WP22-JRA3: A framework for cloud-aerosol interaction studies
Deliverable D22.2: Report on optimized and tested retrieval techniques

Aerosols and clouds ability to scatter and absorb solar and infrared radiation in the atmosphere is causing a direct radiative forcing. Aerosols through their role as nuclei of condensation alter warm, ice and mixed-phase cloud formation processes by increasing droplet number concentrations and ice particle concentrations. They can decrease the precipitation efficiency of warm clouds and thereby cause an indirect radiative forcing associated with these changes in cloud properties. The level of water vapour supersaturation and the number of cloud condensation nuclei (CCN) is also indirectly related to the cloud albedo. In polluted air the number of CCN is supposed to increase rapidly leading to increased CDNC (Twomey, 1977).

Currently quantifying the radiative forcing due to clouds (cloud albedo forcing) is done by studying the change of representative cloud microphysical variables (e.g., R_{eff}) against a representative sub-cloud aerosol quantity (e.g., extinction). The cloud albedo depends on the cloud (geometrical and optical) thickness, the LWC and the CDNC and it is a way to express the amount of reflected and absorbed solar radiation by a cloud. McComiskey and Feingold (2007) have indicated that the radiative forcing of the aerosol indirect effects (IE), which is the difference in radiative flux that occurs as a result of changes in cloud properties for post- versus pre-industrial aerosol concentrations, ranges from -3 to -10 W m^{-2} for each 0.05 increment in IE ($IE = -(dR_{eff}/d\alpha)$), where α is the aerosol amount). Therefore, the accurate quantification of the aerosols IE is necessary for better prediction of climate change.

The general definition of the aerosols IE can be expressed by $IE = -(dC_{var}/dA_{var})$, where C_{var} and A_{var} are the representative variables for cloud and aerosol amounts. New proxies can be defined through:

- $IE = -(dN_{cloud} / dN_{aerosol})$
- $IE = -(dZ_{cloud} / d\alpha_{aerosol})$
- $IE = -(dR_{cloud,eff} / d\alpha_{aerosol})$
- $IE = -(dR_{cloud,eff} / dR\ IE = -(dZ_{cloud} / d\alpha_{aerosol})$

The IE values obtained from the above equations are affected by different types of uncertainty resulting from the errors related to the individual microphysical variables of both clouds and aerosols.

In order to access the indirect effect of aerosols most effectively we need to use state-of-the-art retrieval techniques for both cloud and aerosols parameters. Below is the description of the assessed approaches.

1. Cloud retrieval techniques

Cloud retrieval techniques evaluate the microphysical properties of boundary-layer liquid water clouds. Assessment of currently used methods included properties such as Cloud Droplet Number Concentration (CDNC), Effective Radius (R_{eff}) and Liquid Water Content (LWC) and also the uncertainties related with those values. Three different ground-based remote sensing methods were evaluated within the scope of ACTRIS work package 22 with cooperation from the COST action ES0702 EG-CLIMET. State-of-the-art techniques to retrieve the microphysics from liquid clouds include:

i. SYRSOC – SYnergistic Remote Sensing Of Cloud described in the paper by Martucci and O'Dowd (2011);

SYRSOC is a multi-module technique developed at the National University of Ireland Galway and retrieving the three primary microphysical parameters from liquid clouds (Martucci and O'Dowd, 2011, Martucci et al., 2012, Ovadnevaite et al., 2011), i.e. the cloud droplet number concentration (CDNC), the effective radius (R_{eff}) and the cloud liquid water content (LWC). In addition to the three main microphysical variables, SYRSOC provides a number of parameters describing the cloud droplet spectral properties (relative dispersion), the degree cloud of subadiabaticity, the Doppler spectrum of droplets, the cloud optical depth and the cloud albedo. Extinction from standard 355-1500 nm inverted backscatter LIDAR signal or directly from Raman signal is used as input data for SYRSOC. Other input data are the temperature and humidity profiles from co-located operational microwave-radiometer and the reflectivity/signal-to-noise-ratio and depolarization ratio from co-located Ka-band Doppler cloud RADAR. Data from the 1064-nm and 15-km vertical range Jenoptik CHM15K LIDAR ceilometer, the RPG-HATPRO water vapour and oxygen multi-channel microwave profiler and the MIRA36, 35 GHz Ka-band Doppler cloud RADAR are currently used at the GAW Atmospheric Station of Mace Head (Ireland) to supply the necessary input to SYRSOC.

