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Microphysical and radiative properties of ice clouds using a cloud radar-lidar algorithm

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Abstract. Clouds are an important component of the Earth' climate system. However their parametric representation in large scale circulation model is recognized as insufficient. The present paper synthesizes a 3-years study done on the development and improvement of a radar-lidar synergetic algorithm. Three parts are presented:
(i) we first introduce an inverse model based on the study of in-situ microphysical measurement which is a computation of relationships between instrumental and clouds parameters,
(ii) then, we present the instrumental synergetic algorithm. This algorithm combines the apparent backscatter coefficient of the lidar, the apparent reflectivity from the radar and the inverse model to infer properties of the particle size distribution. The new version of the algorithm is based on a segmentation of the path accounting for the natural variability of normalized concentration in the cloud layer,
(iii) we present the results of the synergetic algorithm on several experimental cases. Retrieved parameters are validated with in-situ microphysical measurements.

1 Introduction

To appreciate the radiative impact of clouds in the dynamics of the global atmosphere, it is important to deploy from space, from aircraft, or from ground, instruments to describe the cloud layering and to document the cloud characteristics (namely liquid and/or ice water content, and effective radius.

Earth CARE (Earth Cloud Aerosol Radiation Explorer) is an ESA mission aiming to address this question. It plans to combine on the same spaceborne platform a cloud radar and a lidar to retrieve the microphysical and radiation properties of clouds. The same combination (radar-lidar) will be also launched with the Afternoon-train of Cloudsat (NASA cloud radar) and Calipso (CNES lidar).

RALI (RAdar-LIdar) developed at IPSL (France), which combines the 95 GHz cloud radar RASTA of the CETP and the 0.5 μm wavelength backscattering lidar LEANDRE of the Service d'Aéronomie, is an airborne demonstrator for this mission.

The Clare98 field campaign used a RALI prototype combining the 95 GHz radar KESTREL of the University of Wyoming and the LEANDRE lidar.

The first tests of RALI were successfully completed during the last Carl2000 and Carl2001 field projects (in November 2000 in Brest and in March 2001 in Bretigny-sur-Orge, France), where both instruments were mounted on board the french ARAT aircraft. The Meteo-France MERLIN aircraft, instrumented with microphysical probes of the GKSS (Germany) for Carl2000 and of the LAMP/Météo-France (France) for Carl2001, was simultaneously flying within the clouds below the ARAT.

We will present in this paper the principles of the algorithm that combines lidar and radar data. Then we will show some simulation results taking into account the natural variability of the intercept parameter of the particle size distribution and we will also present results of this algorithm applied to data from Clare98 and Carl2000.

2 Radar-lidar algorithm

2.1 Synergy algorithm inputs

The radar lidar algorithm is based on three essential elements:

– the apparent reflectivity Z_e from the radar,

– the apparent backscattering coefficient βe from the lidar,

– an inverse model consisting of microphysical power laws relating clouds parameters to instrumental parameters.

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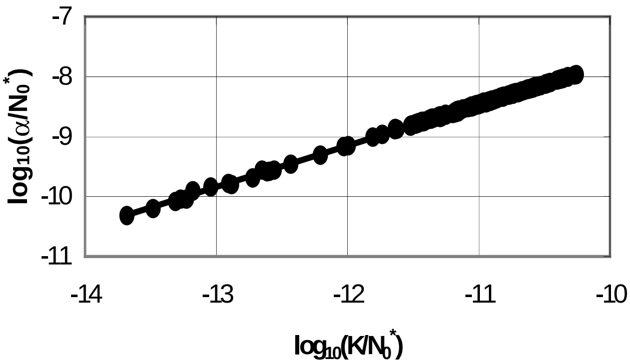

Fig. 1. The α/N_0* versus K/N_0* relationship for the CLARE98 microphysical data set and for a 95 GHz radar (α [km^{-1}], K [dB.km^{-1}], N_0* [m^{-4}]).

