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Improved Measurements Of The Ice Water Content In Cirrus Using A Total-Water Evaporator

by

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Abstract

This note describes an improved method for the measurement of the ice water content (IWC) of cirrus cloud using a total water content (TWC) evaporator. A previous version of this technique assumed that the air in cloud-containing regions was saturated with respect to ice. This assumption has now been replaced with measurements of the water vapour content from a fast-response Lyman-α fluorescence water vapour sensor. The improved measurement of the vapour phase resolves some of the anomalies in measurements that were observed using the earlier technique. The comparison of IWC measurements by this method and from a 2D optical array probe is greatly improved, to the point where the former may be used to validate the choice of algorithm used for the derivation of crystal mass from measured size in 2D probe data.

1 Introduction

An earlier paper (Brown 1993, hereafter referred to as B93) described a method of measuring the ice water content (IWC) of cirrus cloud using total water content (TWC) evaporator. The latter device measures the sum of vapour and condensed phases (Nicholls et al. 1990). Because of limitations on the ability to measure the vapour phase at cirrus altitudes with a sufficiently rapid time-response, it was assumed in B93 that the vapour content within cloudy regions was given by saturation with respect to ice at the ambient temperature and pressure. B93 presented measurements obtained from the UK Meteorological Office C-130 aircraft during the 1989 field phase of the International Cirrus Experiment (ICE). In some cases, good correlation was observed between IWC measurements made with this bulk technique and those inferred from particle size spectra measured by a PMS 2D Optical Array Probe (OAP). However, in other cases there was a significant divergence between the two measurements, indicating the possibility of sub- or super-saturations within the cloudy regions.

A new fast-response Lyman-α fluorescence water vapour sensor (FWVS) has now been installed on the C-130, enabling measurements of water vapour with a time response of around 1 second down to frost points of -80 C. This water vapour measurement may now be subtracted from the TWC to obtain an improved estimate of the IWC. This note presents some measurements of cirrus IWC made using this new method. They demonstrate the improved correlation between between bulk and 2D probe measurements. The measurements are used to test different relationships between particle size and mass, which assume different rates of decrease of density with size. Crystals of around 1 millimetre in diameter are commonly observed in cirrus clouds in mid-latitudes. The correct establishment of the density of these particles is of great importance in the calculation of their reflection and attenuation properties for 94GHz cloud radar (M Gosset and A J Illingworth, personal communication). The density is also an important factor in determining the radiative properties of ice crystals. Most parameterizations of cirrus cloud radiative properties tend to assume a constant value for this density, independent of crystal size (e.g. Fu and Liou 1993). A more realistic representation would obviously be of major benefit.

2 Instrumentation

The operation and calibration of the TWC remains as described in B93. The FWVS was designed and built by the Atmospheric Chemistry group of the UK Meteorological Office. It uses the method described by Kley and Stone (1978), and contains both a detector for the fluorescence from OH radicals produced by the photodissociation of water molecules and also a long path length Lyman-α absorption cell. The ratio of fluorescence to absorption signals is approximately a linear function of the water vapour mixing ratio: measurement of humidity fluctuations, either naturally-occurring or produced by injection of water vapour into the instrument, can be used to obtain a calibration of the instrument which depends only on an accurate knowledge of the absorption coefficient of water vapour at Lyman-α wavelengths. Ström et al. (1994) compare the performance of a number of aircraft hygrometers, including both the TWC probe and FWVS, in cloud-free conditions. They identify certain characteristics of the relative errors between different instruments, of which a constant mixing ratio offset was prominent. Because the TWC probe is still calibrated against a General-Eastern 1011B dew/frost-point hygrometer, there remain some residual differences in calibration between it and the FWVS. To overcome this, the

TWC values are adjusted by the addition of a fixed offset so as to agree with mixing ratios obtained from the FWVS in cloud-free regions. This offset is calculated separately for each flight leg. The IWC is then obtained from

$$q_I = q_T - q(p, T_F) \tag{1}$$

where q_T is the TWC and T_F is the frost-point measured by the FWVS. The value obtained from this equation will be referred to as $IWC_{TW,F}$. B93 used

$$q_I = q_T - q_{sat,I}(p, T) \tag{2}$$

to derive an estimate of IWC which will be referred to in this note as $IWC_{TW,SAT}$. In the calculation of this value, q_T is the value obtained after the addition of any offset described above.