ii. IPT – Integrated Profiling Technique described in the paper by Löhnert et al. (2004);

IPT is a method for deriving physically consistent profiles of temperature, humidity, and cloud liquid water content. This approach combines a ground-based multichannel microwave radiometer, a cloud radar, a lidar-ceilometer, the nearest operational radiosonde measurement, and ground-level measurements of standard meteorological properties with statistics derived from results of a microphysical cloud model. A major advantage of the proposed IPT is that profiles of temperature, humidity, and cloud liquid water are retrieved simultaneously and are physically consistent in terms of different measures.

iii. TUD-RSCPP – TU Delft Remotely-Sensed Cloud Property Profiles described in the paper by Brandau et al. (2010).

This retrieval method relies on a combination of the cloud radar reflectivity; the microwave radiometer estimated liquid water path and on the cloud geometrical thickness from lidar and cloud radar. These observations are used as input data for different vertical cloud models to retrieve profiles of the LWC, the droplet concentration, the effective radius, the optical extinction and the optical depth. The three cloud models are characterized by their predefined in-cloud vertical structure of the assumed gamma DSD parameters (concentration, shape parameter and mean radius). This assumption is necessary to reduce the number of unknowns since the vertical information of the DSD properties from surface remote sensing observations are still lacking. The common assumptions in all three cloud models on the vertical distribution of the DSD parameters are that the cloud droplet concentration and DSD shape parameter remain constant within the cloud layer. The differences in the in-cloud vertical structure of the cloud models are related to the cloud layer mean droplet radius. In the vertical uniform (VU) cloud model, the cloud layer mean droplet radius is uniformly distributed over the cloud layer thickness while the scaled-adiabatic stratified (SAS) and homogeneous mixed (HM) cloud models parameterise the vertical profiles of the mean droplet radius in consideration of possible impacts of the cloud dilution. The SAS cloud model accounts for the entire range of mixing processes available in the atmosphere by a constant reduction in the particle size with height. In case of the HM cloud model, the impact of mixing is associated with the observed vertical variation in the radar reflectivity profile, which is attributed to changes in the mean particle size. The main assumptions constrain the application of the algorithms to liquid water clouds without drizzle formation and it is expected that drizzle-sized particles will produce biased results, because they are dominating the cloud radar reflectivity while their contribution to the LWC, the droplet concentration and the effective particle size are rather small.

Instruments involved in all three methods include cloud radar, microwave radiometer (MWR) and laser-ceilometer. All methods use the same information on cloud phase & type, cloud boundaries, radar reflectivity, ceilometer-backscatter and MWR-derived LWP, respectively MWR brightness temperature. All methods were applied to synthetic measurement calculated from model output using suited forward models available from the EarthCare Simulator. Retrieved microphysical properties can be directly compared to the original model output and thus the accuracy is evaluated as a function of height above cloud base. The methods were also applied to real measurements and evaluated through a short-wave radiative closure using simultaneous broad-band pyranometer measurements. For the initial calibration phase of the three different ground-based remote sensing methods intercomparison the retrieved cloud microphysics have been tested against the provided synthetic ECSIM (EarthCare Simulator) reference.

For each microphysical variable (CDNC, R_{eff}, LWC) the outputs of the retrievals were compared with the ECSIM true value. The magnitude of uncertainties for each parameter in the retrievals is stated in Table 1 below.

	CDNC	R_{eff}	LWC
Uncertainties	> 40%	> 15 %	> 20%

Table 1. The magnitude of uncertainties for each parameter in all of the retrievals techniques.

Based on the blind test performance several conclusions were formulated. Firstly, retrieval techniques are accurate for the cloud types they were developed for. Thus, cloud classification is very important. Secondly, droplets number concentration is the most difficult parameter to retrieve. Lastly, drizzle within the cloud is an important issue and it's characterization within the retrieval needs to be improved.

