Airborne measurements in different clouds

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DOI: 10.13111/2066-8201.2021.13.1.3

Received: 25 August 2020/ Accepted: 05 October 2020/ Published: March 2021

Abstract: *The aim of this paper is to analyze different aspects of microphysical properties of mixed phase clouds, considering also the processes that are contributing to their formation. ATMOSLAB airborne laboratory, equipped with CAPS – Cloud, Aerosol and Precipitation Spectrometer sensors system was exploited to perform three flight research missions focused on cloud microphysics. For this purpose, there was analyzed the variation of 4 major parameters with high influence the cold clouds lifecycle (temperature, pressure, number concentration, effective diameter and 2D images of droplets and ice crystals) and was highlighted the occurrence of nucleation, accretion and droplet coalescence in cirrus and cirrostratus clouds.*

Key Words*: cirrus cloud, airborne measurements, ice crystals*

1. INTRODUCTION

Clouds have an important role in the Earth's energy budget [1]. The radiative properties of clouds depend on microphysics properties, especially on particle size distributions and liquid water content. With a global cloud coverage of 20% up to 30% [2] mixed phase clouds, consisting of liquid droplets and /or ice crystals, present a high scientifically interest due to the formation and evolution process that yet are not well-understood.

The aerosol particles initiating the water phases represent an important factor which influence the clouds composition and all their properties. These particles can be activated as ice nuclei (IN) or cloud condensation nuclei (CCN) [3].

Thus, the presence of ice nuclei (IN) can lead to rapid conversion of liquid droplets into ice active crystals [4]. In many clouds, the formation of ice crystals can lead to a fast growth of ice crystals on the expense of the surrounding liquid droplets. On the other way, an increased fraction of cloud condensation nuclei (CCN) might develop more, but smaller, droplets and, thus, may suppress freezing [4].

Due to the difference of water vapor saturation over ice crystal and liquid droplet, the mix of ice particles and liquid droplets is very unstable. Generally, the continuous change among water phases affects the life cycle of clouds [4, 5].

The need of understanding mixed-phase clouds microphysical characteristics for improving numerical forecast modelling and radiative transfer calculation is a major interest for atmospheric community [6, 7].

Given the high spatial and temporal variability of clouds, properties such as concentration, size and shape vary noticeably on scales of millimeters and seconds [8]. For instance, potentially coexistence of both liquid droplets and ice crystals, with respect to temperature, is limited from 0°C to -40°C [9, 10, 11].

In this context, one of the most important parameters in clouds' studies is represented by the effective diameter of cloud particles [12, 13]. Airborne determinations provide a statistical characterization of the properties of a specified cloud volume in terms of particle size and shape distributions.

Studies of cloud phase composition have been significantly limited by a lack of aircraft instruments capable of discriminating between the ice and liquid phases for a wide range of particle sizes [14].

This work presents a study focus on the evolution of microphysical parameters in mixed-phase clouds based on *in situ* measurements (datasets were collected using an airborne platform equipped with in situ instrumentation).

2. METHODOLOGY

The measurements, presented in this paper, were performed using ATMOSLAB – Airborne Laboratory for Environmental Atmospheric Research (owned by INCAS – National Institute for Aerospace Research "Elie Carafoli"). Equipped for atmospheric research missions, it is based on a Hawker Beechcraft – King Air C90 GTx aircraft. Datasets were collected by CAPS (Cloud, Aerosol and Precipitation Spectrometer) system [15], mounted on the right wing of the airborne laboratory.

This multipurpose particle spectrometer is an integrated measurement system, including three sub – systems (CIP - Cloud Imaging Probe, CAS – Cloud Aerosol Spectrometer, Hotwire LWC sensor) and sensors for temperature and liquid water. CAPS provides the following data: aircraft velocity, atmospheric temperature and pressure, aerosol particle and cloud hydrometeor size distributions from 0.51 to 50µm, precipitation hydrometeors size distributions from 25µm to 1550µm, or 15-930µm with optional 15-micron resolution, particle optical properties (refractive index), particle shape assessments and liquid water content from 0.01 to 3g/m^3.

