

Chapter II.1

Observing Microphysical Properties of Cloud and Rain

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1 Introduction

While we know that the climate is changing, it is still difficult to say with certainty how much it will change in the future. One of the reasons for this is the lack of knowledge we have concerning the atmospheric radiation balance. The sun's radiation heats the earth, but on its way to the surface it is scattered and absorbed by atmospheric constituents like clouds, aerosols, and gasses. The same is true for the heat radiation coming from the earth. Part of it will escape into space, while the remainder will warm up the atmosphere (Fig. II.1.1).

Clouds form an important element of the radiation balance. To understand their impact we have to know the relationship with aerosols. The conceptual picture is as a follows (Fig. II.1.2):

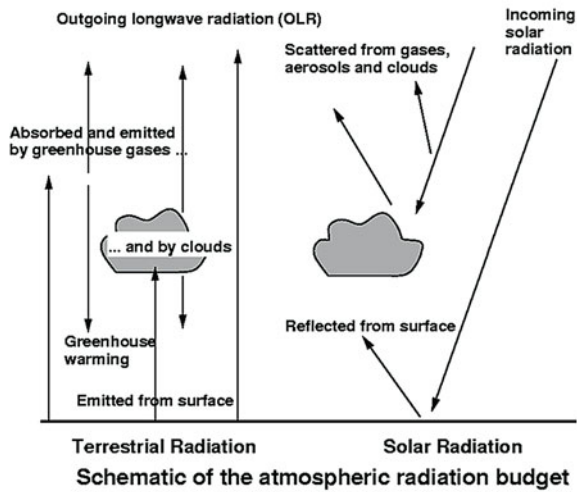
- (1) In extremely clean air water vapor will not condense into liquid easily. The surface tension is very high, so that other water molecules cannot join an embryonic droplet. The droplet will not grow.
- (2) Aerosols lower the surface tension, and consequently droplets can grow more easily around the aerosol.
- (3) With an increasing amount of aerosols more droplets are formed, albeit that they will be smaller: the amount of water vapor is limited.

Clouds reflect sunlight. The degree to which they do this depends on the microstructure: the particle number concentration and the particle sizes. The number of particles depends on the aerosol concentration, and consequently the solar reflection also. An increase of aerosols leads to more cloud droplets leading to more reflection (Fig. II.1.3).

A second effect lies in rainfall formation. Large droplets turn into raindrops more easily than small ones. This implies that an increase of aerosols suppresses rainfall formation. It does not have to lead to less rainfall. It merely delays the formation and sustains the impact of clouds on the radiation balance (Fig. II.1.4).

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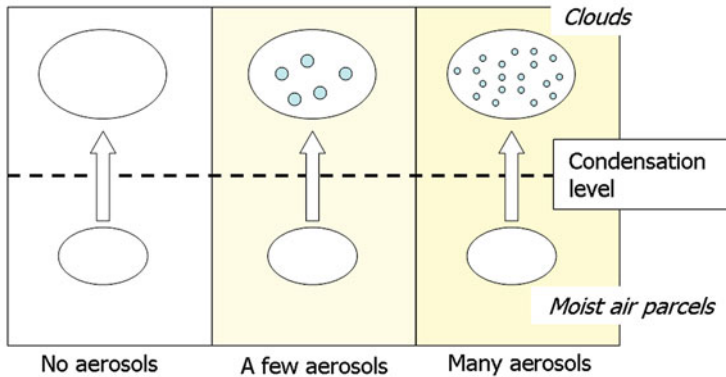
Radiation balance of the atmosphere