2.2 Inverse model

The inverse model, as explained in Tinel et al. (2000), is founded upon a set of power law relationships relating the radar parameters (attenuation K and reflectivity Z), the lidar parameters (backscattering coefficient β and extinction coefficient α) and the normalized distribution parameter N_0*. The power laws are:

$$K = a(D_m)[N_0*]^{1-b(D_m)} Z_e^{b(D_m)} \quad (1)$$

$$\alpha = m(D_m)[N_0*]^{1-n(D_m)} K^{n(D_m)} \quad (2)$$

$$IWC = c(D_m)[N_0*]^{1-d(D_m)} K^{d(D_m)} \quad (3)$$

$$\beta = k\alpha \quad (4)$$

where D_m is the mean volume-weighted diameter and k the phase function.

The coefficients of these power laws (a, b, c, d, m and n) are established from microphysical data sets and depend on D_m. The ice density used in these formulas is founded on the definition of Franciset al. (1998). In the present study we used the Clare98 and Carl 99 microphysical data set. These field projects, which associated airborne (Clare98) and ground-based (Carl99) radar and lidar measurements and microphysical in-situ measurements took place in Chilbolton, UK, in autumn 1998 for Clare98 and in Palaiseau, France, for Carl99. We plan in a near future to use more data sets in order to build up some detailed comparison study. We calculated the reflectivity, the ice water content, the radar attenuation and the optical extinction from those in-situ measurements for different temperatures. When plotting one of those parameters versus another, the dispersion of the points makes any regression impossible. Once normalized by N_0* as in Tinel et al. (2000), the same plot becomes a straight line as illustrated in Fig. 1.

It is then easy to compute a robust regression with a set of constant coefficients to obtain a series of power law relationships. These relations connect the instrumental parameters to the microphysical ones as in Eqs. (1), (2) and (3). Thanks

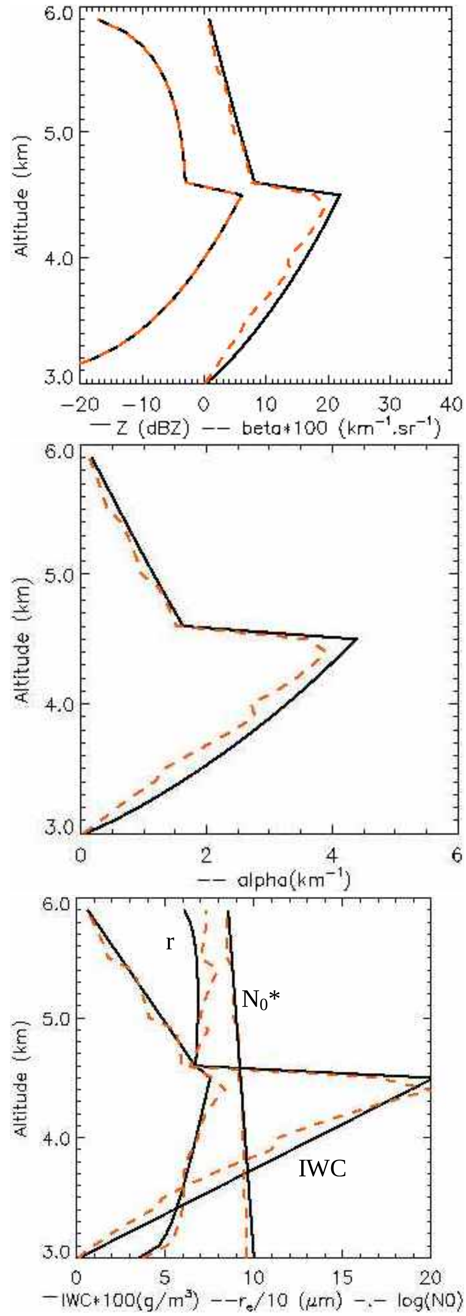

Fig. 2. Expected (plain lines) and retrieved (dashed lInes) parameters from top to bottom: **(a)** radar reflectivity Z[dBZ] and lidar backscattering coefficient β [km^{-1}.sr^{-1}] **(b)** lidar extinction α [km^{-1}] **(c)** Ice water content IWC [g.m^{-3}], effective radius R_e [μm] and N_0* [m^{-4}].

to the use of data at different temperatures, coefficients of the power law relationships have also been parameterized in function of D_m.

