IMPROVED AIRBORNE HOT-WIRE MEASUREMENTS OF ICE WATER CONTENT IN CLOUDS.

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1. Introduction

Ice water content (IWC) is one of the fundamental microphysical parameters of clouds. Currently, there are three techniques used in the measurement of IWC. The first one involves the calculation of IWC from the measurements of particle size distribution, based on the size-to-mass conversion (e.g. Locatelli and Hobbs, 1974; Brown and Francis 1995). The second technique consists of estimating IWC from the measurements of water vapor density which results from total evaporation of ice particles (e.g. Kyle 1975; Ruskin 1976; Nicholls et al. 1990). The third approach utilizes the hot-wire technique (e.g. Nevzorov 1980, 1983; Korolev et al. 1998).

Despite the substantial efforts invested in the development each of the above techniques, there are still considerable uncertainties in accuracy of the IWC measurements. The existing problems are a result of multiple causes: (1) the large range of ice particle sizes covering a scale of four orders of magnitude. This creates specific problems for in-situ sampling and requirements for geometrical characteristics of the probes' inlets; (2) the variable density of ice particles, which does not allow for unique coefficients for size-to-area parameterization, such as the case of liquid droplets; and (3) the present absence of calibrating standards in wind tunnels. As a result of the latter, only one strategy of assessment of the IWC measurement accuracy is currently possible. It is based on multiple comparisons of measurements of instruments utilizing different IWC techniques. Although this approach may not necessarily provide an ultimate conclusion about the accuracy of the IWC measurements, it may reveal some specific measurement problems and help formulate new directions for future improvement of the IWC instrumentation.

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Efforts are in fact currently underway to develop absolute IWC calibrations in a wind tunnel usingice shaved from blocks (Strapp et al. 2008), which will hopefully provide a significant new tool for making progressing on this problem.

In the present paper we compare measurements of three IWC probes: (1) the Sky Tech Research hot-wire Nevzorov probe (Korolev et al. 1998) with a modified TWC sensor; (2) the counterflow virtual impactor (Twohy et al 1998) component of the Droplet Measurement Technology (DMT) Cloud Spectrometer and Impactor (CSI),(www.dropletmeasurement.com/product) using the evaporation technique; and (3) Particle Measuring Systems (PMS) OAP-2DC and OAP-2DP (Knollenberg, 1981) for measurements of particle size distributions, which were converted in IWC based on size-to-mass conversion. The first part of the paper is focused on the problems inherent in the sampling of ice particles by the hot-wire sensors. The second part describes the intercomparisons of the IWC measured from in-situ by the Nevzorov probe, DMT CVI and that deduced from particle size spectra.

2. High speed video tests

The concept of the IWC measurements by the hot-wire Nevzorov TWC sensor is based on the assumption that ice particles remain inside the conical capture volume and then melt and evaporate (see Fig. 2b in Korolev et al. 1998). However, despite this assumption, it has now been unclear for some time as to whether ice particles are truly captured, retained, and evaporated,, or simply rebound off the sensor after striking its surface.

A high speed video recording reported by Emery et al. (2004) and Strapp et al. (2005) showed that ice particles may bounce from the surface of the Nevzorov TWC cone sensor and other hot-wire sensor geometries. The tests were conducted in the Cox & Co wind tunnel. The

