Analysis of ice crystals occuring in the upper high levels of tropical mesoscale convective systems

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1 Introduction:

Ice clouds encountered in altitudes between 8000 and 12000 m are suspected to harm aircraft engines. These regions of ice clouds typically appear in the upper part of tropical systems which formed by deep convection. Very important concentrations of ice crystals and Ice Water Content (IWC) can occur. However, these zones of high ice content are detected neither by the aircraft radar, nor by their icing sensors. It is thus hypothesized, that these ice clouds are characterized by the presence of small crystals in very high numbers.

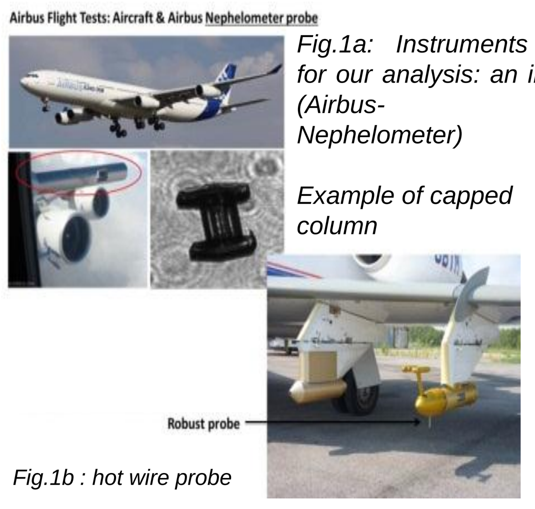


Fig.1a: Instruments used for our analysis: an imager (Airbus-Nephelometer)

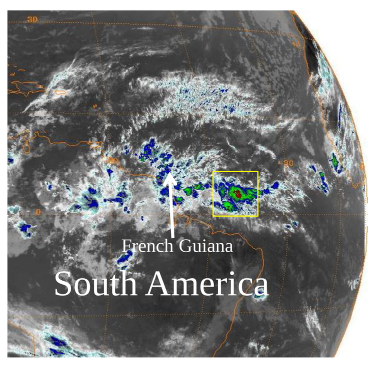
Example of capped column

Fig.1b : hot wire probe

Objective:
To verify the hypothesis of the presence of an important number of small ice crystals, two types of airborne measurements were performed:
- a particle imager (hereafter called Airbus Nephelometer), which takes pictures of hydrometeors (Fig. 1a), and
- a hot-wire probe (Robust probe), which measures the Condensed Water Content by a thermic technology (Fig. 1b).

2 Observations:

A flight campaign took place on 16 Mai 2010 over the Atlantic Ocean (-41° W, 3° N) . Measurements were performed between 11:30 – 13:30 UTC in a large Mesoscale Convective System (MCS) east of French Guiana (see Fig.2a, yellow rectangle).



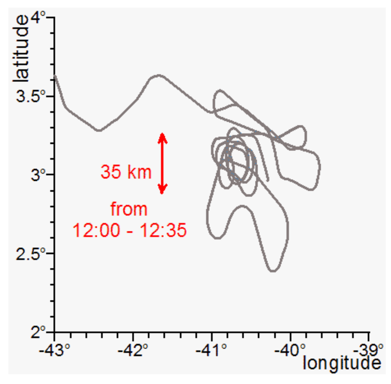


Fig.2: a) GOES 11.7 µm brightness temperature

Fig. 2b) aircraft trajectory when probing the convective cores of the deep system

