## A FRAMEWORK FOR CLOUD-AEROSOL INTERACTION STUDIES

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# ABSTRACT

Aerosols can indirectly influence climate either by cloud albedo or lifetime effect. In order to have better understanding of these processes it is crucial to measure detailed vertical profiles of the radiative transfer and the microphysical evolution of clouds. Best results can be achieved by using advanced sensor synergy techniques. Essential remote sensing instruments used in this study include cloud radars and different types of lidar to obtain vertical structure of the atmosphere, as well as microwave radiometers and radiation sensors for improving the accuracy of the retrieved profiles. Several advanced combined retrieval algorithms will be used to quantify the physical characterization of water clouds and aerosols. Further work will be required on the understanding of the relation between cloud and aerosol.

## 1. BACKGROUND

This investigation is done as a part of the ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure Network) European Project, aiming at integrating European ground-based stations equipped with advanced atmospheric probing instrumentation for observing aerosols, clouds, and short-lived gas-phase species. ACTRIS will play a crucial part in developing new knowledge and policy issues on climate change, air quality and long-range transport of pollutants. One of the main objectives of ACTRIS is to develop new integration tools to fully exploit the use of multiple atmospheric techniques at ground-based stations. ACTRIS aims at providing time series of climate and air quality related variables not directly measured which are presently not available through existing data centres. The objective of this research is to develop experimental means to quantify the indirect effect of aerosols. This effect is defined as a modification of microphysical properties, amount and lifetime of clouds by aerosols [1]. It can be divided into two different processes: (1) microphysically induced effect on cloud droplet concentration and hence the cloud droplet size with the liquid water path held fixed, referred to as the first indirect effect or Twomey effect [2], and (2) microphysically induced effect on the liquid water path, cloud height and cloud lifetime, referred to as the second indirect effect, cloud lifetime or Albrecht effect [3]. Fig. 1 shows the schematic of aerosol indirect effect.



Figure 1. Schematic of the aerosol indirect effects. CDNC means cloud droplet number concentration, and LWC means liquid water content [1].

In this research the focus is given to the first indirect effect. It was shown by Twomey that increased concentration of atmospheric aerosols may increase the amount of solar radiation reflected by clouds. Aerosols can act as cloud condensation nuclei (CCN) creating more droplets which have smaller size. This leads to the increase of cloud albedo, as clouds become whiter and larger. Observation of this mechanism is very challenging due to the cluttering by simultaneous atmospheric processes and the technological means to unravel those do not exist yet. The need for clear measurements of the aerosol indirect effects challenges the state-of-the-art remote sensing technologies and demands the development of new observation techniques. The best results are obtained by using the available instruments in synergy, combining measurements from active and passive instruments. Combined retrieval algorithms can deliver a physically consistent profiles of cloud and aerosol parameters, such as liquid water content (LWC), particle size and optical extinction.

### 2. METHODOLOGY

#### 2.1. Sensor synergy

The aim of the research is to set up the framework for the study of aerosol cloud interactions. Therefore,

defining the combination of instruments, observables and derived parameters is the focal point of this investigation. Studies will be focused on boundary layer water clouds.

Priority is given to the observation of the vertical column of the atmosphere. Active instruments,

especially radar and lidar, are uniquely able to provide essential information about vertical profile. However, the best results are obtained by using the available sensors in synergy. Essential remote sensing instruments used in this study include: microwave radiometers, cloud radar, lidar (ceilometer and Raman lidar), radiosondes and pyranometer for improving the accuracy of the retrieved profiles.



Figure 2. Schematic diagram of sensors used in synergy (from left: cloud radar, microwave radiometer, lidar, pyranometer and radiosonde).

Microwave radiometer provides time-series measurements of column-integrated amounts of water vapour and liquid water. The instrument is a sensitive microwave receiver that detects the microwave emissions of the vapour and liquid water molecules in the atmosphere at different frequencies. Integrated water vapour and liquid water path are derived from radiance measurements with a physically consistent retrieval algorithm. Cloud radar probes the extent and composition of clouds at millimetre wavelengths. It is a zenith-pointing radar that operates at a frequency of 35 GHz or 94 GHz. Main purpose of this radar is to determine cloud boundaries and profile. Also, it reports radar reflectivity of the atmosphere up to 15 km. Lidar measures cloud height and vertical visibility. It employs optical technology, where short, powerful laser pulses are sent out in a vertical or near-vertical direction. The reflection of light caused by haze, fog, mist, virga, precipitation, and/or clouds is measured as the laser pulses traverse the sky. The resulting backscatter profile, or signal strength versus the height, is stored and processed and the cloud base is detected. Radiosondes provide thermodynamic state of the atmosphere as a function of altitude: temperature, pressure, relative humidity and wind speed and direction. Jumps in temperature and humidity are usually used to determine the top of the boundary layer. Fig. 2 shows the schematic of used instruments and observables.