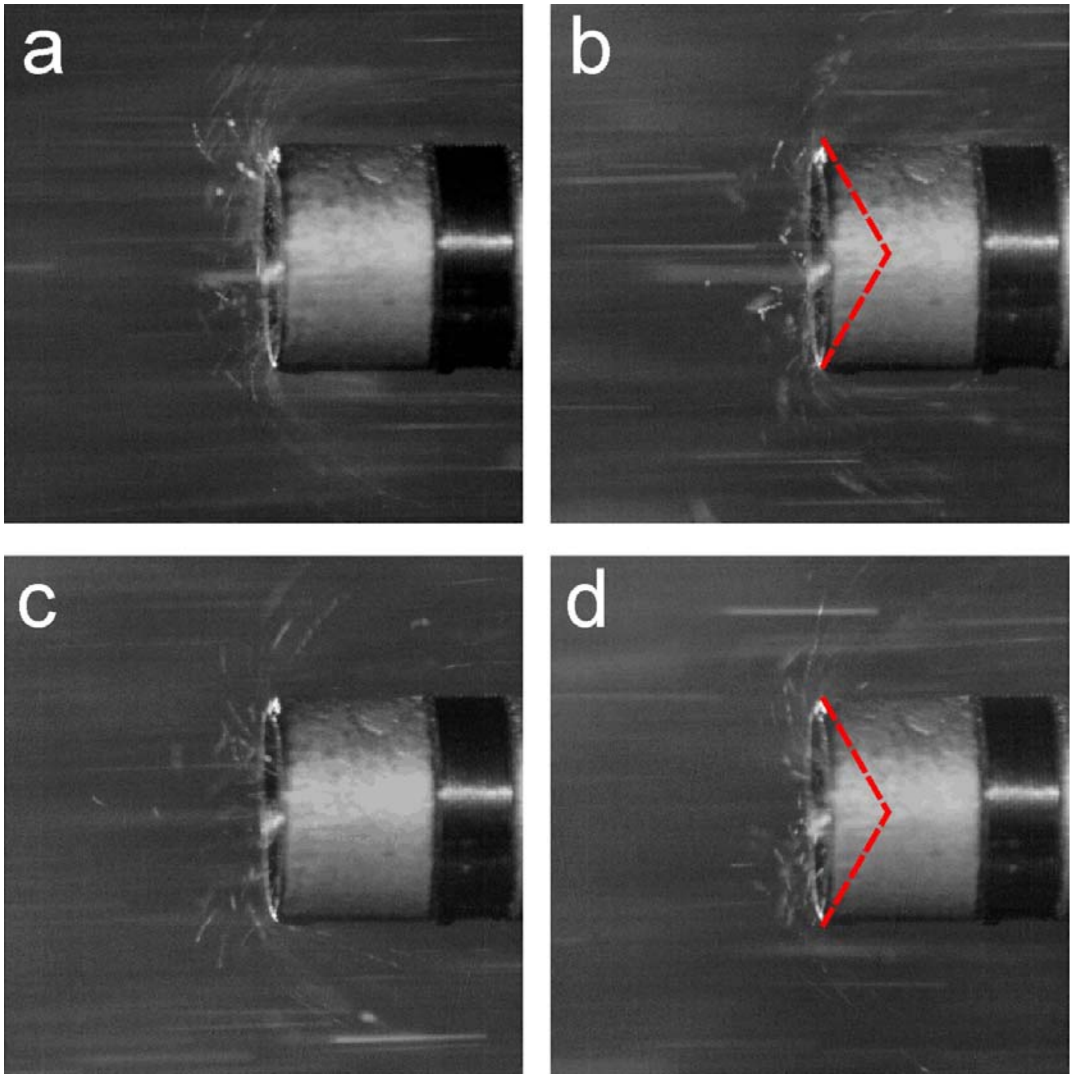

Figure 1. The images of the Nevzorov TWC sensor 120° cone taken with high speed video camera in the flow of ice particles in the Cox & Co wind tunnel. Red dashed lines in (b)&(d) indicate the shape of the hollow cone of the hot-wire sensor. Air speed 70m/s.

Cox wind tunnel has the capability of producing an ice spray by shaving ice blocks. The shaved ice particles had an irregular shape with a characteristic size ranging from 15 μm to 400μm. Fig. 1 shows images of the side view of the Nevzorov TWC sensor in the flow of ice particles. The pictures were taken in the Cox &Co wind tunnel with help of the Phantom V5.0 high frame rate camera manufactured by Vision Research, Inc. As seen from Fig. 1 some of the particles rebound off the TWC cone surface into the air-stream and are swept away. The bouncing of the ice particles results in an underestimate of the measured IWC. However, the efforts to quantify the IWC losses by counting the incoming ice particles, which approach the sensor cone and then rebound off based on high speed video frames, proved unsuccessful.

The ice particles produced in the Cox wind tunnel studies may have a higher density and less fragile structure than most vapor-grown ice crystals. The OAP-2D imagery indicates that the majority of the artificial ice particles produced in the wind tunnel had a quasi-spherical shape (Emery et al. 2004). Such particles may behave like solid balls resulting in elastic bouncing on the impact with the sensor surface (Fig. 3a).