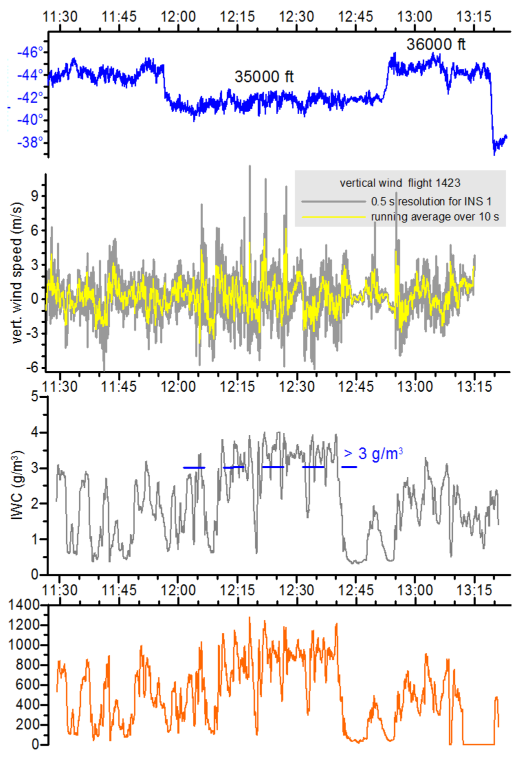


Fig.3 : Temperature, vertical wind, IWC and crystal number concentration (# per liter)

In situ sampling focused on convective cores which were encountered after 12 UTC (see Fig.2b). Most measurements restrict to the innermost most convective part of the thunderstorm. More distant locations allowed the probing of stratiform outflow. All observations were made in flight levels between 10500 and 11000 m.

Observational results:

Temperature: the range of TAT observations restrict to -40° to -46°C (regular air traffic cruising level)

vertical wind: typically ranges between +3 and -3 m/s. In the period from 12.00 to 12.30 updrafts of more than 6 m/s were encountered. Most prominent: medium updraft zone of 2-3 m/s with horizontal extensions of 10-15 km occur

IWC: IWC determined from the hot wire probe and the AIRBUS imager both indicate values from 1 to 4 g/m³. Most values > 3 g/m³ occur in the most convective zone from 12 to 12:30.

Crystal number concentration: its range is quite variable. Values of 800 to 1000 crystals/liter were encountered in the most convective zone, while only 100 per liter occur in the stratiform regions

3 Microphysical Observations:

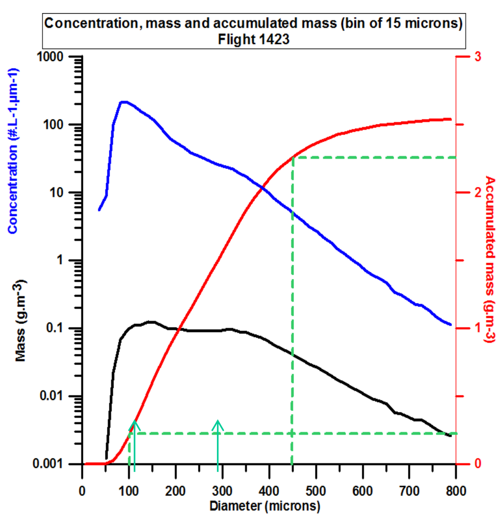


Fig. 4: Size distributions of particle number concentration (blue) and of particle mass (black); accumulated ice mass (red)

- Number distributions were determined from measurements with the Airbus Nephelometer. The illustrated spectra are averaged from 11:30 to 13:00
- The maximum concentration is located at particle sizes of 100 µm. Size above 1.5 mm (not illustrated) could not be detected.
- Mass distribution is calculated under the assumption that crystal behave like hexagonal columns using:
$m = 7.38\,10^{-11} * D^{1.9}$ (Brown and Francis, 1995)
80% of the IWC is determined from the particles sizes in the range from 100 to 450 µm.
Two modes appear in the mass distribution: one at 120 µm and a second one around 320 µm

Preliminary result: due the higher number concentration and the small sizes of the crystals we can conclude that freshly formed, pristine ice crystals were mainly observed

4 Detection of the particle shape – image recognition

Ice crystals habits detected by the Airbus Nephelometer are columns, plates, aggregates and to a considerable amount also *capped columns*

To characterized the shape of ice particles, many geometrical parameters like maximal length, width, surface, perimeter, or aspect ratio can be used. We mainly focus on the aspect ratio.

The aspect ratio can be defined as : ***As_{geo}= width / length***

length is the maximal distance between two pixels passing the center of gravity,
width is perpendicular to the *length,* also passing through the center of gravity (see Fig.5)

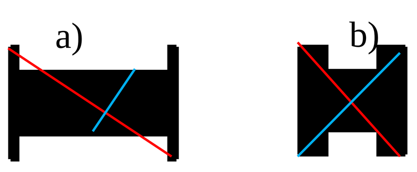
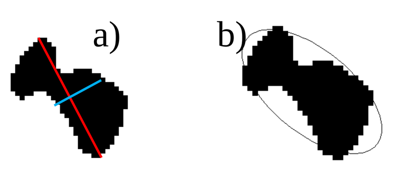


*Fig. 5: Two examples when applying **As_{geo}** to capped columns. Width is in blue, length is in red.*
a) Long capped columns, with a small calculated width.
b) Short capped columns, with large calculated width.