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Fig. II.1.1 Schematic of the radiation budget of the atmosphere

cloud formation



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Fig. II.1.2 Conceptual picture of cloud formation as related to aerosol content

impact on radiation balance

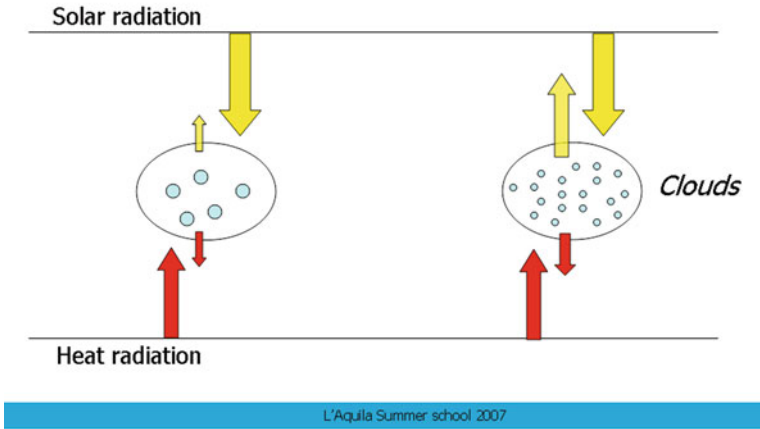


Fig. II.1.3 Clouds impact on radiation balance

rainfall formation

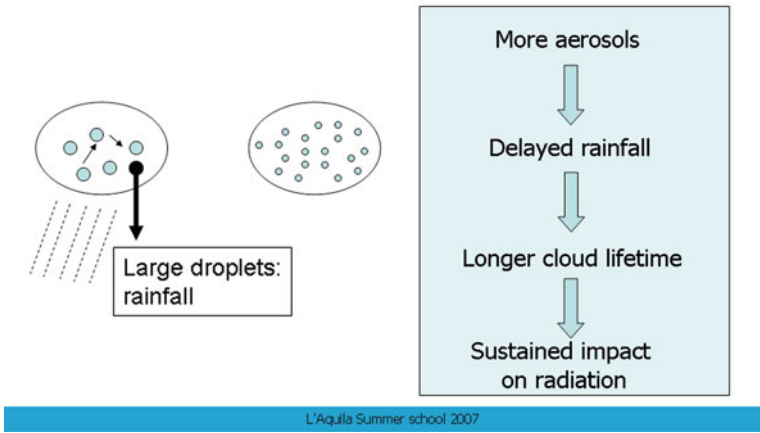


Fig. II.1.4 Aerosol impact on rainfall formation

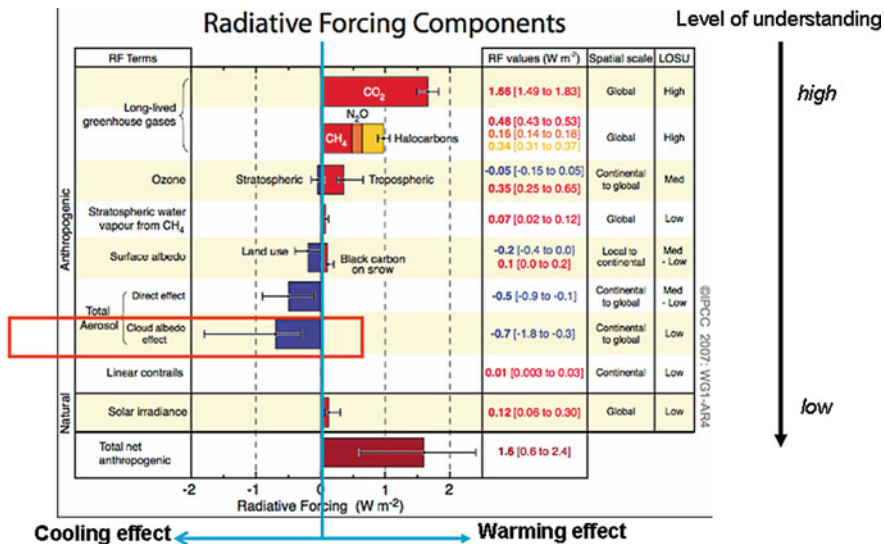
2 The Role of Clouds and Aerosols

In the International Panel on Climate Change (IPCC) 2007 report, an overview is given of the level of uncertainty in our knowledge of the different radiatively important elements of the climate system. Greenhouse gases are well understood. They warm the earth, and the degree to which they do this is well quantified. This is not the case for the cooling effects of clouds and aerosols. They are by far the least understood, as represented by the error bars in Fig. II.1.5.