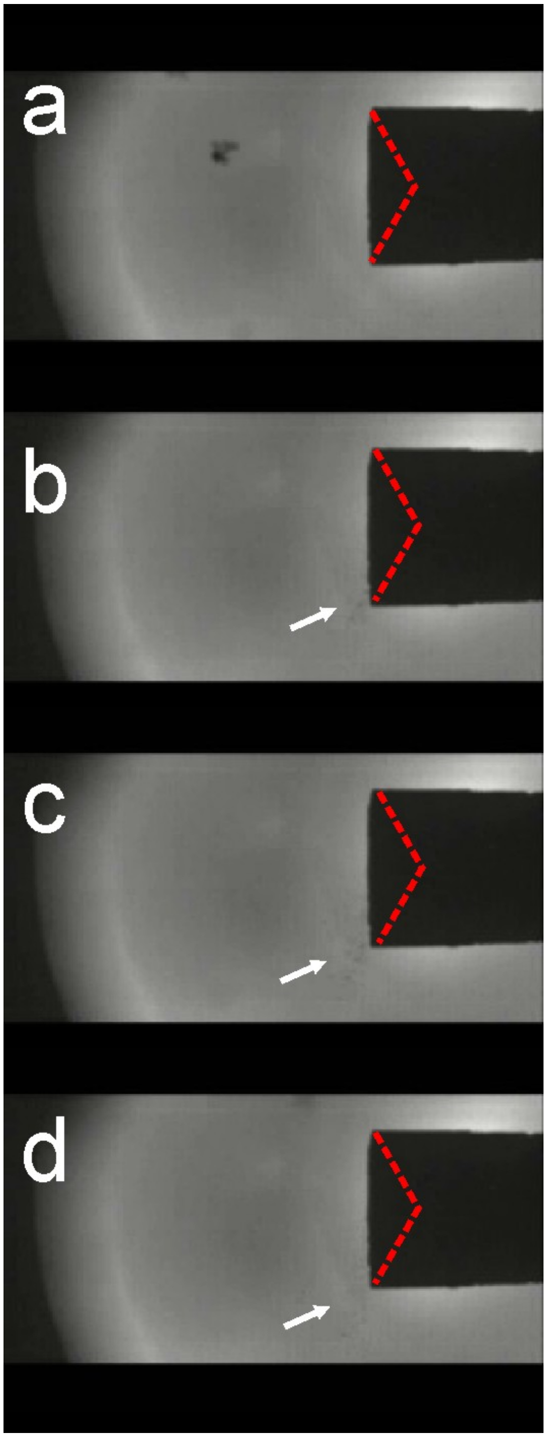

Figure 2. Sequence of video frames captured by the high speed video camera of the impact of the spatial dendrite (a) with the standard (120^o) Nevzorov TWC hot-wire sensor cone. Arrows in (b,c,d) indicate the outflow of the powdered ice particles resulted from the shattering of the dendrite shown on (a) after the impact with the cone. The measurements were obtained during the NRC Convair-580 flight in Ns on 18 December 2004. Red dashed lines indicate the shape of the hot-wire sensor cone.

Because of the specific features inherent in the wind tunnel environment, a decision was made to run tests only in natural clouds, where it is known that the turbulence, particle trajectories, and particularly the ice particle properties would be different. A series of tests were conducted using the National Research Council (NRC) Convair-580 in December 2004 using a total of 16 flight hours. The particles striking the TWC sensor of the Nevzorov probe were imaged using a Phantom V5 high speed camera.

Fig. 2 shows a sequence of video frames captured of the impact of the spatial dendrite with the Nevzorov TWC cone. Image analysis of numerous events of impact between ice particles and the sensor cone indicated that the ice particles shattered into a large number of small ice fragments, a fraction of which were visibly swept away from the cone with the airflow. Arrows in Fig.2b, c, d indicate the outflow of the small ice particle fragments which resulted from the shattering of the dendrite shown on Fig. 2a before it entered the TWC cone.

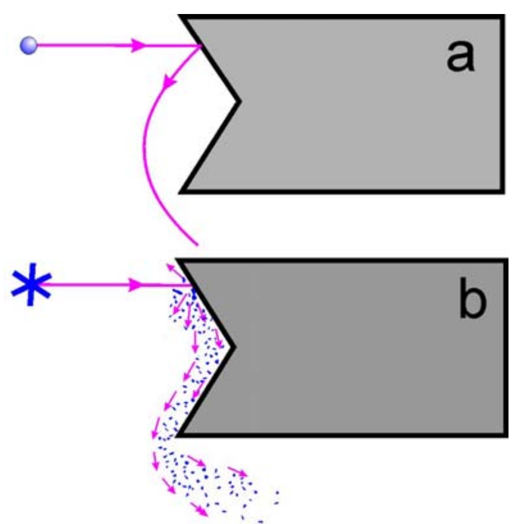

Figure 3. Conceptual diagram of the elastic (a) and inelastic (b) bouncing of ice particles with shallow TWC sensor cone.

The comparisons between the high speed videos recorded in the wind tunnel and the natural cloudy environment revealed differences in the behavior of artificial and natural ice particles after their impact with the TWC cone. On one hand, in a high density case, the artificial ice particles may behave more like solid balls, with elastic bouncing on impact. Whereas, naturally grown ice particles with complex morphology and low densities, such as a spatial dendrite, tend to shatter into a large number of small fragments. Some fraction of this shattered ice may be removed from the cone by airflow, or bounce elastically from the surface. The conceptual diagram in Fig. 3 demonstrates the difference between the behavior of artificial and natural ice particles of this type. It is reasonable to assume that natural ice particles with more compact geometry and higher densities may behave more similarly to the artificial ice produced in tunnels, although no such data were available from the flight tests with the high speed video.

