. Aircraft usually collect data when flying along a horizontal leg at a speed of about 100 m/sec (or even greater). The usual sampling time of 5 seconds provides an average horizontal resolution of the order of 500 m. Estimations of vertical profiles of cloud microphysical parameters from aircraft measurements are hampered by sampling a cloud at various altitudes at different times.

Angular resolutions of the National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) K_a-band radar and precision radiation thermometer (PRT)-5 infrared (IR) radiometer used to obtain remotely sensed cloud microphysical parameters are about 0.5° and 2°. This corresponds to a horizontal resolution of about 60 m and 260 m, respectively, at a typical cirrus altitude of 7.5 km. Radar data averaging was performed in this analysis to overcome this difference. The vertical resolution of the remotely sensed profiles of cloud microphysical properties was determined by the 37.5-m transmitted pulse.

The accuracy of aircraft horizontal and vertical coordinates relative to the location of the ground-based instruments was on the order of dozens of meters. This also was contributing to the uncertainty of matching resolution volumes of aircraft and remote instrument sampling. This uncertainty has to be taken into account when making any comparisons between cloud microphysical parameters obtained remotely and in situ from aircraft.

November 26, 1991, was one of the priority cirrus cases during the Second International Satellite Cloud Climatology Project Regional Experiment (FIRE-II) (Uttal et al. 1993). Persistent cirrus cloud was seen over a time period of more than 3 hours. Before 1830 UTC, the cloud was rather tenuous and its IR brightness temperature was rather close to the clear atmosphere background. After 1830 UTC, both the radar and IR radiometer began sensing the cloud more reliably. After about 2130 UTC, the cloud thickened and a substantial amount of liquid water appeared inside it. During these three hours, the National Center for Atomospheric Research's King Air research aircraft equipped with particle measuring instrumentation was flying in the vicinity of the experimental hub where the ETL radar and radiometer were located. This provided an ample opportunity for comparisons of aircraft in situ and ground-based remotely measured data.

Ice Mass Content Data

Remote Sensing Method Data

The remote sensing technique which was used to obtain vertical profiles of cloud ice mass content requires measurements of radar reflectivity and Doppler velocity and IR brightness temperatures in the atmospheric "window" of 10–11.4μm. Doppler velocities are used to estimate particle terminal fall speeds. Brightness temperature measurements are converted to cloud optical thicknesses after accounting for the intervening atmosphere. Both ground-based instruments are pointed vertically. Theoretical details of this method have been given by Matrosov et al. (1992, 1994). When making retrievals here, it was assumed that the effective density ρ of cirrus particles diminishes with particle maximum dimension L (mm):

$$\rho\ (g/cm^3) = 0.1/L$$

This equation is in general accord with results of direct microphysical measurements which showed that mass of typical cirrus particles (L>100 μm) increases approximately as L^2 rather than L^3. It was also assumed in retrievals that particle shapes can be described by prolate spheroids with a major-to-minor aspect ratio of 2.5. Such aspect ratio is consistent with particle 2D images.

The radar-radiometer remote sensing method (Matrosov et al. 1994) uses another a priori parameter in the retrieval algorithm (i.e., the exponent in the particle terminal fall speed-size relationship). The data presented here were obtained assuming this exponent to be 1.3. However, some newer results (Mitchell 1995) show that a lower value of about 1.1 could be more appropriate for cirrus particles.

Figure 1 shows the scatter plot of ice mass content (IMC) values retrieved by the radar-radiometer method and measured radar reflectivities. The presented data show a significant variability. Minimum and maximum retrieved values of IMC were about 0.0001 and 0.35g/m^3 respectively. The minimum measured value of equivalent reflectivity was about -33 dBZ, which is close to the sensitivity threshold of the NOAA ETL K_a–band radar at cirrus cloud altitudes. The solid line shows the best power law regression fit through nearly 16,000 samples. This best fit was obtained with all the samples having the same statistical weight. The reflectivity values in the best fit equations are in mm^6/m^3.

In Situ Aircraft Data

Figure 2 shows the IMC-radar reflectivity scatter plot as measured by the particle measuring system (PMS) aboard the aircraft.

2D-C probe samples were used to infer IMC values and calculate radar reflectivity. The procedures of obtaining particle microphysical information from 2D probes are described by Heymsfield et al. (1990). The in situ data sample volume contained about 1800 points and corresponded in time to the remotely measured data shown in Figure 1 (1830-2130 UTC). The information for each sample point is a 5-second average.