Processing of 2D probe data is again as described in B93. The crystal diameter is taken as the mean of diameters measured parallel and perpendicular to the probe photodiode array orientation. Crystal mass is then derived using the expression derived from that given by Locatelli and Hobbs (1974), appropriate to "aggregates of unrimed bullets, columns and side-planes",

$$M = a.D^b \tag{3}$$

where M is the particle mass in grams, D its diameter in microns, $a = 7.38261 * 10^{-11}$ and $b = 1.9$. For diameters smaller than 100 μm Equation 3 implies masses greater than that of a solid ice sphere of the same diameter and is therefore applied only for diameters above this limit. All crystals with diameter smaller than $100\mu m$ are assumed to be ice spheres (*ie.* $a = 4.18711 * 10^{-13}$ and $b = 3$). Where the measured size spectrum extends to sizes larger than the $800\mu m$ upper limit of the 2D Cloud probe, IWC_{2D} is obtained by summing contributions from the Cloud probe for diameters smaller than $500\mu m$ and from the Precipitation probe for diameters larger than this threshold. This is referred to hereafter as the standard IWC derivation from the 2D probes.

3 Results

The data described in this note was obtained on two flights, A189 on 23 April 1992 over the North Sea, and A193 on 30 April 1992 to the South-West of the UK. In both cases, the aircraft sampled cirrus layers which extended over a depth of 2-3 km. The crystal habit was found to be predominantly quasi-spherical irregular, with occasional bullet-rosettes and columns, justifying the blanket use of equation 3. All data were processed as 5-second averages, corresponding to a sample length of 650-700 m at typical airspeeds.

Figure 1 shows a time series of measurements of IWC_{2D}, $IWC_{TW,F}$, and $IWC_{TW,SAT}$ from a flight leg at an altitude of 6.4 km. Whilst there is good correlation between the measurements during the second half of the run, and between the 2D probes and $IWC_{TW,F}$ during the first half, $IWC_{TW,SAT}$ has negative values. These suggest the presence of sub-saturated regions (when the vapour content assumed for saturation and subtracted from the TWC is greater than the actual vapour content). The implied relative humidity in the sub-saturated regions is approximately 90% with respect to ice.

The overall correlation between IWC_{2D} and $IWC_{TW,F}$ is shown in Figure 2. The larger relative scatter of data points below $0.01gm^{-3}$ is readily apparent. This results from residual calibration errors in the total water probe relative to the FWVS and instrumental noise in the TWC probe. A linear least-squares fit to the whole dataset gives

$$IWC_{2D} = (0.7254 \pm 0.0055) IWC_{TW,F} + 0.0049$$

with a correlation coefficient of 0.932. These results are comparable with those given by Knollenberg et al. (1993) for IWC measurements in tropical anvil cirrus. In the latter case however, the ice water was concentrated mainly in particles smaller than 100 μm in diameter, which were measured using a Forward Scattering Spectrometer Probe (FSSP) and assumed to be ice spheres. In the current dataset, the majority of samples have the dominant contribution to the IWC from particles in the size range $200 - 800\mu m$.

The slope of the least-squares fit differs from that given in B93 for the comparison of IWC_{2D} and $IWC_{TW,F}$. This is probably because in B93 the TWC data was adjusted consistently with the assumption of saturation within cloud so as to avoid negative values of $IWC_{TW,SAT}$. The current dataset suggests that subsaturated regions are observed in the majority of the horizontal flight legs, therefore the leg-averaged values of $IWC_{TW,SAT}$ obtained by B93 were probably an overestimate.