Strapp et al. (2005) compared the response of hot-wire sensors of different geometry to shaved ice particles in the Cox and Co. Icing Wind Tunnel, showing that a 16 mm deep sensor displayed far fewer particles bouncing out of the capture volume than the 2 mm deep Nevzorov shallow sensor. Furthermore, 16 mm deep sensor measured at least 2 times larger IWC than the Nevzorov standard shallow sensor. This work indicated that the efficiency of the capture of ice particles by hot wires could potentially be increased greatly by modifications to the sensor geometry.

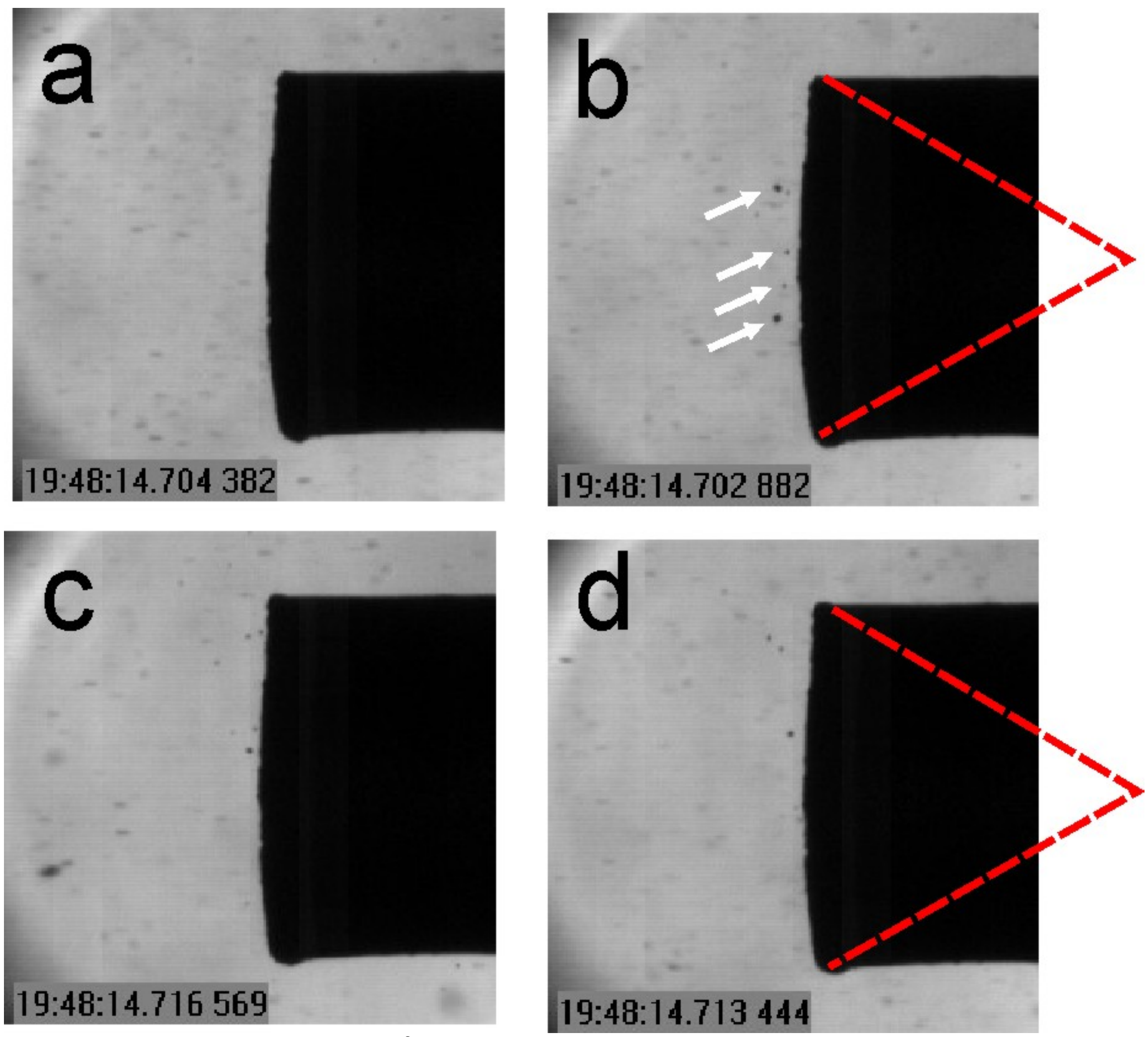

Figure 4. The images of the modified (60^o) Nevzorov TWC sensor cone taken with the high speed camera in the flow of ice particles in the Cox &Co wind tunnel. Arrows in (b) indicate the ice particles rebounded from the cone. The rebounded ice particles in (b,c,d) appear as quasi-circular images. Image frame in (a) does not contain rebounded particles. Red dashed lined in (b)&(d) indicate the shape of the hollow cone of the hot-wire sensor. Air