Comparisons of Figures 1 and 2 reveal a general agreement between remotely sensed and in situ data. The power law best fit lines are quite close. However, in situ data are mostly concentrated between 0.01 and 0.1 g/m^3, and remotely sensed data are distributed more

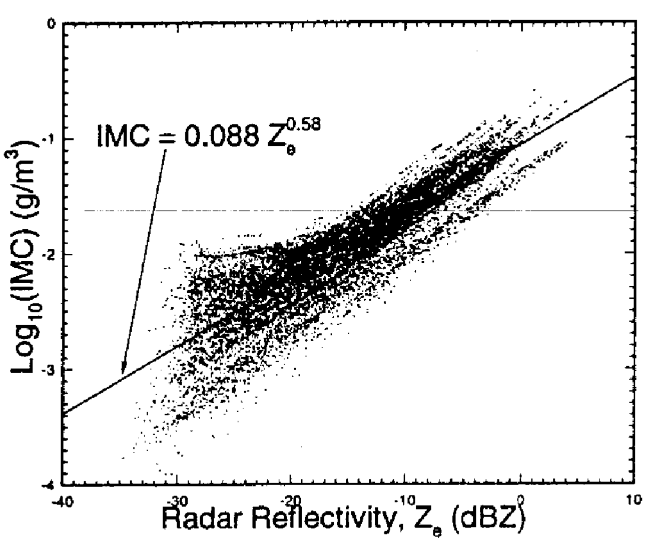

Figure 1. Radar reflectivity-IMC scatter plot for the 26-NOV-91 cirrus case. Remotely sensed data.

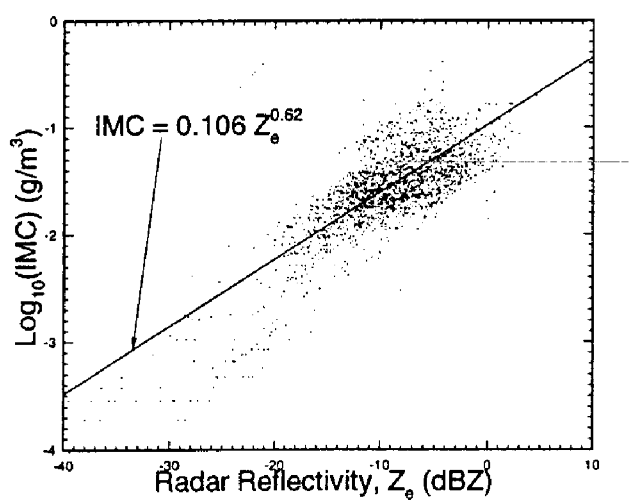

Figure 2. Radar reflectivity-IMC scatter plot for the 26-NOV-91 cirrus case. Aircraft in situ data.

uniformly between 0.001 and 0.1 g/m^3. This should not be considered as a significant discrepancy because, as aircraft coordinates show, most in situ samples were taken dozens of kilometers away from the sampling volumes of the ground-based instruments. This most likely means that the aircraft was sampling cloud volumes with relatively high values of IMC and, hence, higher reflectivities.

Comparisons of Remote and In Situ Data

Most meaningful comparisons were the ones made when the aircraft was passing directly over the ground-based instruments. Dashed lines in Figure 3 show projections of aircraft tracks on the horizontal plane during the time when remote sensing data were collected (1830-2130 UTC). Position (0,0) marks the hub where the radar was located.

Figure 3 shows that the aircraft passed over the (0,0) point just once. However, because of uncertainty in determining aircraft coordinates and exact ground-based instrument location relative to the (0,0) point and also because of limited interest of comparing just one point, the area of direct comparisons should include passes in proximity of the (0,0) point.

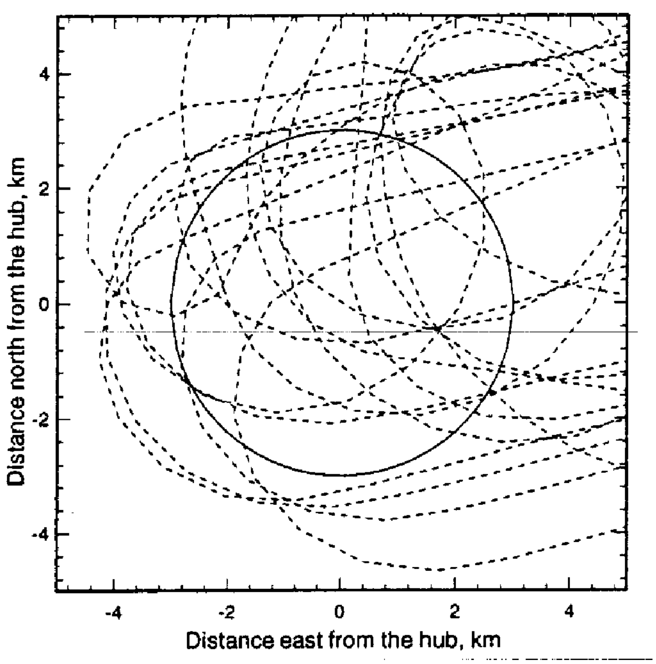

Figure 3. Aircraft flight tracks over the hub.