In mid-latitude cirrus, particle sizes commonly extend into the millimetre range. The establishment of the correct mass of these larger particles is of crucial importance to the calculation of the radar reflectivity and attenuation of cirrus for 94GHz cloud radar. M Gosset (personal communication) has shown that for 1mm diameter particles, the attenuation is an order of magnitude larger for solid ice spheres than for particles described by Equation 3, and nearly forty times greater for particles of 2.4mm diameter. It is therefore of interest to compare the use of different size-to-mass conversions for the 2D particle image data. Mitchell et al.(1990) give alternative coefficients in Equation 3 of $a = 6.4 * 10^{-12}$ and $b = 2.27$ to give the mass of bullet-rosette crystals. This relationship gives comparable masses to the standard method for millimetre-sized crystals but lower values for smaller diameters, and is referred to as the 'Alternative' IWC derivation. As a further alternative, the values $a = 3.319 * 10^{-12}$ and $b = 2.6$ were also employed for diameters larger than $100\mu m$. These give particles which have a density of $0.4gcm^{-3}$ at a diameter of one millimetre, compared to $0.07gcm^{-3}$ for the standard expression, and similarly all crystals smaller than $100\mu m$ in diameter are assumed to be ice spheres. This is referred to as the 'Dense' IWC derivation. The variation of the bulk density (ie. the mass relative to a water sphere of the same diameter) implied by these three expressions is shown in Figure 3.

The validity of the three expressions used for calculating the IWC_{2D} is tested by plotting the ratio $IWC_{2D}/IWC_{TW,F}$ as a function of D^*, the scale diameter of an inverse-exponential fit to the measured size spectrum ($N(D) = N_0 exp(-D/D^*)$). For such a spectrum particles with a diameter of $D = bD^*$ produce the largest contribution to the total IWC. Thus errors in the calculated particle mass at this diameter will produce the largest differences between IWC_{2D} and $IWC_{TW,F}$. For an expression which correctly interprets the crystal mass over the entire size spectrum, the value of the IWC ratio $IWC_{2D}/IWC_{TW,F}$ should be equal to 1 for all values of D^*.

Since a scatter plot of IWC ratio against D^* with all the available data values tends to obscure the necessary detail, the points were first grouped into classes of D^* of width $25\mu m$. The mean and standard deviation of all the values within each D^* class were then calculated, and are shown in Figure 4. The steady increase of the IWC ratio with D^* for the 'Dense' assumption confirms that this expression increasingly overestimates the masses of the larger particles. Both the other expressions give IWC ratios which remain close to 1 across the whole range of D^*, however the 'Alternative' expression has a clear tendency to underestimate the IWC relative to $IWC_{TW,F}$ in the range of D^* from 50 to 150 μm. Thus over the whole range of D^* from 25-400 μm, the expression given by Equation 3 with the standard coefficients, $a = 7.38261 * 10^{-11}$ and $b = 1.9$, appears to give the best estimate of IWC from the 2D probe. It is noteworthy that there is no tendency for the IWC ratio to decrease as D^* decreases below $50\mu m$. This might be expected, for example, if the 2D probe were systematically underestimating the concentration of crystals smaller than $150\mu m$. Such undercounting has been reported for sizes smaller than $100\mu m$ (Baumgardner 1988).

4 Summary

The use of a fast-response hygrometer to measure the atmospheric water vapour content in conjunction with the total water content evaporator provides a significant improvement in the estimation of IWC using the latter instrument, by comparison with an earlier method in which all cloudy regions were assumed to be at saturation with respect to ice. The variation of the ratio $IWC_{2D}/IWC_{TW,F}$ as a function of D^* confirms that the standard coefficients $a = 7.38261 * 10^{-11}$ and $b = 1.9$ used in Equation 3 give the best estimate of IWC from the 2D probe data. These coefficients may therefore be suitable for use in deriving the IWC of mid-latitude cirrus cloud from a particle size spectrum in any situation in which all crystals are clearly of the same quasi-spherical irregular habit seen in the present data.