The fraction of bounced particles is expected to depend on the geometrical characteristics of the sensor. The ice particles striking the shallow cone with the wide angle are expected to experience just one bounce before they leave the sensor (Fig. 3a). However, ice particles entering a cone with sharper angle may bounce several times within the cone's surface, thus reducing the probability of exiting the sensor before their complete evaporation (Fig. 5a). To reduce the ice bouncing efficiency, a special 'deep' TWC sensor cone was constructed with a 60^o angle . This also results in a deeper catch volume requiring particles to bounce further into the airstream to exit the capture volume.

Figure 4 shows video frames of the modified deep TWC cone exposed to the flow if ice particles. The video in this sequence was shot with a different exposure rate that does not result in the particle streaks as in the case of Figs. 1a-d. The bounced particles in this video appear as quasi-spherical sharp images, whereas the ice particles in the undisturbed flow appear as elongated streaks due to their higher velocity. Bouncing ice particles are indicated by the arrows in Fig. 4b. It appeared that most video frames of the deep cone did not contain evidence of particles bouncing out of the capture cone (Fig. 4a).

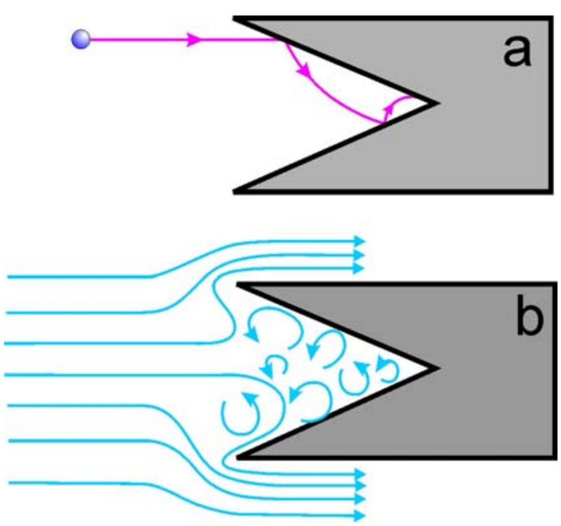

Figure 5. Conceptual diagrams of (a) elastic bouncing of ice particles in the deep TWC sensor cone; (b) vorticity inside the deep cone.

The high speed video gives a general idea whether ice particle bouncing exists or not. Nevertheless, the quantification of the underestimation of IWC due bouncing based on high speed video analysis does not seem plausible. In particular, the shattering of fragile ice particles results in a large number of small ice fragments that may not be visible on the image frames because of coarse pixel resolution and limited depth-of-field, and therefore can not be accounted for in an estimate of mass-loss. Furthermore, an assessment of the bouncing of any original particles smaller than the practical size limit of the camera also cannot be quantified.

3. In-situ comparisons of IWC techniques

In order to characterize the underestimate of IWC due to bouncing, the standard Nevzorov shallow (120^o) and new prototype deep (60^o) TWC sensor cones were mounted on the same sensor vane (Fig. 6a). This configuration allows for simultaneous measurements of IWC to be taken by both sensors. The Nevzorov probe along with a DMT CVI (Fig.6b) (Twohy et al. 1997) and PMS OAP-2DC/2DP were mounted on the NRC Convair 580. The measurements of IWC were obtained from glaciated clouds measured during the Canadian CloudSat Calipso Validation Project (C3VP) in Southern Ontario. The ice clouds were identified based on the measurements Rosemount Icing Detector and suite of cloud particle spectrometers as described in Korolev and Isaac (2006) Mixed phase and liquid clouds were not included in the following analysis.