Another reason for enlarging the comparison area was because of the actual ground separation between the radar and the PRT-5 radiometer (about 800 m). This effect was mitigated by accounting for the cloud advection along the radar-radiometer line.

The solid line in Figure 3 shows the 3-km-radius circle with the center at the (0,0) point. Direct comparisons were made inside this circle. There were 15 aircraft passes into this circle from 1830 to 2130 UTC. Four of them occurred, however, when an intervening low altitude cloud containing liquid water phase prevented measuring the cirrus IR downwelling brightness temperature and, hence, no remotely sensed cirrus data were obtained. During one pass, the radar was performing RHI scans rather than taking data in the vertical mode required for obtaining cloud data remotely. In addition, during one more pass no PMS in situ data were recorded.

All these reasons left only 9 points for direct comparisons when in situ and remote samples were very close both in space and time.

Enlarging the circle radius to increase the number of points for direct comparisons of remotely sensed and in situ IMC values would create a risk in comparing significantly separate cloud volumes. This could lead to wrong conclusions, because, as revealed by both remote and aircraft measurements, IMC and other cloud parameters demonstrated a significant horizontal variability on a scale of few kilometers. Further reducing this radius would result in having too few points for comparisons and make the comparisons not representative.

Figure 4 shows the results of IMC comparisons. The in situ data for each aircraft pass were averaged over the time when the aircraft was inside the 3-km-radius circle. The mean time of each pass is shown near the corresponding comparison point. The one-to-one data correspondence line is also shown in Figure 4 for better reference. The variability of IMC values in the comparison samples exceeds two orders of magnitude for both remote and aircraft data.

The altitudes of compared samples covered mostly the middle and low part of the cloud and varied from about 6000 m above ground level (AGL) (2114 UTC) to about 8550 m AGL (1940 UTC).

The relative standard deviation of in situ aircraft data from remotely measured data shown in Figure 4 is about 53%. However, as seen in Figure 4, the differences between the remote and aircraft results for most of the comparison times (1950, 2020, 2037, 2100, 2105, and 2114 UTC)

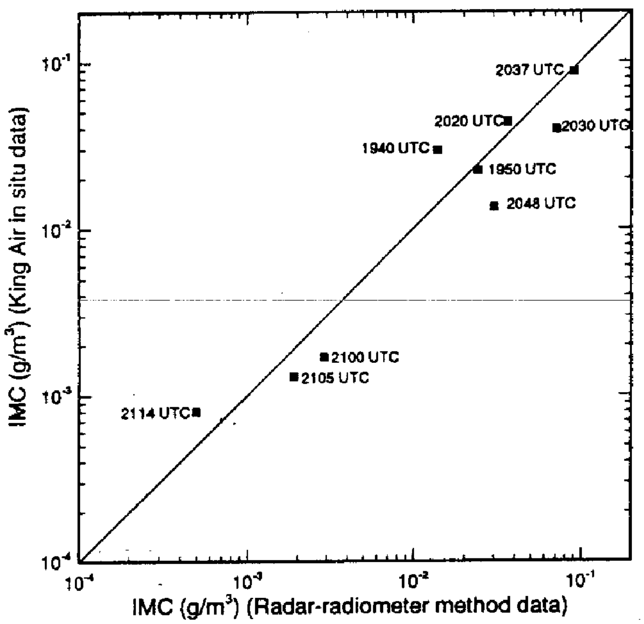

Figure 4. Comparisons of remote and aircraft data.

were better than that. The general agreement can be considered quite satisfactory given the uncertainty of both remote and 2D-probe measurements.

Conclusions

The November 26, 1991, cirrus case from FIRE-II provided a good opportunity to compare remotely measured cloud parameters with in situ aircraft measurements. Both remote and aircraft measurements showed a great (almost 4 orders of magnitude) variability of IMC during the experimental event from 1830 to 2130 UTC. The variability of measured IMC values during times when the aircraft was passing in the vicinity of the hub exceeded two orders of magnitude. For these times the direct comparisons were made between remote and in situ measurements. These comparisons showed a 53% standard deviation between aircraft and remote data. Many individual comparisons showed agreement better than that.

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