The measurements are acquired during 3 flights from Romania, Bucharest (44°25′57″N 26°06′14″E) to Germany: Friedrichshafen (47°39′15″N 09°28′45″E) and Berlin (52°30′2″N 13°23′56″E) on 17.04.2012, 21.04.2012, respectively 05.06.2012 above the same region of Europe.

The flight path was starting from Bucharest, to the western part of Romania above Hungary, Austria at a cruise altitude between 6000-8500 m ASL, reaching Germany after 4 hours.

In comparison with specific research flight missions focused on cloud characterization, the results presented here are acquired during regular flights and targeted the cloud base, the cloud center or the cloud top.

One main limitation of the measurements presented here is the volume swept out by the cloud probe that has an elongated shape and corresponds to the flight track, so the *in situ* cloud sampling can be considered as quasi-1D measurement.

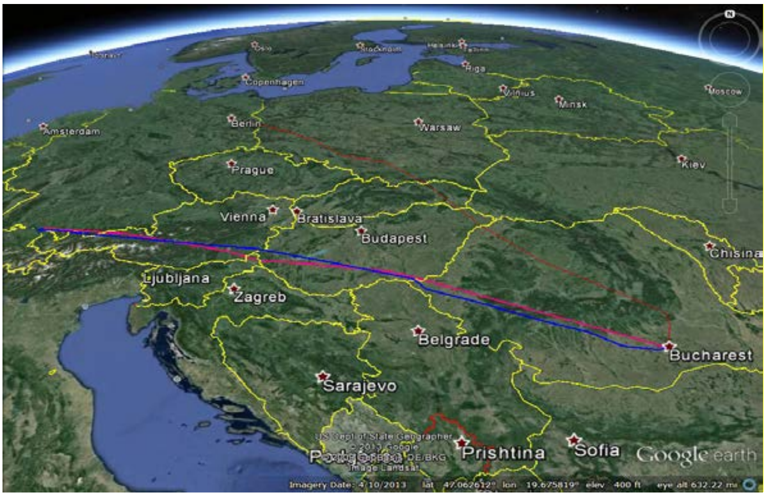

Fig. 1 Flight path for: **Flight 1**: Bucharest– Friedrichshafen, 17.04.2012;
Flight 2: Friedrichshafen – Bucharest, 21.04.2012; **Flight 3**: Bucharest- Berlin 05.06.2012

3. RESULTS AND DISCUSSIONS

Airborne aerosol and cloud particle measurements are important to extend our knowledge of their distribution, properties and interaction [9]. Cloud sampling from aircraft is a particular challenge due to the inertial effects at high aircraft cruising speeds of some big enough drops or ice crystals. The cases analyzed here correspond to different clouds and should be interpreted with caution considering that mounting location, effect of probe housing, aircraft, droplet splashing and breakup and also ice particles bouncing and shattering can introduce significant errors in microphysical measurements.

3.1 17.04.2020 (Cirrostratus cloud)

On the day of 17[th] of April 2012 during a fairy flight from Bucharest to Friedrichshafen, after 32 minutes of flight the CAPS started the horizontal sounding of a cirrostratus cloud. The sounding was performed at altitude of 7271 m ASL, for approximately one hour. Time variations of temperature and pressure are represented in Fig. 2.