The calculation of the mass of ice particles from their 2D imagery was performed based on the size-to-mass parameterization $M=aD^b$ (Mason 1957). The coefficients a=7.38 10^{-11} and b=1.9 were provided by Brown and Francis (1995), as originally determined by Locatelli and Hobbs for "aggregates of unrimed bullets, columns, and side planes". IWC was computed by the integrating the mass of ice particles over size distribution measured by the OAP-2DC & 2DP. In order to improve the statistical significance of the particle size distributions the OAP data were averaged over four second time intervals. The measurements of the Nevzorov probe and CVI were averaged over the same

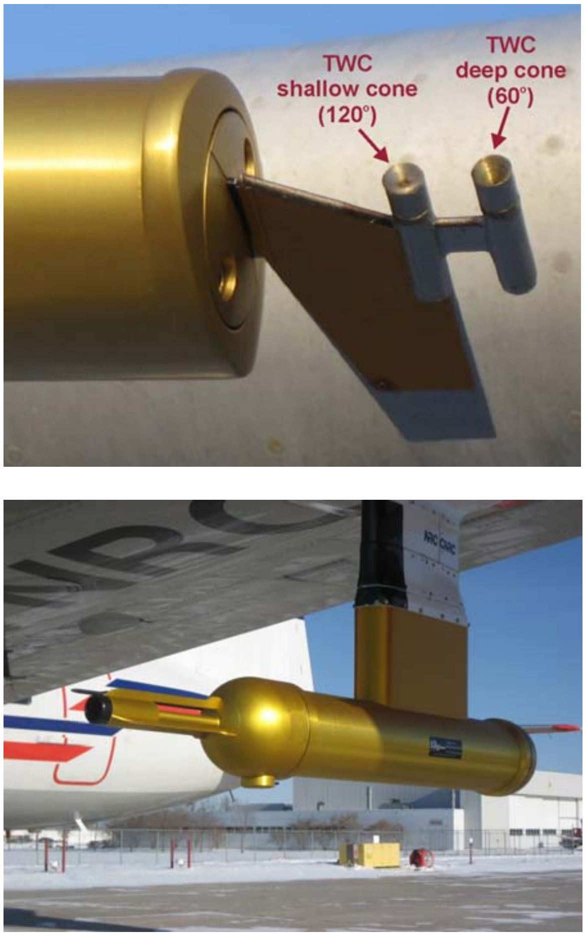

Figure 6. Modified Nevzorov sensor head; both shallow and deep sensors mounted on the same vane (top). DMT CVI probe installed on the NRC Convair-580.

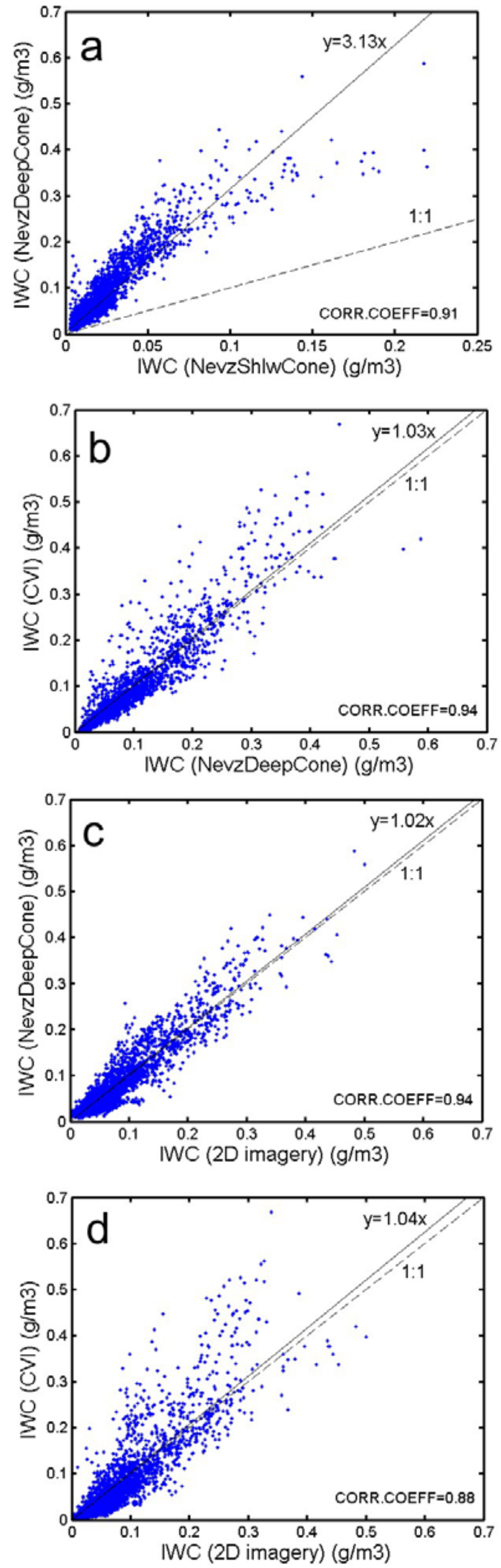

Figure 7. Scatterdiagrams of IWC measured by the Nevzorov deep and shallow TWC sensors, DMT CVI and OAP-2DC&2DP in ice clouds with D_{max}<4mm.