2. Aerosol and water vapour retrieval techniques

An intercomparison of algorithms for aerosol retrieval was performed in the ACTRIS project as the continuation of the work performed within the EARLINET. This was done for elastic backscatter lidar and for Raman lidar algorithms. The method of intercomparison and results are described in the papers by Böckmann et al. (2004) and Pappalardo et al. (2004). Main conclusions from Böckmann for the intercomparison of algorithms for (elastic) backscatter lidar retrievals are: An intercomparison of backscatter algorithms has been performed in three stages that represent increasing knowledge of the necessary input parameters. In stage 1 neither the necessary reference value nor the height-dependent lidar ratio was given. In stage 2 the prescribed lidar ratio was provided, and in stage 3 the reference value was also given. It became clear that the estimation of the lidar ratio that is required for real measurements has a large effect on the calculated aerosol backscatter profile. The calculated profiles can differ by more than 50% if no information on the lidar ratio is available. This effect decreases with increasing wavelength. Therefore additional measurements, such as sunphotometer observations, are of importance because they can provide the needed lidar-ratio information. The effect of the reference value was rather small in the chosen cases; however, at 1064 nm the result can depend strongly on this value, which also has to be estimated for real measurements. The errors of the algorithms themselves, when all input parameters were known, were tested in stage 3. The remaining mean relative errors of the calculation in cases 2 and 3 are at the order of 2%–4% and can be regarded as negligible when they are compared to the uncertainties caused by misestimating the input parameters' lidar ratio and reference value. Main conclusions from Pappalardo et al. (2004) for the intercomparison of algorithms for Raman lidar retrievals are: The intercomparison has focused mainly on the aerosol extinction evaluation starting from nitrogen Raman lidar signals at two wavelengths and then on the retrieval of aerosol backscatter by use of the combined Raman elastic-backscatter lidar technique. This intercomparison shows that the aerosol extinction evaluation can be accomplished with good accuracy for all participating groups. For Stage I (without any ancillary information), mean deviations of the retrieved aerosol extinction profiles from the solution were within 15% and 20% in the 350–2000- and the 3000–4400-m height ranges, respectively, and, for Stage II (with additional information) were within 10% and 20% in the 350 –2000- and the 3000 – 4400-m height ranges, respectively. The errors provided by each group are consistent with what was expected; moreover, all the calculated deviations from the solution were found to be within the expected errors. Results of the intercomparison for the aerosol extinction profiles show also that, with a common fixed spatial resolution, the various Raman algorithms used influenced not the errors but only the mean deviations from the solution. This intercomparison has shown satisfactory results for the aerosol backscatter coefficient also. Both relative and absolute deviations typically were within the maximum allowed deviations that had been fixed within the EARLINET. This intercomparison shows in particular that, even without any reference value for the backscatter, the retrieval of the aerosol backscatter starting from simultaneous Raman and elastic lidar signals is satisfactory, demonstrating how much more powerful the Raman elastic-backscatter lidar technique is compared with that for which only elastic lidar signals are available. Finally, the lidar ratio intercomparison has demonstrated the capability of each participating group to obtain lidar ratio profiles in the planetary boundary layer with a mean deviation from the solution within 30% (Stage I) and within 20% (Stage II). For the lidar ratio, a particular case was also considered: the evaluation of the mean value of this parameter within an aerosol layer at higher altitudes that is representative of typical layers related to special events such as Saharan dust outbreaks, forest fires, and volcanic eruptions. Good results were obtained for this case as well: Mean deviations from the solution were 2–15% at 355 nm and 2–12% at 532 nm. For water vapour (Raman lidar), to our knowledge, no such intercomparison of algorithms has been performed. The main source of error in the water vapour Raman lidar technique lies in the calibration and for conditions of low water vapour concentrations in instrumental effects that may lead to systematic errors, for example fluorescence that may lead to a wet-bias in the upper troposphere. These matters are discussed in LeBlanc (2008, 2011). There is discussion, mainly on the subject of the methods of calibration (LeBlanc (2011), Whiteman (2011)). Theoretical considerations about accuracy of Raman lidar observations on water vapour (and aerosols) are discussed by Whiteman (2003).

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