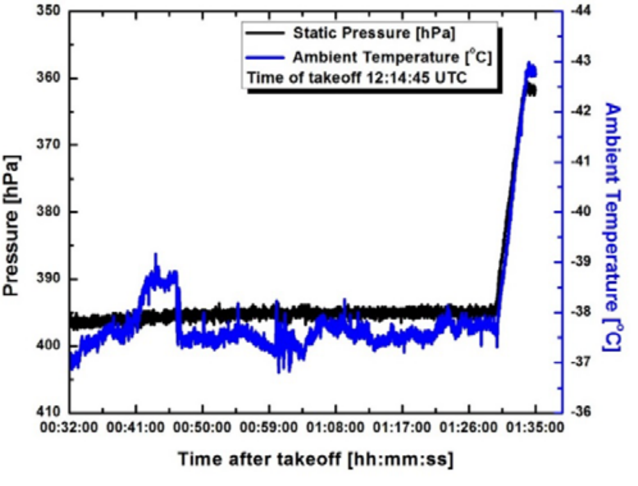

Fig. 2 Time variation of static pressure and ambient temperature

The temperature variations indicate ice crystals formation starting with minute 32 to minute 38 from super cooled water droplets that crystallized on small aerosol particles (ice nucleation). After the crystal formation, important accretion processes occurred facilitating the formation of ice conglomerates of large dimensions until minute 1:30 (Figs. 3-5). Further, the measurements where performed in an ascending flight (Fig 2). Figure 3 presents the data acquired with the CAS and CIP, the sensors indicating the presence of small aerosol particles and super cooled water droplets in high concentrations. There was noticed a wide range of ice crystals dimensions with a maximum concentration of 90 particles/ cm^3, when the instrument was in the middle of the cloud in the last 5 minutes, ascending flight.

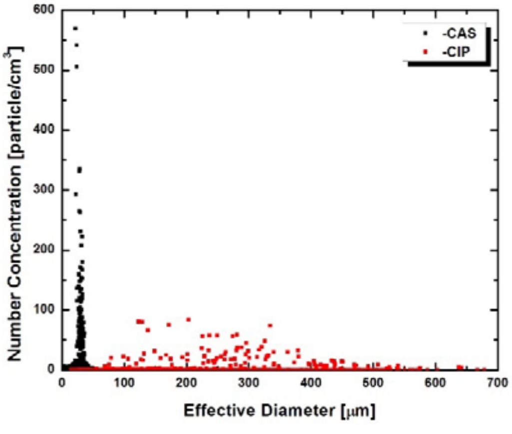

Fig. 3 Number concentration versus effective diameter from CAS and CIP

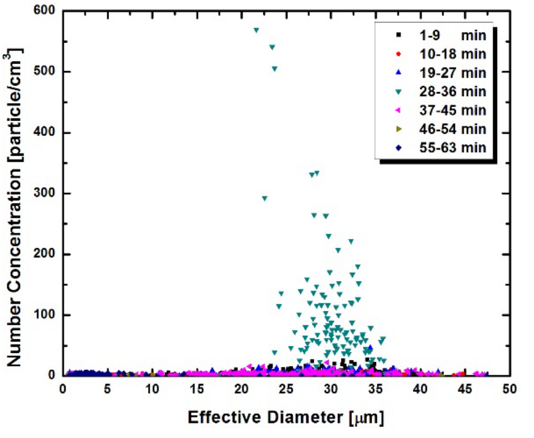

Fig. 4 Number concentration versus effective diameter from CAS

The values of effective diameters (Figs. 3 - 5) and distinctive number concentrations measured by CAS and CIP prove the presence of aerosols and ice nuclei in the first minutes (Figs. 3 and 4) and then ice crystals (Fig. 5).

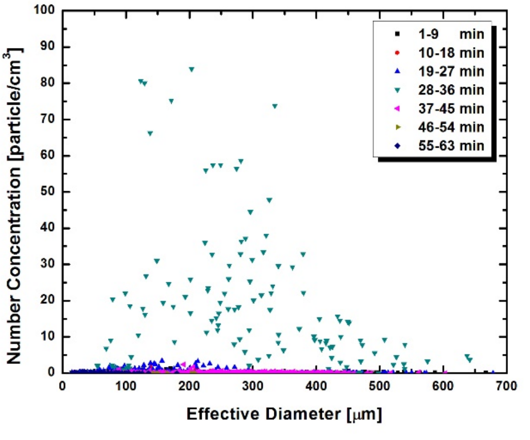

Fig. 5 Number concentration versus effective diameter from CIP

The presence of super cooled water and ice crystals of different sizes was confirmed by 2D images recorded real-time by CIP, part of the CAPS system (Fig. 6). The images collection highlights typical shape of droplets and ice crystals, e.g., plate-like, specific for cirrostratus clouds, and confirms the results reported in the literature [3, 16].