This inverse model will be used in the synergetic algorithm.

2.3 Retrieval algorithm

Thanks to the similarity between reflectivity and backscattering coefficient exact expressions (written respectively by Hitschfeld and Bordan, 1954; Klett, 1981), it is possible to write the exact expressions of the radar attenuation and lidar extinction as written by Testud et al. (2000).

$$K(r) = \frac{K(r_0) Z_a^b(r)}{Z_a^b(r_0) + 0.46 b K(r_0) \int_r^{r_0} Z_a^b(s) ds} \tag{5}$$

$$\alpha(r) = \frac{\alpha(r_0) \beta_a(r)}{\beta_a(r_0) + 2\alpha(r_0) \int_r^{r_0} \beta_a(s) ds} \tag{6}$$

where r is the distance from the radar and the lidar and r_0 the bottom of the integration length (airborne system). To retrieve those two last profiles, the values of K and α at r_0 are set from the following constraint:

$$\int_{r_1}^{r_0} \alpha(s) ds = m[N_0*]^{1-n} \int_{r_1}^{r_0} K^n(s) ds \tag{7}$$

where r_1 is the top of the integration length (airborne system).

Combining Eqs. (5), (6) and (7), it is possible to retrieve $\alpha(r_0)$ through an iterative process initiated with a first guess of N_0*. We assume in this calculation that N_0* is constant between r_0 and r_1. $[r_0, r_1]$ is the integration length corresponding to a distance equal to 5 instrumental gates. The iteration process converges toward a value of $\alpha(r_0)$. We also assume that the reflectivity attenuation is negligible in ice clouds. The knowledge of $\alpha(r_0)$ and $Z(r_0)$ allows to calculate the value of $N_0*(r_0)$ (from the power law relationships), which is equal to the value of $N_0*[r_0, r_1]$.

Once we obtain the α profile, and an IWC profile, (from Z and N_0*), it is possible to retrieve an effective radius (r_e) profile.

The present method is an improved version of Tinel et al. (2000), as the value of N_0* is segmented along the retrieved profile (because of the variation of temperature with altitude and particles aggregation).

3 Application of the algorithm to a simulated case

3.1 First steps

This simulation is a first case simulation which does not take into account the instrument noise and the multiple scattering of particles. The power laws used in this simulation are from the inverse model described in the first part of the paper.

The principle is the following. We start with two variable profiles of IWC and N_0* (Fig. 2c) for a 3 km height field. Once we get those two profiles, we calculate the Z and α profiles from the combination of Eqs. (1), (2), (3) and (5). An assumption is made on the k parameter which is set to a constant value of 0.05 (it is assumed in the literature that k varies from 0.01 to 0.1 in iced clouds). It is then possible to calculate an effective backscattering coefficient β profile. It

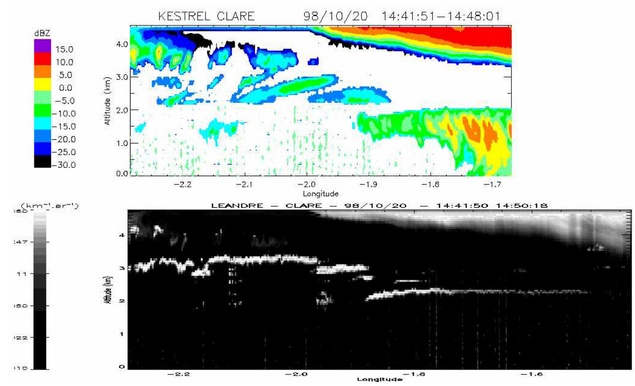

Fig. 3. Illustration of apparent reflectivity (top) of KESTREL radar and apparent backscattering coefficient (bottom) of LEANDRE lidar during Clare98 on 20 October 1998.

is also assumed in this simulation that the atmospheric temperature ranges from $-9°$C to $-15°$C.