There remains a problem of calibration errors in the TWC data relative to the FWVS. These are typically of the same order of magnitude as the IWC itself, and in the present dataset have been removed by comparing measurements in cloud-free regions. It may be possible in the future to use the FWVS routinely to calibrate the TWC probe, thus removing one of the major cause of uncertainty in the calculation of IWC using the combination of these two devices.

Acknowledgements

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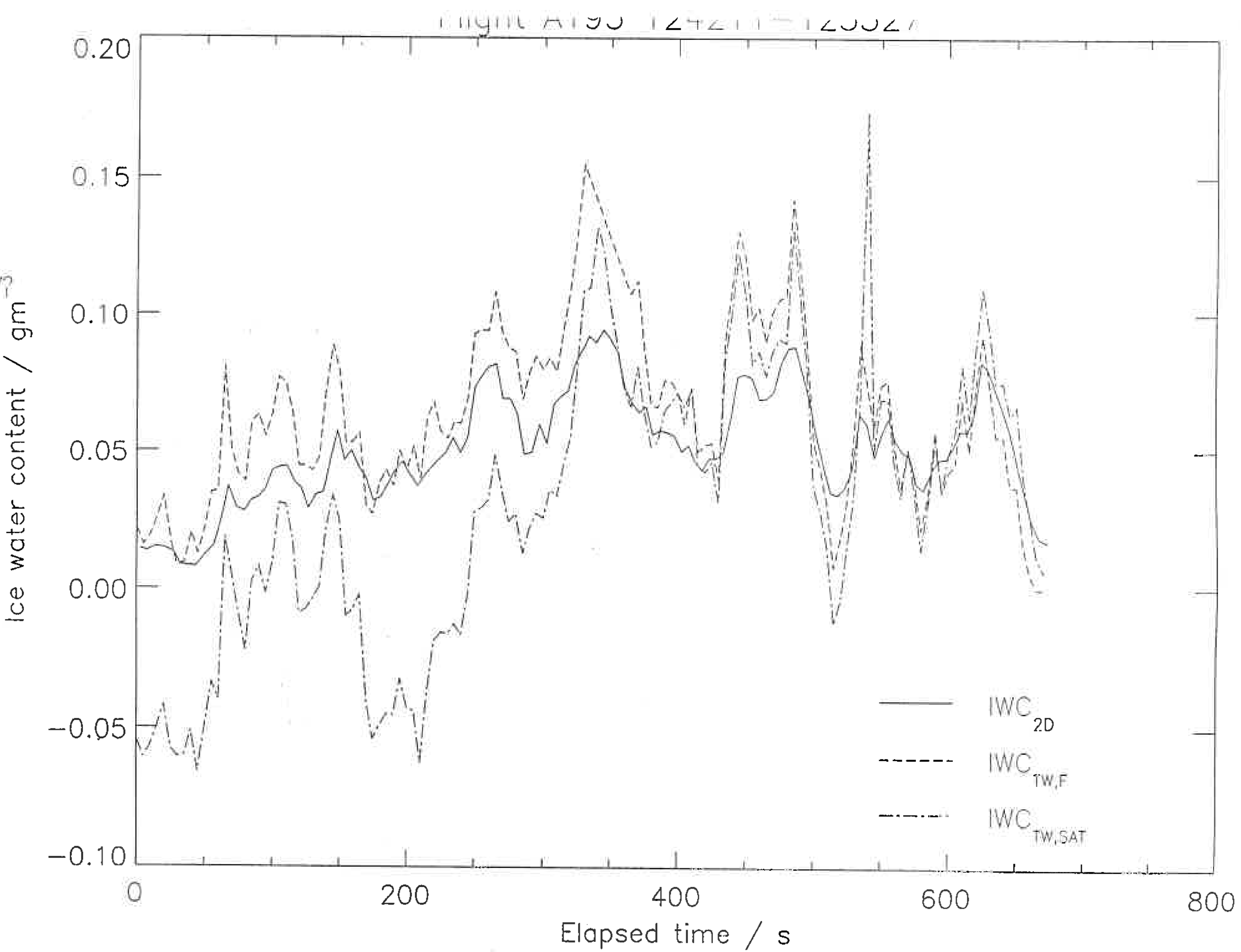

