WP22- JRA3: A framework for cloud-aerosol interaction studies

Deliverables D22.6: Report and documentation on scaled-down observation methods for implementation at cloud profiling sites

Scheme for Monitoring Aerosol - Cloud Interactions

In this workpackage we focused on the formation of an optimal observation scheme of aerosol-cloud interactions. Although a broad range of strategies to quantify the interactions between aerosol and cloud already exists, different scales and methods used make it difficult to compare the results of those investigations. Thus, our main goal was to develop a scheme that would be easy to implement at various cloud-profiling observatories of the ACTRIS network.

The current stations make high resolution observations of vertical profiles with cloud radar, ceilometers, and microwave radiometers. The combination of those instruments provides the necessary information for the evaluation of the interaction between aerosol and clouds. For quantifying the concentration of aerosol below the cloud we use an integrated value of the Attenuated Backscatter Coefficient derived from ceilometer measurements. Information about the cloud droplets (concentration and size) is obtained from the Integrated Radar Reflectivity Factor. In order to make sure that we are observing the first indirect effect we need to put a constraint on the amount of water available in the column under consideration. For this we use the Liquid Water Path provided by the microwave radiometer.

In addition, we use the retrieval of liquid water cloud properties (Knist, C.L., 2014) to obtain the microphysical characterization of the clouds. This retrieval is also based on the combined measurements from radar, lidar and microwave radiometer.

Observation of Aerosol - Cloud Interactions

In this scheme we assume that the number concentration of cloud droplets is related to the number concentration of the aerosol below the cloud. If that is the case, then we expect to observe aerosol-cloud interaction when the Attenuated Backscatter Coefficient below the cloud is increasing at the same time as the Radar Reflectivity Factor is decreasing. Further, we compare the Attenuated Backscatter Coefficient to the retrieved value of the Cloud Droplet Effective Radius, which is also expected to decrease with an increased amount of aerosols below the cloud. The increase of the Attenuated Backscatter Coefficient could also be driven by the increase of the aerosol size (as the backscatter can be approximated to the number concentration of the aerosol particles times the square diameter of the aerosol particles). However, in such a case we won't be able to observe changes in the cloud.

A number of factors, such as meteorology or cloud drop properties, can influence changes in cloud. For that reason, we put a constraint on the liquid water path, as suggested by Twomey (Twomey, 1974). This limitation ensures that the variability in the cloud will be primarily due to changes in microphysical properties associated with variation in aerosol. Further, we limit the cases only to non-precipitating liquid-water clouds with no drizzle present (this selection is based on the Cloudnet target classification).

Although this method is also based on a synergy of remote sensing instruments, we use widely available systems for a quick and efficient evaluation of aerosol influence on cloud. The main advantages of this method include fast data processing and a possibility to apply this framework easily at new or existing observational sites. Moreover, this approach enables to process large time series of data and is less restrictive in cases selection than most microphysical cloud properties retrieval algorithms used to obtained cloud droplet size in previously performed studies.

Aerosol - Cloud Interactions Data Procedure

1. Data selection: water clouds.

The Cloudnet categorization system contains information on the nature of the targets in each resolution volume. The information is in the form of an array of bits, each of which states either whether a certain type of particle is present (e.g. aerosols), or whether some of the target particles have a particular property. The data with categorization Bit 0 (Small liquid droplets are present) and Bit 4 (Aerosol particles are present and visible to the lidar) can be analysed. In some cases also Bit 1 (Falling hydrometeors are present) can be used, but only if it’s small drizzle particles. This should be checked manually based on the other variables. Data should be further evaluated based on the “quality bits” variable, which contains information on the quality of the data at each pixel.

2. Instrument availability and accuracy.

Data from all relevant instruments is examined. The data sets of interest include: Microwave radiometer liquid water path, radar reflectivity factor, lidar attenuated backscatter coefficient and the related error estimates. The liquid water path derived from HATPRO microwave radiometer is retrieved with an accuracy better than 20 g/m^2. The radar reflectivity accuracy is assumed to be better than 5dBZ. Some technics have been developed to evaluate the accuracy of these ground-based remote sensing instruments with for example the profiling with in-situ sensors as already done at SIRTA observatory for the BASTA FMCW cloud radar (see following section). Furthermore the selected data is limited to non-precipitating clouds with no drizzle present by putting a constraint on the value of the radar reflectivity factor (only process data if it is smaller than -20dBZ).