The next step consists in calculating the attenuated backscattering coefficient profile which is one of the three input parameters of the algorithm. We consider that reflectivity is not attenuated. It is then possible to apply the algorithm.

3.2 Results

Figure 2 represents the expected and retrieved parameters through the simulation. The solid lines represent the expected parameters and the dashed lines the retrieved parameters. The segmentation provides well retrieved profiles even if slight differences appear. Mean standard deviations have been calculated. The values are:

$$\sigma(\alpha) = 0.315\,\text{km}^{-1}$$
$$\sigma(r_e) = 5.257\,\mu\text{m}$$
$$\sigma(\beta) = 0.016\,\text{km}^{-1}.\text{sr}^{-1}$$
$$\sigma(IWC) = 0.0116\,\text{g.m}^{-3}$$
$$\sigma(\log(N_0*)) = 0.185 \tag{8}$$

These values are small and correspond approximately for all parameters to a 10% relative error. This would be acceptable for radiative transfert calculations.

This simulation is really a first test of the algorithm. It has been made to prove that it is possible to retrieve a nearly-variable N_0* profile. The represented variability in Fig. 2 is slight and more simulations are needed in order to check the sensitivity of the algorithm on N_0* variability.

4 Application of the algorithm to real data

4.1 Clare98

The Clare98 field campaign took place in Chilbolton (UK) in autumn 1998. This experiment is part of the ESA's Earth Observation Preparatory Programme (EOPP). The objectives of this campaign were to collect and analyse radar and lidar

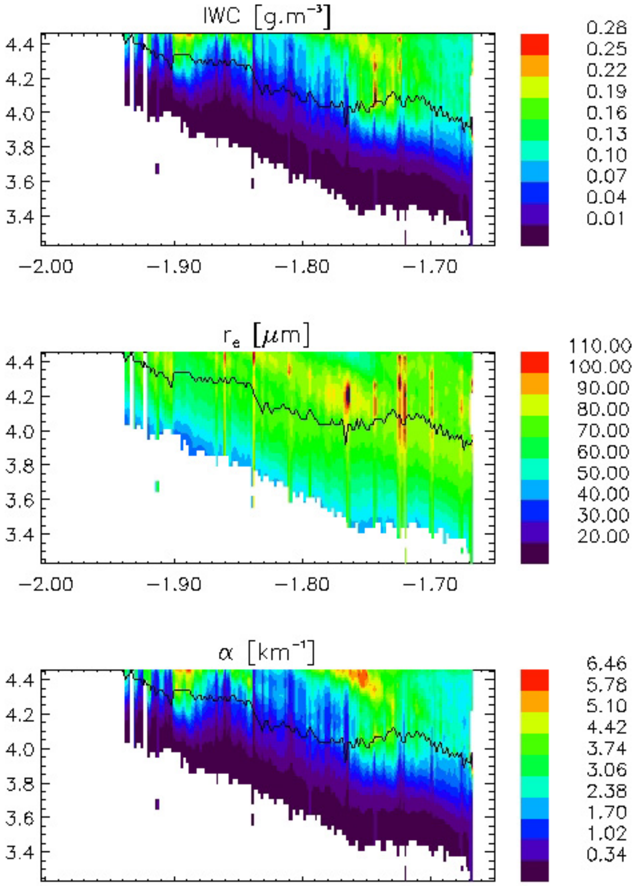

Fig. 4. From top to bottom: retrieved ice water content, effective radius and extinxtion parameters from the synergetic algorithm for the iced stratus (Clare98).