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Fig. 1

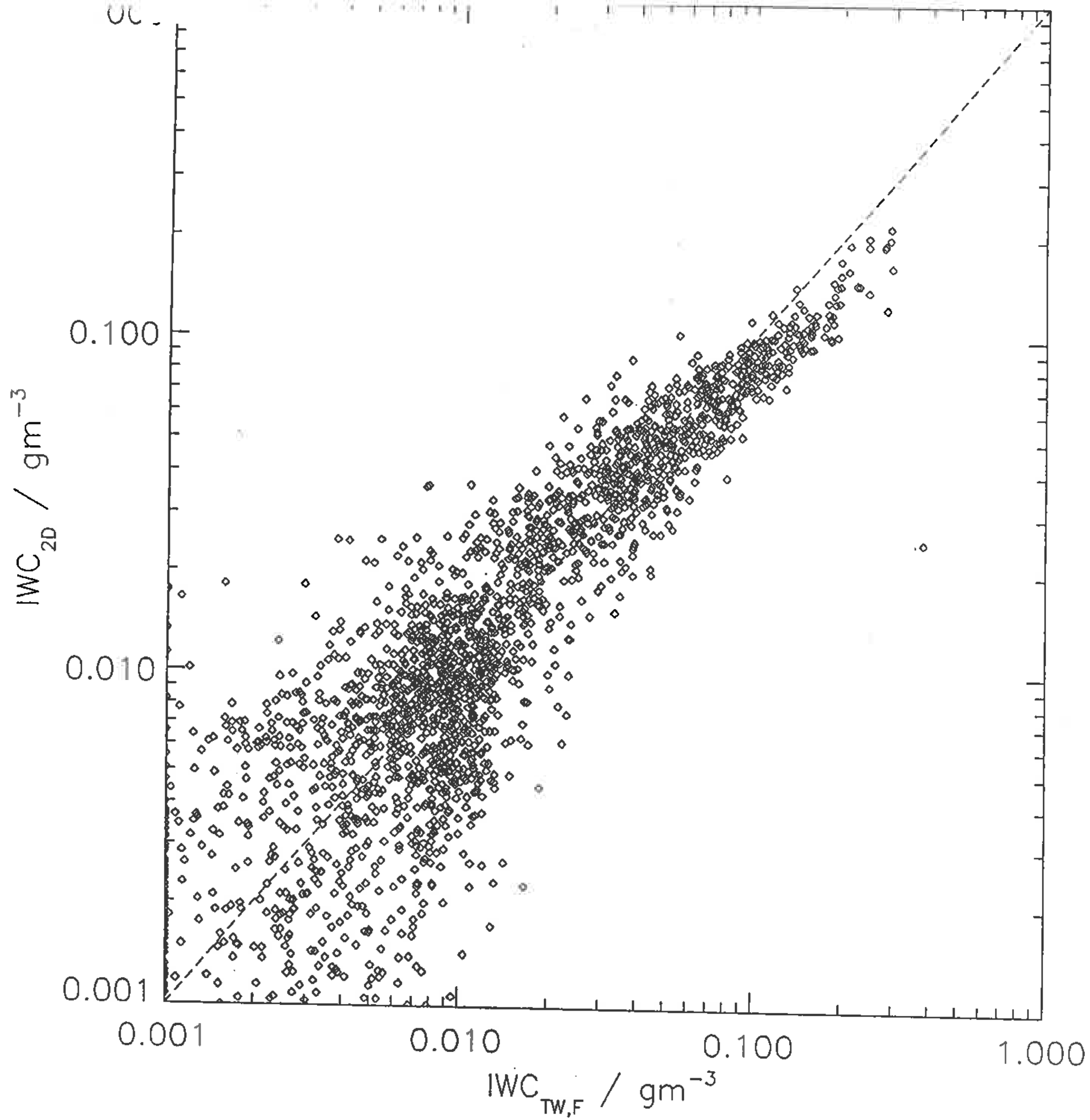

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Fig. 