time intervals in order to synchronize all measurements and enable the intercomparisons of all probes

The comparisons reveal that IWC measurements by four the IWC probes, are all linearly related to one another. However, the slope of the linear regression is a function of the size of ice particles. Fig. 7 shows scatterdiagrams of IWC measured by different pairs of instruments for the ice clouds with particle D_{max}<4mm. Fig. 8 shows the scatterdiagrams of IWC measured by the same pairs of probes but particle D_{max}>4mm. As seen from Fig. 7a, the IWC measured by the Nevzorov deep cone sensor is approximately three times higher than that measured by the shallow cone. The rest of the probes – the Nevzorov deep cone, CVI, and size-to-mass conversion – agree relatively well with one

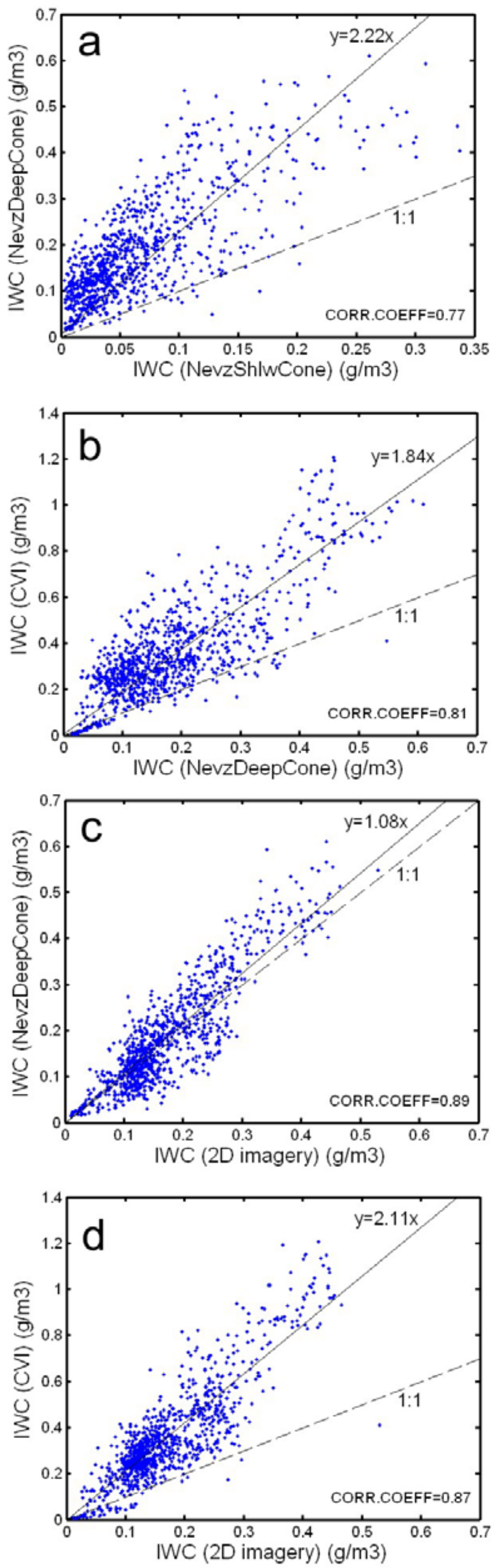

Figure 8. Scatterdiagrams of IWC measured by the Nevzorov deep and shallow TWC sensors, DMT CVI and OAP-2DC&2DP in ice clouds with D_{max}>4mm.

another for ice clouds with particle D_{max}<4mm. For the case of clouds with large ice particles (D_{max}>4mm) the correlation between the IWC measurements is degraded and the slope changes.

Fig. 9 shows the dependence of the slope versus the maximum size of ice particles in the measured size distributions. The obtained results suggest that the proportion between IWC measured by different instruments changes with the particle size. Interestingly, the IWC measured by the Nevzorov deep cone agrees reasonably well with that deduced from the OAP size distributions for the whole size range. Fig. 9 indicates that for small ice particle clouds with D_{max}<3mm, the Nevzorov deep cone gives very similar IWC values to the CVI. For large ice particles (D_{max}>10mm), the IWC measured by the CVI is than two times greater than that measured by the Nevzorov deep cone. At all particle sizes, the Nevzorov shallow cone measures a factor of 1.5 or more lower than the other probes, and is clearly the probe with the lowest readings.