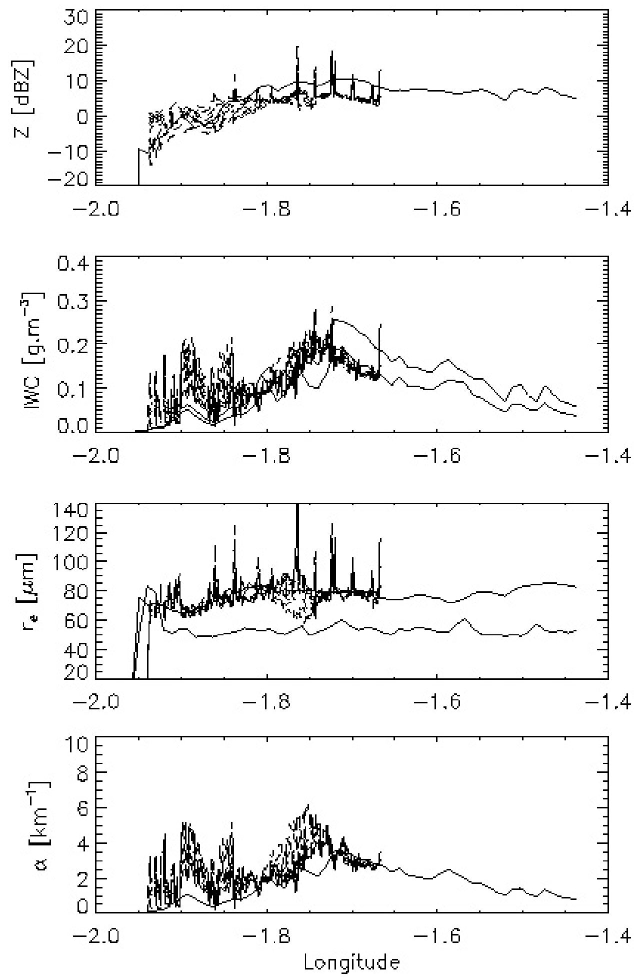

Fig. 5. From top to bottom: reflectivity, ice water content, effective radius and extinction parameters. Dashed lines: in-situ measurements. Plain lines: retrieved parameters from the synergetic algorithm.

as well as in-situ data to support the development of retrieval algorithms and to consolidate the scientific requirements of the future EarthCARE mission. A considerable number of instruments were available for the campaign, on ground and airborne. The French ARAT aircraft was equipped with a RALI system and the C130 of the UKMO with in-situ microphysical probes.

The subsequent data analysis is focused on a particular leg (20 October 1998 from 14:41 to 14:48 UTC) where the ARAT was flying at 4.8 km altitude and the C130 was flying at 5.5 km altitude along the same leg. The altitude of the freezing level was around 1.8 km. Thanks to a good coordination between the two aircrafts, a very satisfactory coincidence in space and time of the ground tracks of the two aircrafts was met on this leg. Different cloud systems have been observed during this leg (Fig. 3). The values of the apparent lidar backscattering coefficient indicate some liquid clouds as the lidar only sees the top of these clouds (at the altitudes of 2 and 3 km).

Figure 4 shows a retrieved vertical cross section of α, IWC and r_e between -1.7 and $-2°$ W. The mean values of effective radii in the upper part of the cloud are 75 μm, the ice water content 0.15 g.m^{-3}. The retrieved values in this part of the cloud are validated by the comparison with in-situ measurements (2DC and 2DP probes) from the C130 . Figure 5 shows very good retrievals from the synergetic algorithm: retrieved values by the algorithm are consistent with the in-situ measurements. Since the C130 aircraft was flying at the altitude of 4.8 km and radar and lidar data were available under 4.5 km, retrieved values from 4.2 to 4.5 km are represented. The consistency of retrieved parameters with in-situ measurements improves the robustness of the inverse model.

4.2 Carl2000

The two last field campaigns which combined airborne radar and lidar were the Carl2000 in November 2000 and Carl2001 in March 2001 campaigns.