2

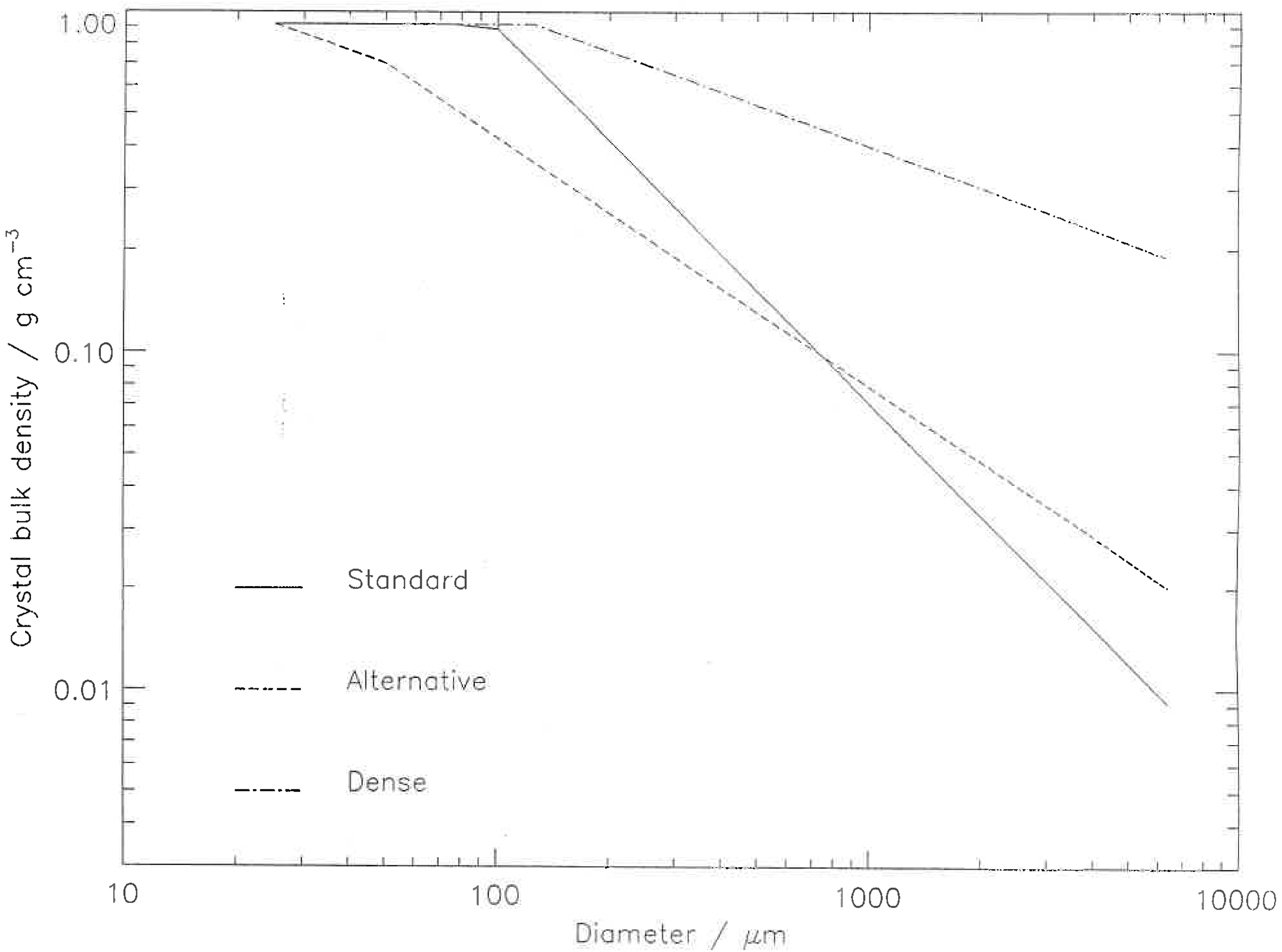

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Fig. 3