3. Instrument cross-correlation and evaluation.

The lidar and radar signals are cross-correlated, based on direct observables from the instruments: the lidar attenuated backscatter coefficient as an aerosol proxy and the radar reflectivity factor as the cloud proxy. As a number of factors can influence changes in cloud, such as meteorology or cloud drop microphysical properties, a constraint on the liquid water path is put, as suggested by Twomey (Twomey, 1974). This limitation ensures that the variability in the cloud will be primarily due to changes in microphysical properties associated with variation in aerosol.

A validation of BASTA FMCW cloud radar has been developed at SIRTA observatory by comparing with in-situ measurements. In fact, a tethered balloon has been deployed with a particle size optical counter named LOAC (Light Optical Aerosol counter, see. Renard et al., 2014) to measure particle size distributions (both aerosols and droplets) during fog and low stratus events. Droplet size distributions along the vertical was used to calculate associated reflectivity [Mie, 1906] and next compared to the reflectivity measured with BASTA cloud radar. The following chart shows the methodology and the scatter plot of the calculated versus measured reflectivity, which shows a satisfying level of agreement between the two technics. This evaluation confirms the absolute calibration of the cloud radar derived from a reflector.

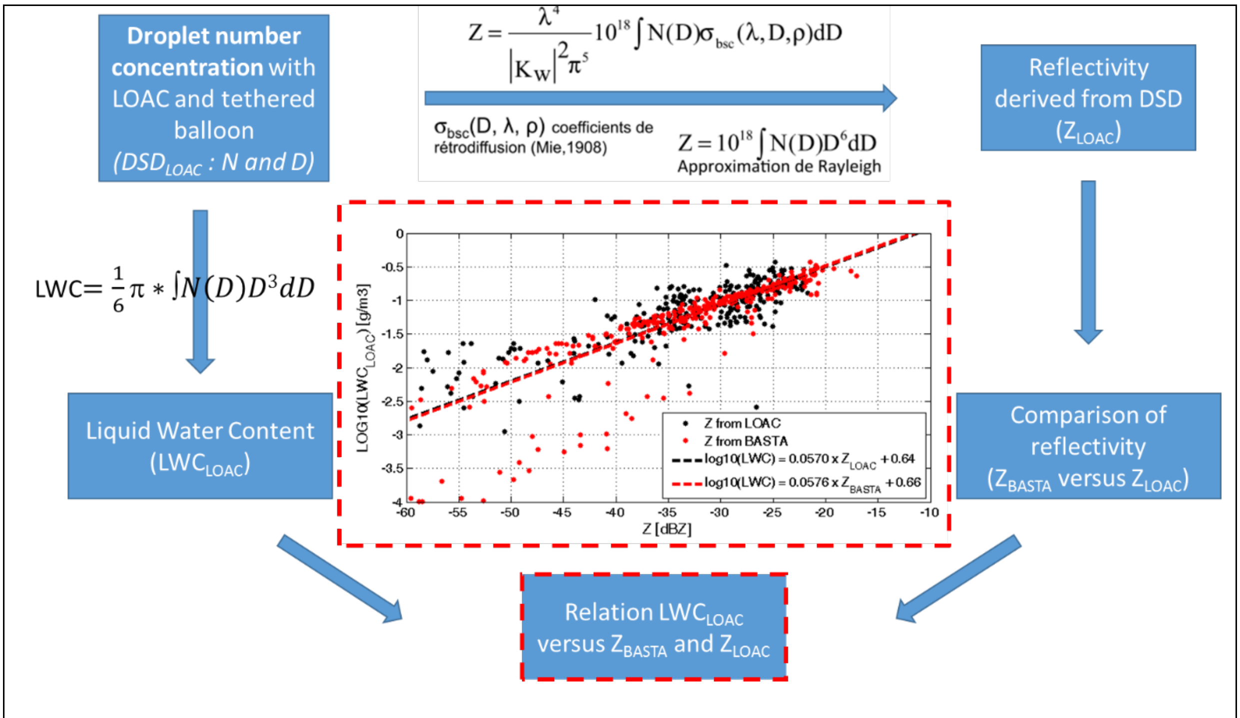

Figure 1. *Evaluation of the BASTA FMCW cloud radar reflectivity with the profiling of in-situ sensor.*

4. Aerosol source evaluation.

To evaluate the source of the aerosols a back trajectory analysis is performed. Archive trajectories can be computed with the HYSPLIT Trajectory Model (Draxler and Rolph) to detect the origin of the air mass. We can also have an idea the chemical composition of the aerosol (black carbon, NOx, etc.) and so the hydrophilic nature of the aerosols.