### 2.2. Indirect effect index

Starting point of the observational framework will be the aerosol indirect effect index (IE). It was defined by Feingold [4] as the partial derivative of the logarithm of cloud droplet radius with respect to the logarithm of the aerosol extinction:

$$IE = -\frac{dln(r_e)}{dln\alpha} \tag{1}$$

The IE represents the relative change in the  $r_e$  for a relative change in  $\alpha$ . Indirect effect is positive in sign when an increase in the optical thickness of aerosols results in a decrease in the effective radius of the cloud droplets. This dependency was based on the studies [5] and [6], where investigation of the clouds over the Atlantic Ocean showed that polluted clouds had smaller droplets than the clean clouds. The difference in thickness between clean and polluted clouds affects the correlation between the optical thickness and effective radius as reported by [7]. In case of comparing only cases with comparable geometrical thickness this correlation is negative. However, if the most polluted cases are also take into account, then the trend suggests positive correlation between the two values. Other research [8] suggest that the slope between optical thickness and effective radius is positive when considering polluted clouds. This is due to the increase in liquid water content and absence of drizzle size droplets and vice versa for clean clouds.

It is important to understand the relation between aerosol and clouds. We need to establish if a variation in aerosol background results in a variation of the cloud structure. It is not clear whether IE index at the form proposed by Feingold is a good tool for this evaluation. Therefore we will test different aerosol and cloud properties against each other in order to establish the best possible comparative values for observation of cloud formation against a variable aerosol background. We will also evaluate where those values should be compared, if it should be below or above cloud base or in more than one point. In order to have the best possible representation of microphysical properties of aerosol and clouds we will use a 2D kinematic cloud model with ĸ-Köhler aerosol chemistry and Monte-Carlo coalescence scheme [9]. The model provides a description of the droplet formation process at the initial stage of cloud-formation triggered by vertical air motion (i.e. in convective or orographic clouds). The model utilises the method of lines for numerically solving the so-called dynamic equation of aerosol growth by condensation. Output from the model will be used as an input to the EarthCARE SIMulator (ECSIM). ECSIM is the European Space Agency - EarthCARE End-2-End mission simulator. It contains packages of forward and instrument models for the simulations of the four instruments onboard the satellite cloud radar, lidar, multispectral imager, broadband radiometer and a package of "ground based" forward models for cloud radar, lidar and surface fluxes. Through a number of simulation with the use of those two models we will redefine the IE index.

In order to separate cloud-aerosol interactions from the entangled meteorological processes, separate regimes will be distinguished. The starting point for this segregation will be setting up cloud categories where important parameters will be kept uniform. Those parameters will include liquid water path, vertical extent, presence of drizzle and level of adiabaticity [10].

## 2.3. Retrieval algorithms

The remote sensing techniques should be able to measure the relevant cloud and aerosol properties, including profiles of the cloud droplet number concentration and liquid water content.

The starting point for the retrieval techniques will be the integrated profiling technique (IPT) [11],[12], the retrieval technique of liquid water cloud properties described in Brandau *et al.* (2010) [13] and the snergistic remote sensing of cloud technique (SYRCOS) [14].

IPT is a method of 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, radiosonde measurement, and groundlevel measurements of standard meteorological properties with statistics derived from results of a microphysical cloud model. All measurements are integrated within the framework of optimal estimation to guarantee a retrieved profile with maximum information content.

Technique introduced by Brandau *et al.* provides droplet concentration, effective radius and optical thickness on a basis of ground-based remote sensing observations and a vertical cloud model. Main instruments used in that approach include cloud radar, microwave radiometer and ceilometers. The model assumptions are related to a subadiabatic approach, in which cloud mixing processes are predefined to be homogeneous. A gamma droplet size distribution with a fixed shape parameter is considered to relate the observations with the retrieval products. The technique is applied to water cloud cases. Fig. 3 presents retrieval schematic.



*Figure 3. Schematic diagram of the Brandau* et al. *retrieval technique.* 

The SYRSOC technique is for retrieving warm cloud microphysics using synergistic ground based remote sensing instruments. It utilises a Ka-band Doppler cloud RADAR, a LIDAR-ceilometer and a multichannel microwave radiometer. SYRSOC retrieves the main microphysical parameters such as cloud droplet number concentration (CDNC), droplets effective radius (reff), cloud liquid water content (LWC), and the departure from adiabatic conditions within the cloud.

# 3. APPLICATION

The main objective of this work is to develop an observational framework for cloud-aerosol interaction studies in Europe. It will be achieved in two steps. Firstly, by developing optimized sensor-synergetic algorithms for the physical characterisation of clouds and aerosols in the context of cloud formation and its impact on climate change. Secondly, by establishing and testing observation strategies for the study of cloudaerosol interactions through combined use of remote sensing, in situ observation and atmospheric models.

The methodology will be applied to all cloud-aerosol profiling sites of the ACTRIS network in order to have consistent and large-coverage observations of the first indirect aerosol effect.

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