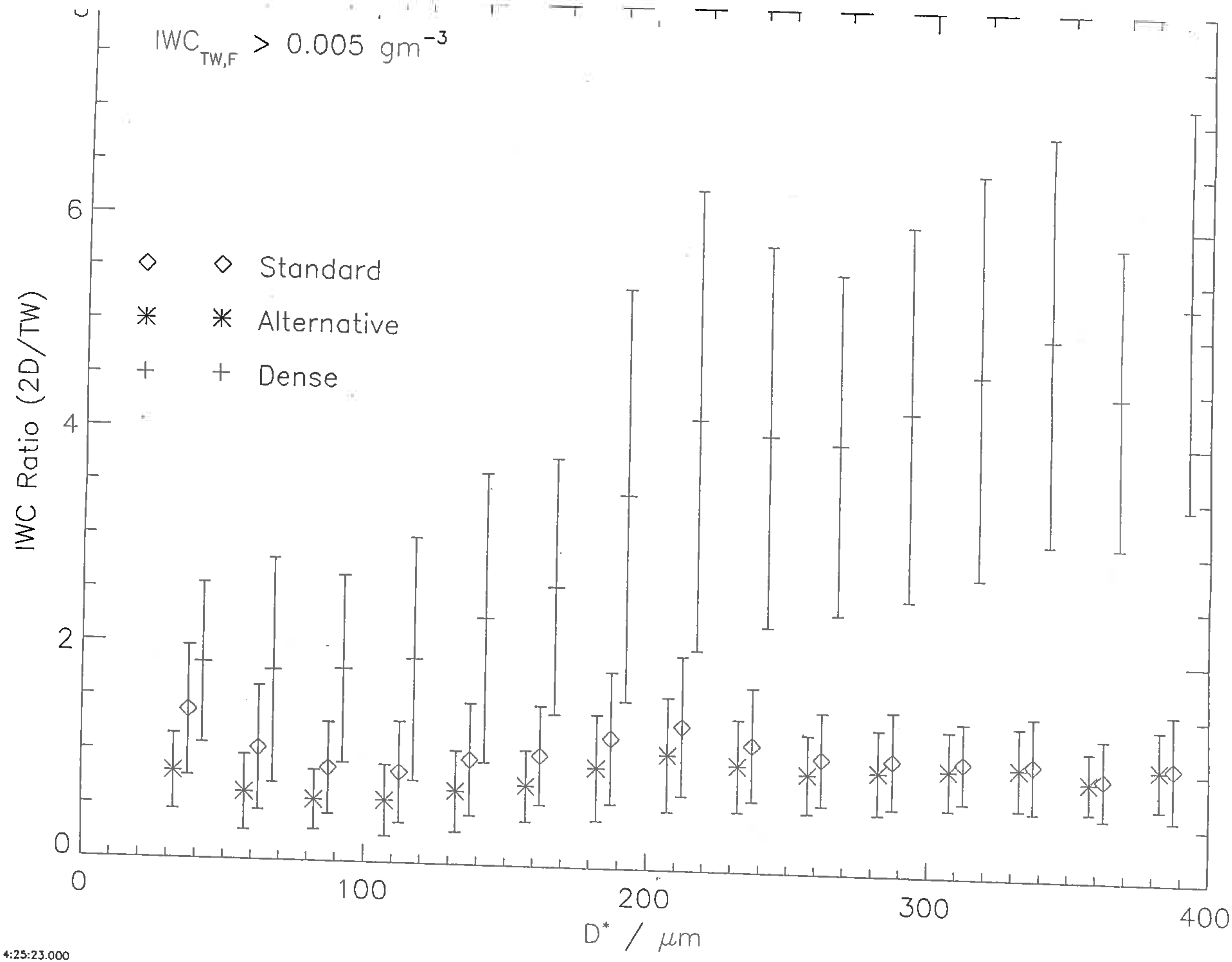

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Fig. 4

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