Using **As_{geo}** for the automatic image recognition of ice particles allows to distinguish columns, plates and graupels (irregular shapes). Some crystals habits (like bullet rosettes, capped columns), however, escape this method.



When capped columns occur the use of **As_{geo}** can lead to incorrect results. This is mainly due to the arbitrary orientation of the crystals images as depicted in Fig.6a.

Fig. 6 : a) As_{geo} and b) $As_{ellipse}$

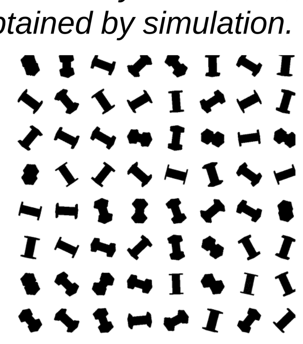
For this reason we apply also another definition for ***As,*** the ***elliptical*** aspect ratio

$As_{ellipse}$ = minor axis / major axis .

The reconstruction of the ellipse is presented in Fig.6b. It has the same center of gravity and the same inertial moment as the crystal image.

In order to test to what extent both aspect ratio **As_{geo}** and **$As_{ellipse}$** can be used for the recognition of complex crystal forms, one million of randomly orientated capped columns were simulated (Fig.7) using the same geometrical model.

Fig. 7: Examples of 2D projection for 3D capped columns, randomly orientated, obtained by simulation.



Results for **As_{geo}** and **$As_{ellipse}$** are given on transparency **5**

5 Results:

a) Results for $As_{ellipse}$: Fig.8a shows the frequency distribution of the aspect ratio for all simulated images. Its maximum is located at $As_{ellipse}$ around 0.55.
In the bottom of the figure two populations of crystal images are presented. The left one shows those which are well oriented for a more accurate image recognition while the images with As > 0.7 presents projections of capped columns which cannot be used for the detection of the crystal shape.
However, this analysis doesn't allow to distinguish capped columns shaped crystals from others particles shapes as columns or aggregates. Therefore we propose a further step by combining both measures of the aspect ratio.

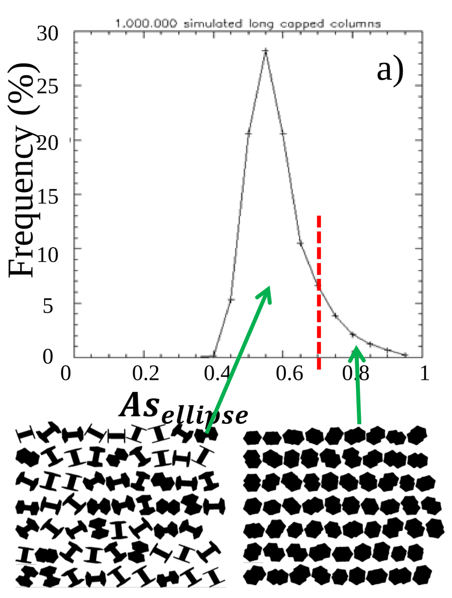
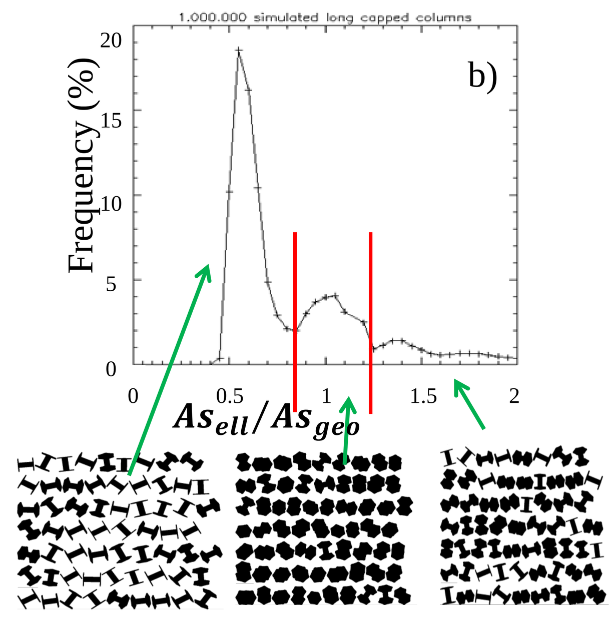