5. Cloud microphysics.

Further analysis requires obtaining the microphysical properties of the cloud in order to evaluate if the change in the lidar attenuated backscatter coefficient and the radar reflectivity factor correspond with the change of the number concentration and cloud droplet size. It can be achieved by two methods: (1) Retrieval of Liquid Water Cloud Properties - as described in Knist, 2014. (2) By estimating an extinction coefficient at the cloud base. To retrieve the extinction coefficient a stable lidar profile inversion can be used (Klett, 1981), taken into account the effects of multiple scattering. The extinction coefficient is used to estimate the size of cloud droplets in the lower part of the cloud only.

Case study - Cabauw observatory - 2014-10-02

The presented method for monitoring Aerosol-Cloud Interactions is very dependent on an appropriate case selection. There main selection criteria include:

1. Boundary layer liquid water clouds only;
2. No precipitation in the profile - including drizzle;
3. Liquid Water Path above 15 g/m^2 and below 200 g/m^2;
4. Cloud base is below 2000 m.

The main goal is to be able to account for the impact of aerosol on persistent Stratocumulus layer. The study case from the Cabauw Observatory presented below (Figure 2.) complies with the majority of those requirements. During the selected time period (between 14.2 and 15.8 on 02.10.2014) there were short periods of drizzle, however, they were filtered from the data through applying filtering based on the Cloudnet categorization.

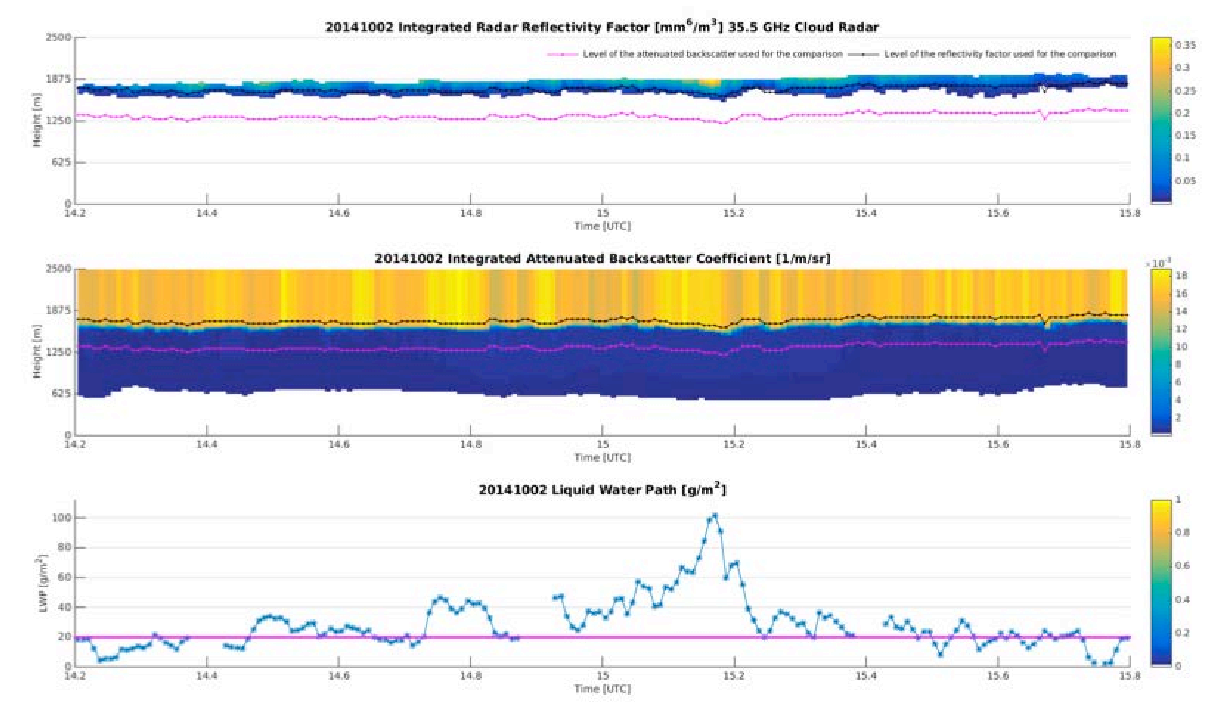

Figure 2. *Study case from 2014-10-02. The above figure shows the time series (from 14.2 to 15.8) of Integrated Radar Reflectivity Factor, Integrated Attenuated Backscatter and Liquid Water Path. The purple line shows the level of the Attenuated Backscatter Coefficient used for the comparison, the black line represents the level of the Radar Reflectivity Factor and Cloud Droplets Effective Radius. On the Liquid Water Path plot purple line represents the value of the LWP above which data is being*

considered (15 g/m2).