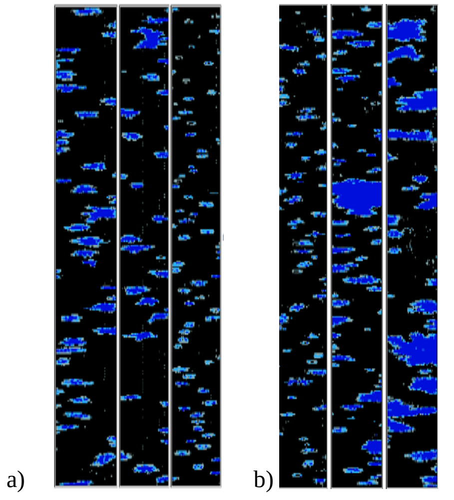

Fig. 6 CIP 2D images: a) supercooled water in the first minutes of the sounding in the cirrostratus cloud, b) ice crystals in the last minutes. The different blue shades correspond to 3 levels of shadows created when the particles images are recorded.

Given the temperature range -20 to -40 (fig. 2), the reported Cloud Imaging Probe images (Fig. 6) included predominant crystal types as polycrystalline forms, columns, plates and bullets, as it was determined by Heymsfield and Platt [17]. One additional aspect that should be considered is the clustering of ice particles and the crystal shattering on the probe's inlets, and the repercussions on datasets quality [18, 19, 20]. Field et al. reported that clustering of ice particles in cirrus clouds may be the result of shattering of crystals with dimensions higher than 350µm. Therefore, this effect should be taken into account also for the reported data in this work since the particle effective diameter are above the reported limit of 350µm.

3.2. 05.06.2012 (Cirrus cloud)

The second flight analyzed is the case of fairy flight from Bucharest to Berlin, after 32 minutes of flight the CAPS started the sounding of a cirrus cloud.

The ATMOSLAB laboratory flew in an ascending path for 8 minutes that corresponds to the pressure variation presented in Fig. 7. For the next 30 minutes the flight path was horizontal at an altitude of 7823 m ASL.

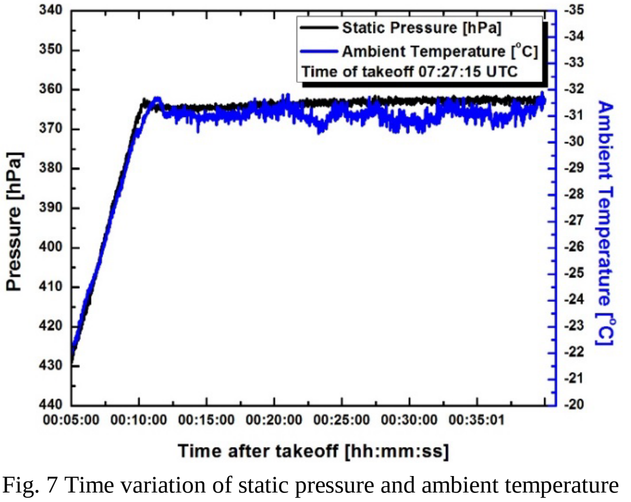

Fig. 7 Time variation of static pressure and ambient temperature

The temperature variation is strongly connected with the flight pattern. After the first 8 minutes of ascending, the variation of temperature indicated the formation of ice crystal in two distinct intervals from minute 25 to minute 30, and from minute 30 to minute 35. In this timeframe, the aircraft flew directly through the cirrus cloud, in the rest of the time, the aircraft was in the immediately proximity of the cloud. Figure 8 reveals typical ice crystal dispersion for the two timeframes mention before.