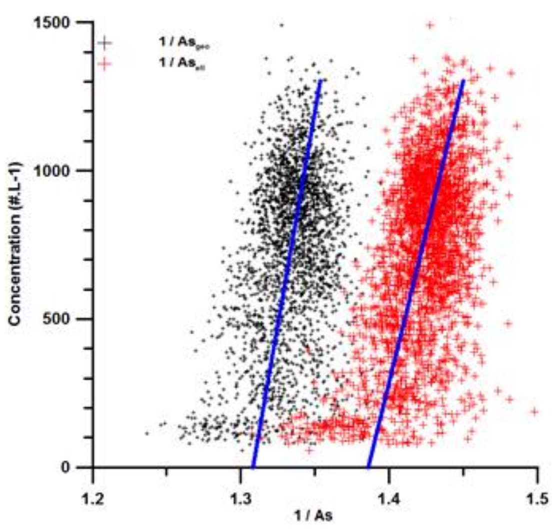
Fig. 8 : Frequency distributions of :
a) $As_{ellipse}$
b) As_{ell}/As_{geo}

b) Combining *$As_{ellipse}$* and *As_{geo}* : Fig.8b shows the frequency distribution of the ratio ($As_{ellipse}/As_{geo}$). We can detect three different modes. The bottom figures depict examples of crystal populations corresponding to the three modes. The center mode around $As_{ellipse}/As_{geo}$ ~1 represents particle shapes for which the geometrical width and the elliptical minor axis almost agree. These zone of non ambiguous images allows to better determine the well oriented capped columns.



➔ thus, using both criteria:
(1) **$As_{ellipse}$** < 0.7 and (2) **$As_{ellipse}/As_{geo}$** $\notin$ [0.85, 1.25]
will allow to better detect well oriented capped columns.
This method was tested by analyzing the Airbus Nephelometer data. An example of results are shown in Fig.9.

Fig. 9 : Application of capped column detection to the Airbus Nephelometer measurements.



c) Application of the aspect ratio for microphysical studies on ice crystals

Both aspect ratios **$As_{ellipse}$** and **As_{geo}** were analyzed with respect to the observed ice crystal number concentration and the IWC.
Fig.10 shows the crystal number concentration versus the inverse values of both aspect ratios for measurements performed in the above presented MCS. We can see that the mean inverse aspect ratio increases with the crystal number concentration. This result holds for both **$As_{ellipse}$** and **As_{geo}** .
The same behavior was detected for the IWC.
This observational finding indicates that crystal growth prior to the observations took place in regions of high ice super-saturation, which promotes small aspect ratios (corresponding to an elongated crystals shape). This is most surprising as crystal number concentrations are very important (> 1000 per liter) and a fast consumption of the water vapor should be expected.

*Fig. 10 : Scatter plots of crystal concentration in convective areas. The abscise is defined by the inverse of aspect ratio. Red points are for **$As_{ellipse}$** and **black** points are for **As_{geo}**. Each point presents an average over 200 m. Blue lines present best fits of the observations.*

Conclusion:
- We propose a new method for the detection of capped columns in real cloudy conditions. It is based on two parameters : **$As_{ellipse}$** and **$As_{ellipse}/As_{geo}$**. **$As_{ellipse}$** allows selecting well oriented images while the ratio **$As_{ellipse}/As_{geo}$** helps to reject less complex particle images.
- We observed an anti-correlation between crystal aspect ratios and crystal concentration in the most convective region of the cloud. This is probably due to the presence of high super-saturation in the subjacent cloud layers, which permits the development of elongated crystals.
- Further research is needed to better detect complex crystal shapes which occur in elevated cloud layers.