The level at which the data from radar and lidar are compared is based on the distance from the cloudbase - we estimate the cloud base height from the lidar measurements. The concentration of aerosols taken for the comparison (in the form of the attenuated backscatter coefficient) is 300 m below the cloud base. The concentration of the cloud droplets (in the form of radar reflectivity factor and cloud droplet effective radius) is located 70 m above the cloud base.

Removing time steps where drizzle was detected decreases the amount of data points available for the analysis. Although very limiting, this filtering is necessary to observe the interaction between aerosols and clouds. Figure 3 shows the time series of the retrieved microphysical data.

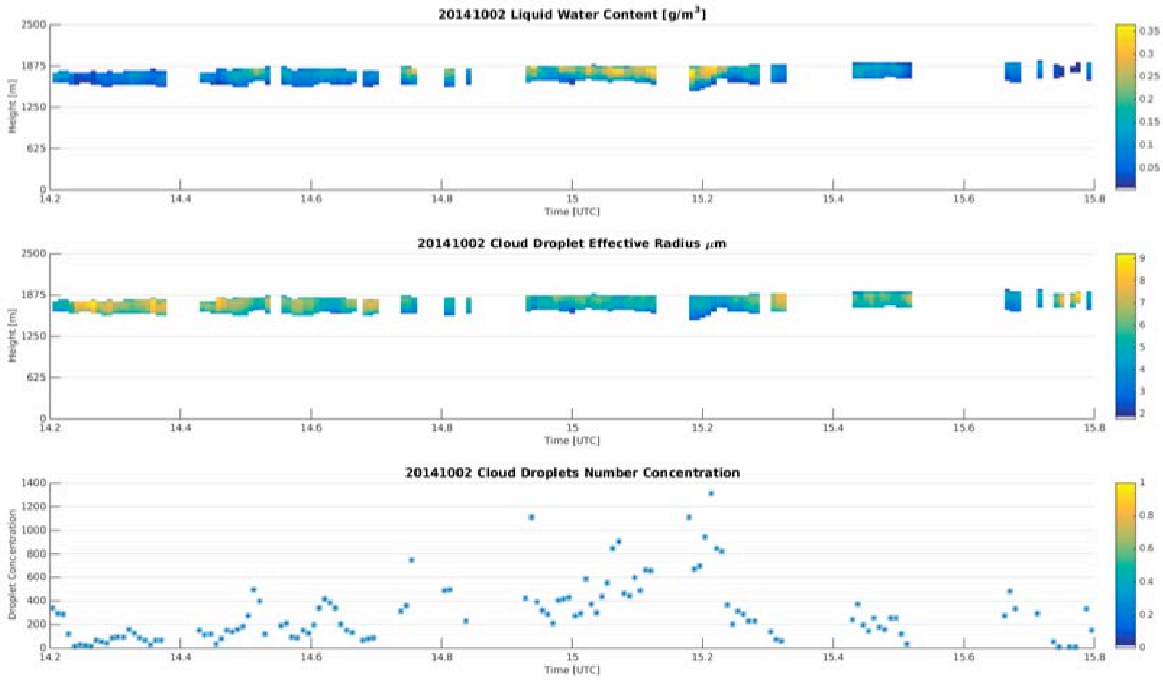

Figure 3. *Study case from 2014-10-02. The above figure shows the time series (from 14.2 to 15.8) of retrieved Liquid Water Content, Cloud Droplet Effective Radius and Cloud Droplet Concentration Number. Gaps in the data series correspond to the time steps when the presence of drizzle was detected by the Cloudnet categorization scheme.*

In the first step of the analysis we compare the Attenuated Backscatter Coefficient below the cloud with the corresponding Cloud Droplet Effective Radius within the cloud for each time step. The data is divided into bins on the Liquid Water Path. Figure 4 presents the result of this comparison divided into 9 bins, each of 5 g/m2. The results coincide to the relation we expect: the increase of the concentration of the aerosol below the cloud (approximated by the Attenuated Backscatter Coefficient) corresponds to the decrease of the Cloud Droplet Effective Radius. We can observe this relation only in the lower values of the Liquid Water Path. When the LWP exceeds 50 g/m2 there are other processes that take over the aerosol - cloud interaction. Thus, the relation between aerosol concentration below the cloud and cloud droplet size changes. We suspect that with the higher values of LWP collisional droplet growth and the entrainment at the top of the cloud influence the relation between aerosols and clouds.