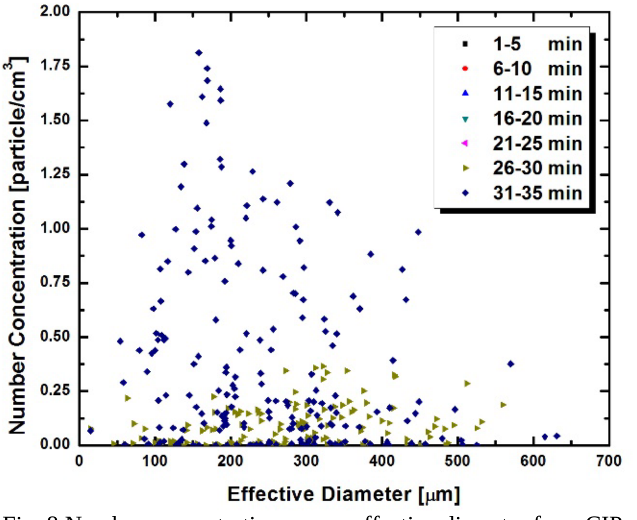

Fig. 8 Number concentration versus effective diameter from CIP

Putting together the data recorded with the CAS and CIP (fig. 9), the sensors are indicating the presence of small aerosol particles and super cooled water droplets, but in lower concentrations than in previous case (17.04.2012).

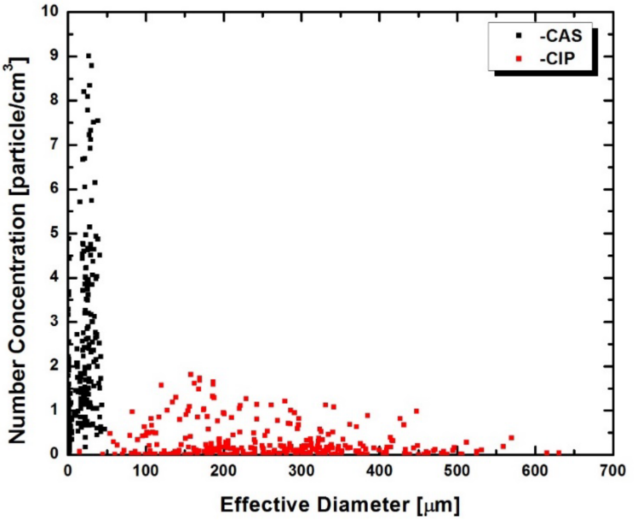

Fig. 9 Number Concentration versus Effective Diameter from CAS and CIP

The ice crystals that formed the cirrus cloud sounded on the date of 5th of June 2012 were exposed to a growing process caused by accretion and deposition in the last two time intervals in the figure 10.

In the temperature range reported in this case, -22° to -32° C, the grown shapes of the ice crystals are plate-like [3].

The here reported number concentration for both instruments (CAS and CIP) are in agreement with odder measurements performed in cirrus clouds. Ice concentrations from 0.2 to 1cm^{-3} were observed in cirrus, this value is one to two orders of magnitude higher than most previous measurements [17, 20]. Measurements in synoptically generated cirrus where up to 5 cm^{-3} of ice with no contribution of particle shattering [19]. Figure 9 confirms that more than 90% of the particles in this second case are below 350µm, so that the shattering effect of the particles is not significant here.