The synergetic algorithm has been applied to those data. Figure 6 shows the apparent radar reflectivity and lidar backscattering coefficient for one straight flight pattern on 10 November 2000. That shows a good penetration of the

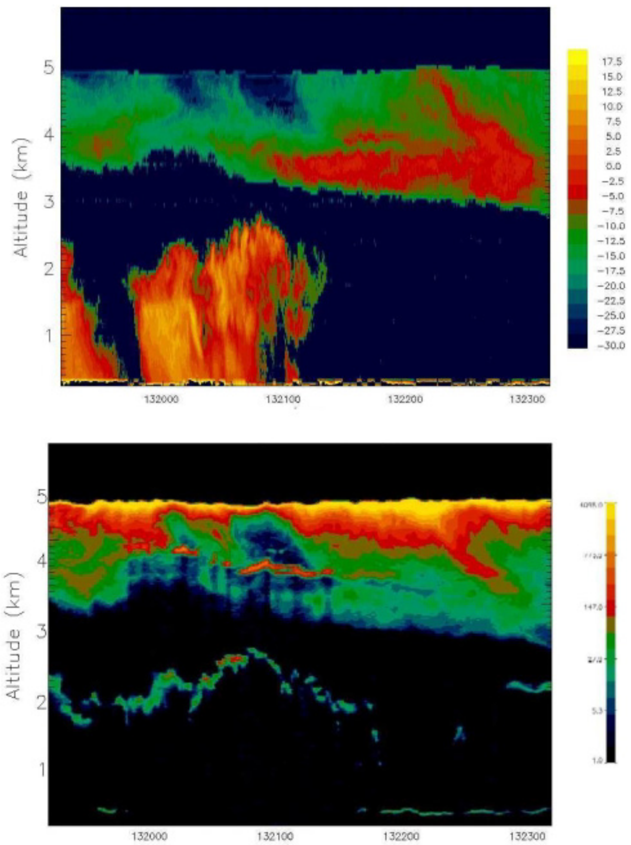

Fig. 6. Illustration of apparent reflectivity (top) of RASTA radar and apparent backscattering coefficient (bottom) of LEANDRE lidar during Carl2000 on 10 November 2000.

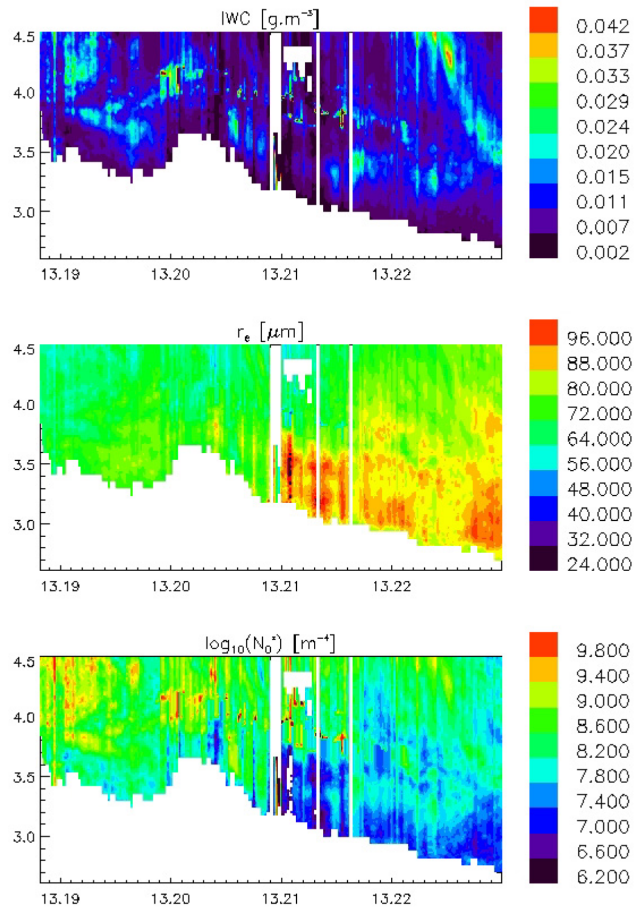

Fig. 7. From top to bottom: retrieved ice water content, effective radius and N_0* parameters from the synergetic algorithm for the iced stratus. CARL'2000 – 10 November 2000.

lidar and radar beam into the upper cloud layer (iced stratus). The lower cloud layer, which is a precipitating layer, is well described by the radar. The backscattered power of the lidar shows the top of this precipitating layer. Thin supercooled layers are also seen by the lidar (at an altitude ranging from 3.9 km to 4.2 km).