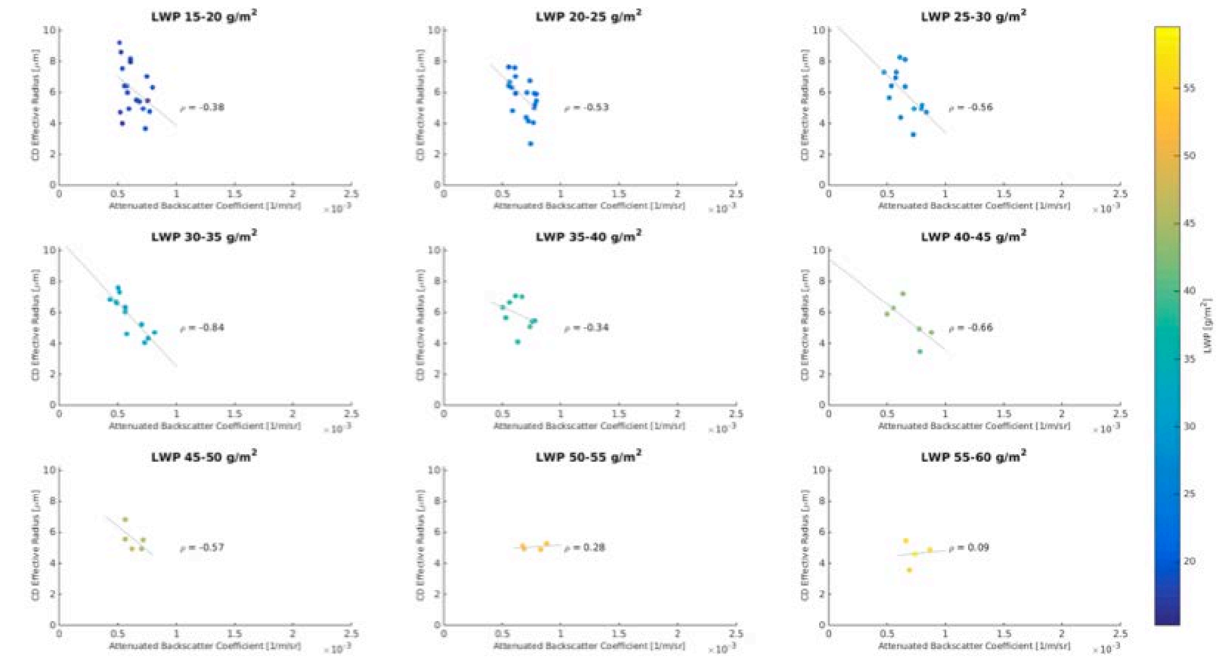

Figure 4. *The above scatter plots show the relation between the Attenuated Backscatter Coefficient (300 m below the cloud) and the retrieved Cloud Droplet Effective Radius (90 m from the cloud base). Data is divided into the bins of Liquid Water Path (each bin corresponds to 5 g/m2). The colour of the dot is also representative of the value of the LWP in the time step compared. Every plot shows the correlation coefficient corresponding to the appropriate LWP bin.*

(48)

Further, we test what is the relation between the Attenuated Backscatter and Radar Reflectivity Factor for the same bins of Liquid Water Path. We observe that the correlation between the direct observables is less pronounced (see Figure 5).