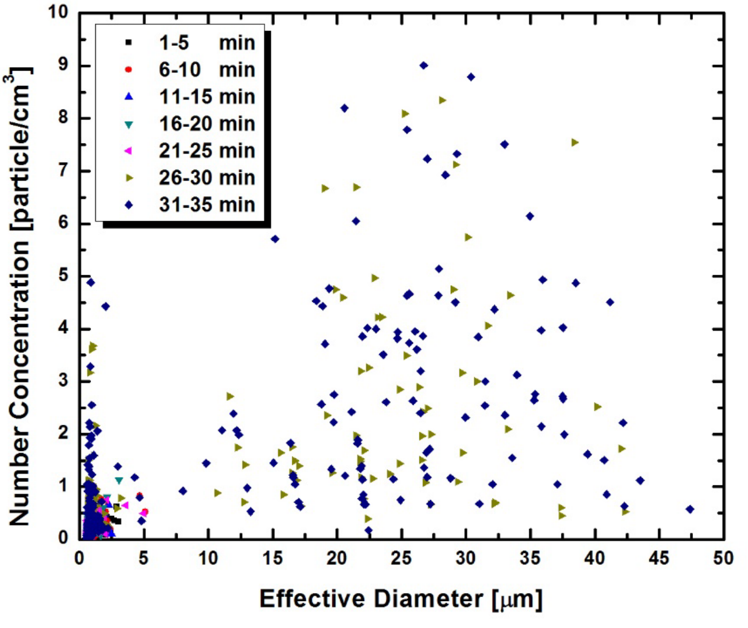

Fig. 10 Number Concentration versus Effective Diameter from CAS

The crystal dispersion may reveal that the cloud was in the state of formation or that the aircraft influenced the ice crystals density near the instrumentation. Further investigations may be necessarily to understand the influence of the aircraft and its instrumentation on the cloud measurements.

3.3. 21.04.2020 (Mixed – phase cloud)

Mixture of water droplets and ice crystals are found most often between -5ºC and - 25ºC [3]. Most commonly, in mixed-phase clouds, the drop formation proceeds the glaciations within the clouds [21].

The exact interaction between aerosol and ice is still under investigation, the relative importance of freezing modes is not known, and in general the physical and chemical processes underlying heterogeneous ice formation is limited [22].

The third case studied a cold cloud. The flight took place at an altitude of 5100 m, flight in a horizontal line for 8 minutes. During this straight flight a temperature gradient of 2 degrees was measured (fig. 10.a).

Known heterogeneous nucleation mechanisms are immersion, condensation, deposition and contact freezing [3]. Looking at Fig. 10.b (the number concentrations versus effective diameters) it is clear that at the sounding moment in the cloud occurred a multitude of processes, and none of these was dominating.

Observations of IN show a high temporal, spatial and seasonal variability [23]. The knowledge of IN active concentration in mixed-phase clouds is crucial in the prediction of ice formation for this type of cloud. Analyzing the number concentrations versus effective diameters for both CIP and CAS sensors, it was observed that CAS detected significant quantities of interstitial aerosol (fig 10.c) confirmed due low values of the effective diameters of the CAS detected particles and the presence of few ice crystals and supercooled water droplets with effective diameters between 200 – 750 µm.