It is worth mentioning that most ice clouds with large ice particles (D_{max}>4mm) were associated with temperatures -15<T<10C (Fig 10a). This temperature range corresponds to the dendrite ice growth regime. Dendrites typically unambiguous conclusion as to which instrument provides the most accurate result in this region

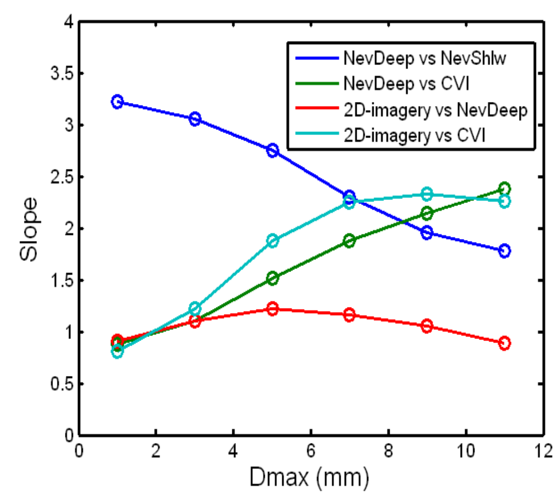

Figure 9. Slope of the linear fit versus D_{max} for pairs of different IWC instruments indicated in the legend. Each data point on the diagram was calculated for 2mm interval of D_{max}.

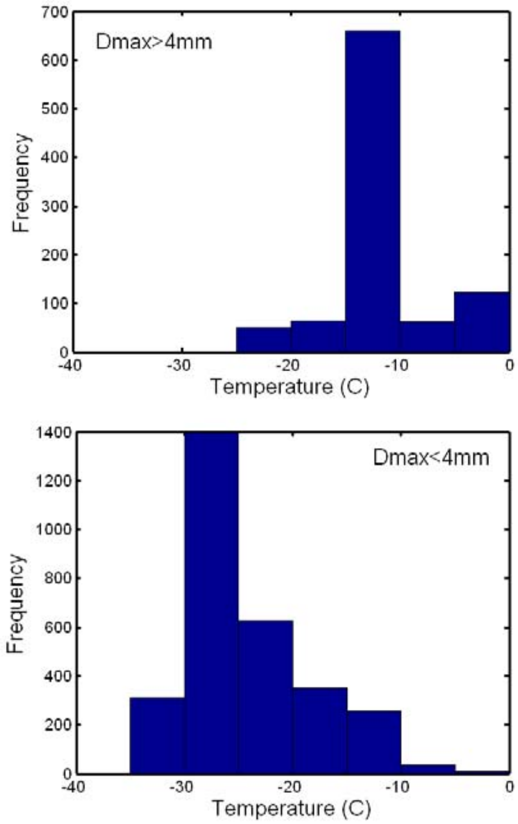

Figure 10. Frequency distribution of temperatures corresponding data presented in Fig.8 (ice particles D>4mm) (top) and that shown in Fig.7 (ice particles D<4mm) (bottom).

form large fluffy low density aggregates. The results of this study do not allow for an of maximum discrepancy. One may speculate that a potential underestimation of IWC by the Nevzorov deep cone sensor is caused by the vorticity in the cone, resulting in the sweeping away of miniscule particles resulting from dendrite shattering (Fig. 5b). On the other hand, one may hypothesize that an overestimation of IWC measured by the CVI may be caused by the shattering of dendrites due to their collision with the shroud, with a subsequent focusing of the inlet tube.

4. Conclusions

The data from this study supports the following conclusions:

1. IWC measurement taken by the new prototype Nevzorov deep cone, DMT CVI and IWC calculated from OAP particle size spectra agree well for ice clouds with ice particles D_{max}<4mm. This agreement suggests that all three techniques may provide reasonably accurate IWC measurements for small ice particles (D_{max}<4mm). When larger ice particles are present, the CVI measures higher IWC values than both the Nevzorov deep cone and OAP. Interestingly, IWC measured by the Nevzorov deep cone and that estimated by applying mass-diameter relationships to OAP imagery are approximately equal throughout the entire range of ice particle sizes.
2. For ice particle spectra with D_{max}<4mm, the IWC measured by the standard Nevzorov shallow cone is approximately 3±0.2 times lower than that measured by the Nevzorov deep cone and CVI. Assuming that the close agreement between the CVI and the deep cone indicates that both are measuring approximately correctly, this allows for corrections of IWC data sets collected with the Nevzorov shallow cone TWC sensor during previous flight campaigns, in cases where large particles are not present. The correction must take into account any liquid fraction in the cloud, which will be measured at a much higher efficiency.
3. The obtained results do not allow for an unambiguous conclusion about the accuracy of the IWC measurement devices when large particles such as large dendrites and aggregated ice particles are present, and when large discrepancies between the different sensors are observed. More studies are required to resolve this problem.

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