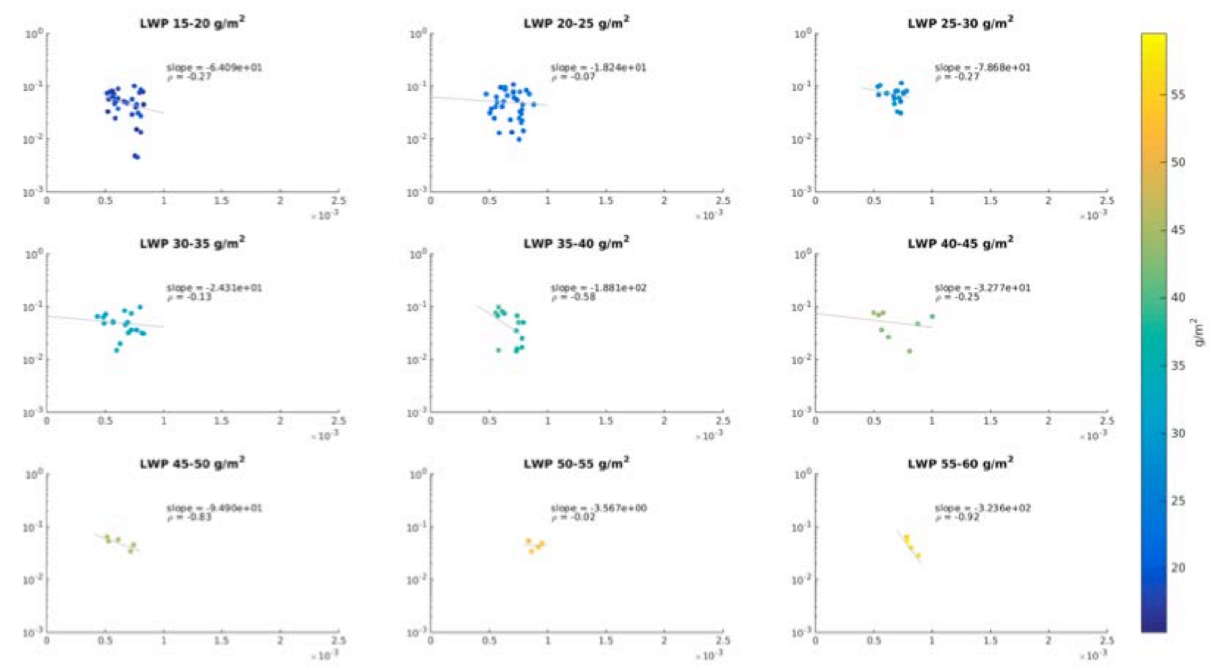

Figure 5. *The above scatter plots show the relation between the Attenuated Backscatter Coefficient (300 m below the cloud) and the Radar Reflectivity Factor (90 m from the cloud base). Data is divided into the bins of Liquid Water Path (each bin corresponds to 5 g/m2). The colour of the dot is also representative of the value of the LWP in the time step compared. Every plot shows the correlation coefficient and slope of the least square regression fit line corresponding to the appropriate LWP bin.*

(48)

In addition, we compare the Attenuated Backscatter Coefficient below the cloud with the retrieved value of the Cloud Droplet Number Concentration (Figure 6). As expected, the Cloud Droplet Concentration is increasing with the increase of the Attenuated Backscatter (increase of the aerosol concentration).