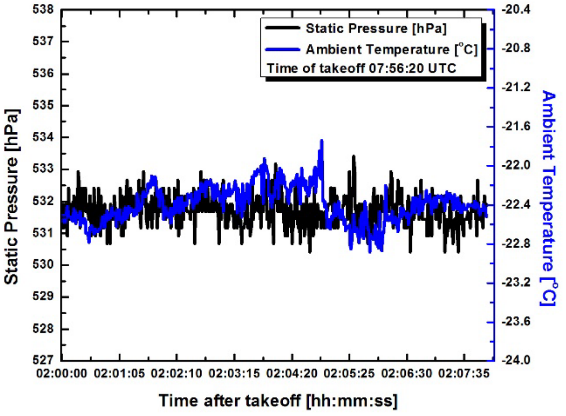

Fig. 11.a Time variation of Static Pressure and Ambient Temperature

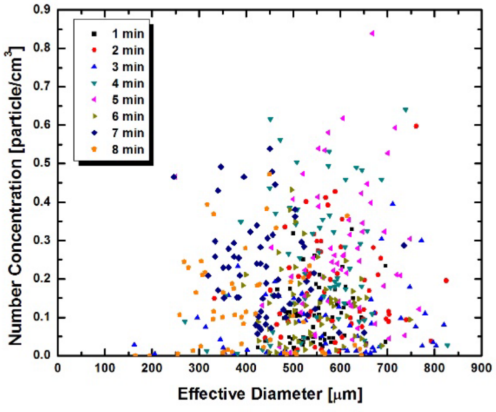

Fig. 11.b Number Concentration versus Effective Diameter from CIP

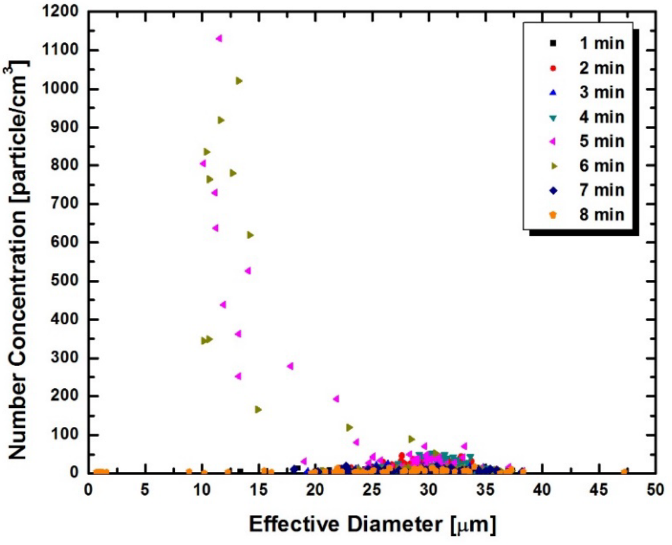

Fig. 11.c Number Concentration versus Effective Diameter from CAS

Depending on the type of sampled cloud, the its number concentrations can be as low as a few per cubic meter (case 2) or high as several thousand per cubic centimeter (case 3) [9].

This last case reveals the same bimodal particle size distribution, displaying a maximum in number concentration near 30 µm (fig. 11.c) and another smaller maximum near 400 µm (fig. 11.b).

CIP recorded data suggest that in all 8 minutes all possible cloud processes occurred, the second maximum in the particle size distribution is not well defined, therefore no process is dominating.

4. CONCLUSIONS

Microphysical measurements were collected during 3 regular flights using ATMOSLAB laboratory and in situ airborne instrumentation, in a temperature interval from - 21ºC to - 42ºC. Analysis temperature, pressure, number concentration, effective diameter and 2D images of droplets and ice crystals, allows to discriminate about the occurrence of processes as nucleation, accretion and droplet coalescence in cirrus and cirrostratus clouds. The measurements showed that cirrus particle size distribution is bimodal in all 3 cases displaying a maximum in number concentration near 30 µm and another smaller maximum near 200- 300 µm for the temperature range - 36ºC to - 42ºC (case 1) and - 22ºC to -32ºC (case 2), similar to those reported by Ivanova, 2001 and Lawson et al., 2006. For the last case, mixed-phase cloud, the particle size distribution is bimodal, displaying a maximum in number concentration near 30 µm and another smaller maximum near 400µm, but not well defined.

One major observation concluding this study is that the ice crystal dispersion figures may reveals either the cloud was under formation state or either the aircraft influenced the ice crystals density nearby the instrumentation. Further investigations may be necessarily to understand the influence of the aircraft and its instrumentation on the in cloud measurements.

ACKNOWLEDGEMENTS

This work was partially supported by a grant of the Ministry of National Education and Scientific Research, RDI Programme for Space Technology and Advanced Research - STAR, project number 38/2012, and partially by PN National Program, project contract 8N/2019, code: PN19010502.

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