The presence of those supercooled layers is confirmed by the in-situ measurements. The Merlin was flying within the cloud at an altitude of about 4–4.2 km, and the measurements of the TW probe onboard the aircraft indicates the presence of cloud water in this part of the cloud (with a LWC mean value of 0.05 g.m^{-3}).

Figure 7 shows the retrieved microphysical and radiative parameters from the synergetic algorithm. Effective radius values range from 60 to 100 μm in the ice cloud with aggregation at the bottom of the cloud. Values of the ice water content are ranging from 0.015 to 0.04 g.m^{-3} in the ice part of the cloud. In this present case effective radii are calculated with the hypothesis of the presence of ice only. We apply two different algorithms for this supercooled layer: the first one takes into account the reflectivity. Since the N_0* value is not really different below and above the supercooled layer, we use this value and the reflectivity to calculate the ice water content of this layer (from the power law relationships). The second algorithm concerns the liquid water content. Since liquid water is mainly seen by the lidar, we consider an inverse model which takes into account only the lidar measurements. We use a constant value of f : 0.05sr^{-1} as found in water droplets by Pinnick et al. (1983). This should be more representative of the truth. Figure 8 shows the retrieved liquid water content and effective radii for the liquid phase. Values of the liquid water content are weak: they range from 0.005 to 0.004 g.m^{-3}. The mean value of the effective radii is about 5 μm, which is a value mean observed by Hogan et al. (2002) in supercooled layers.

5 Further work

The next step will be to study the extension of the microphysical database set which will allow us to generalize the power relationships expressions,
The simulation is being extended with the introduction of noise instrument and the variation of k parameter (backscattering coefficient to the extinction parameter ratio),
The new power law relationships retrieved and the improvement of the algorithm due to the simulation study is currently

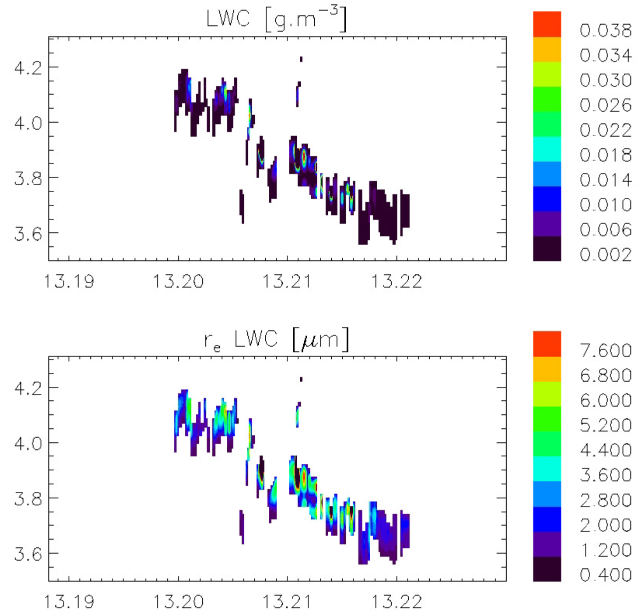

Fig. 8. Retrieved liquid water content (top), and effective radius (bottom) from the synergetic algorithm for the supercooled layer. CARL'2000 – 10 November 2000.

applied to the database set from Carl 2000 and Clare 2001. A dynamical approach, as explained in Protat et al. (2002) will be applied to these data to study the dynamics to microphysics interactions.

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