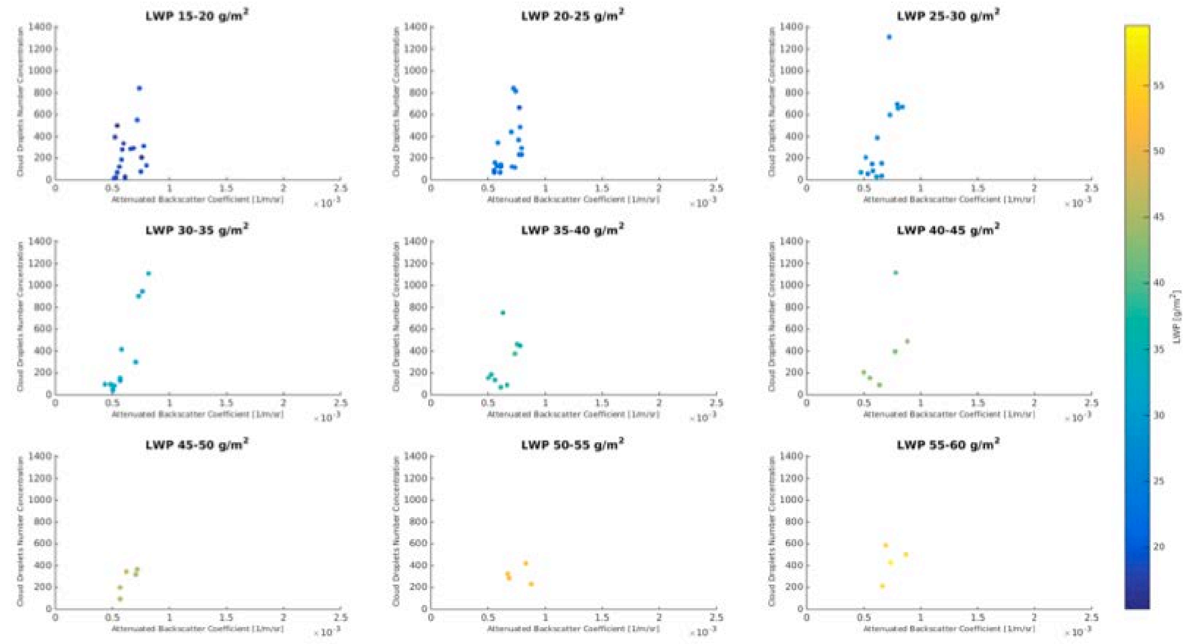

Figure 6. *The above scatter plots show the relation between the Attenuated Backscatter Coefficient (300 m below the cloud) and the retrieved Cloud Droplet Number Concentration. Data is divided into the bins of Liquid Water Path (each bin corresponds to 5 g/m2). The colour of the dot is also representative of the value of the LWP in the time step compared.*

Based on the presented study we see that the relation between the aerosols concentrations below the cloud and the cloud droplet size is related. We can see better correlations when comparing the retrieved Cloud Droplet Effective Radius than when comparing the direct observable from radar. The cloud - aerosol relationship stands out most clearly for moderate LWP (< 50 g/m^2). Using the ground-based remote sensing instruments gives this method a potential to be applied at many different observatories.

Case study - SIRTA observatory – 2015-01-06

A future step for this validation could be to compare the retrieved cloud microphysics with the in-situ measurement we can have. Some feasibility tests have been conducted at SIRTA observatory during low stratus and fog events. Figure 7a shows a flight performed with the tethered balloon equipped with LOAC sensor. Droplet size distribution was measured between surface and 500m agl and a liquid water closure was conducted: LWP measured with HATPRO MWR compared to the LWP derived from the fitted Z-LWC between BASTA and LOAC profiling (Figure 7b).

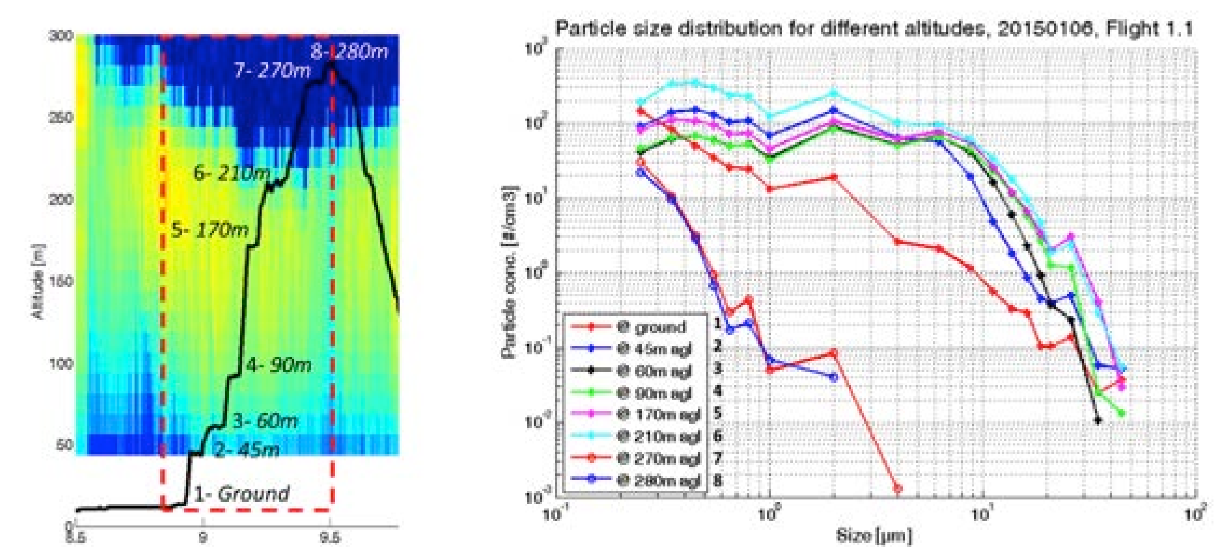

Figure 7a. *Tethered balloon flight equipped with the LOAC sensor and associated droplet size distribution along the vertical. Left: radar reflectivity profile during 1 hour, and altitude of the in-situ sensors. Right: size distributions obtained at the different altitudes.*

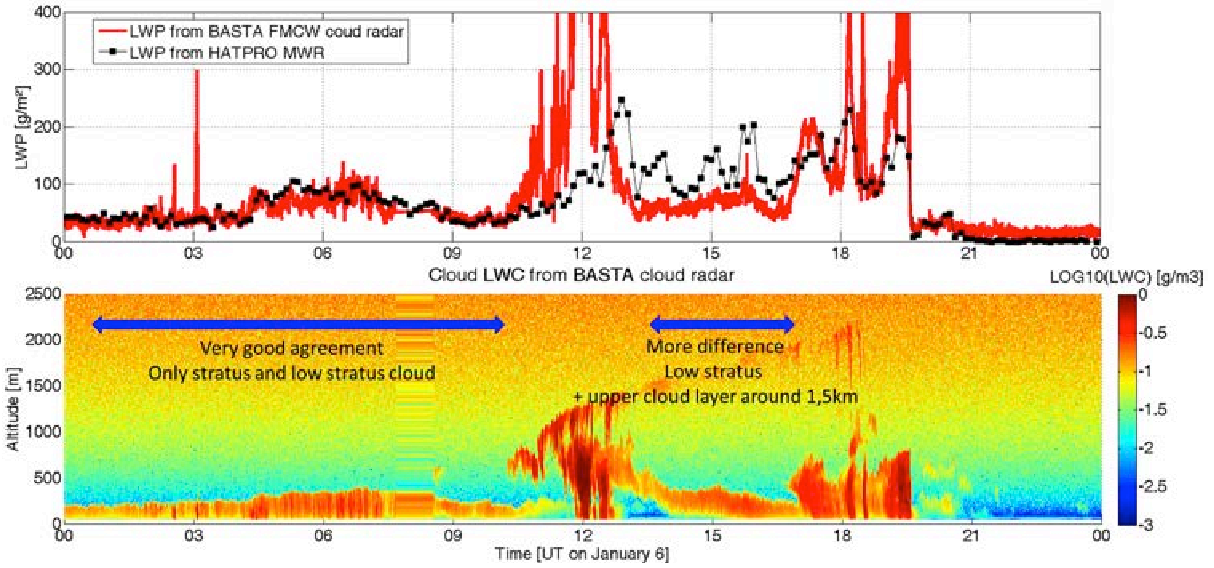

Figure 7b. *Top: Comparison between LWP measured from HATPRO MWR and derived with LOAC-BASTA algorithm. Bottom: 2D plot of the Liquid Water Content during all the event on January 6 2015.*

Conclusions and recommendations

- The proposed aerosol-cloud interaction method relies on measurements of automatic-lidar-ceilometer attenuated backscatter, cloud radar reflectivity and microwave radiometer liquid water path. It requires three complementary instruments.
- These instruments are commercially available. However, users should perform calibration
    - Automatic-lidar-ceilometers can be purchased from different manufacturers. One should take care to use instruments that provide data that can be related to a physical quantity such as attenuated backscatter. Calibration procedures exist. Calibration codes are being developed within the TO-PROF EU Cost Action (ES1303).
    - Cloud radars exist now in significantly less expensive configurations than 10 years ago, but from a limited number of manufacturers. Calibration procedures exist but further experimentation is necessary to develop a consensus and recommendations. This will be carried out as part of the H2020 ACTRIS-2 project.
    - Robust microwave radiometers for LWP retrievals have been available on the market for over 10 years now. Calibration, operation and retrieval procedures exist. A recommendation handbook is under development within MWRNET and the TO-PROF EU Cost Action.
- The method developed under WP22 shows encouraging results that link the increase of the concentration of the aerosol below the cloud to the decrease of the Cloud Droplet Effective Radius. Relationships are found for clouds with moderate liquid water path (20 < LWP < 50 g/m^2).
- To implement the method automatically, a robust target categorization must be available to identify cloud base, drizzle, and aerosol backscatter. We used the Cloudnet target classification, which should be improved to provide better aerosol classification.
- Closure studies between Lidar and radar profiling and in-situ profiling using instruments installed under a tethered balloon are revealed to be very useful at least for three applications
    - Validation of radar calibration by comparing measured radar reflectivities to reflectivities calculated from droplet size distributions
    - Deriving Z-LWC relationships
    - Comparing aerosol-cloud interactions from in-situ measurements and from remote sensing measurements

References:

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