Therefore, the following question needs to be answered:

- How do changes in the aerosol background affect the radiation balance through cloud formation?
- What is the anthropogenic component?
- What is the regional variability?

How can these uncertainties be reduced? We have to answer the questions mentioned above. This cannot be done without proper observations, and that is where the difficulty comes in. How to do such observations? Cloud properties can be measured with instrumented aircraft, but that is not the optimum way for long-term monitoring. Aircraft observations have a limited time span and cannot be performed continuously. For this we need remote sensing techniques.



Source: International Panel on Climate Change IPCC 2007

Fig. II.1.5 Level of understanding of radiative forcing components as reported by the IPCC in 2007

What causes the complexity of the problem?

- Many concurrent atmospheric processes (entrainment, mixing, turbulence, advection, etc.).
- A large range of temporal and spatial scales.
- A multitude of different physical parameters.
- Needed observation techniques are not available yet.

Cloud–aerosol interaction is difficult to separate from other physical processes in and around clouds. We want to know the relation between variations in aerosol loading and variations in the number of droplets. A simple observation of these two parameters is not sufficient, because other processes may also change the cloud droplet number concentration.

3 The Need for Multi-Sensor Strategies

Clouds and aerosols are not easy to measure. Single sensors are never enough to depict the whole picture. There are no instruments which can do it all. Different sensors have to be combined in a clever, synergistic way. The combination of instruments should give more than the sum of results of the individual sensors.

The following table lists the geophysical parameters needed to investigate the cloud–aerosol interaction and the typical technique that is used to observe them.

Aerosols	Lidar, passive
Clouds	Radar, lidar, passive
Radiation from ground and space	Passive
Boundary layer dynamics	Radar
Water vapor	Lidar, passive, gps

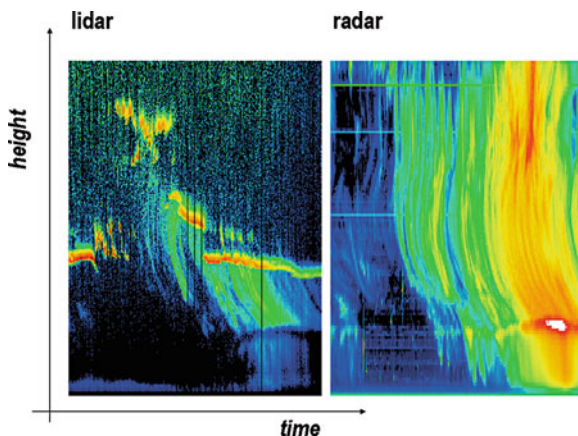
In Fig. II.1.6, the left panel shows a lidar observation of light rain. The right panel shows a radar measurement of the same event. Both instruments were pointed vertically. Clearly, these two instruments reveal different aspects of the clouds. The layers observed in the lidar image are due to water clouds that the radar does not see. The radar signal is mainly caused by ice, melting ice (the white area), and rain fall. Note the decrease of the lidar signal at the melting layer.

If we want to study the role of clouds in the climate system we have to measure the temporal and spatial distribution of the microphysical properties. Once we have these, we can calculate the impact of the clouds on the radiation balance using the appropriate theories of light scattering.

What do we have to know?

1. Cloud thickness
2. Liquid/ice water content

Fig. II.1.6 Observation of light rain with different instruments



3. Effective radius
4. Number concentration
5. Vertical profile

Every remote sensing technique assumes a certain model of the object that is being sensed. In our case we use the model of a quasi-adiabatic water cloud. One of the features of such clouds is that the liquid water content increases with altitude. With this we can predict the qualitative shape of a radar profile and its relationship with cloud property. In this approach we integrate the radar profile with height (iZ) and calculate the link between the liquid water path, the number concentration, and iZ . The liquid water path (the height integral of lwc) is measured by a microwave radiometer. So, by combining radar and radiometry we can derive the number concentration (Fig. II.1.7).

Figures II.1.8 and II.1.9 are the examples of the approach. The measurements were done at the atmospheric radiation measurement (ARM) site in Oklahoma. Figure II.1.8 shows a radar measurement of a water cloud in the ellipse (between 20 and 22 UTC). Figure II.1.9 gives the corresponding liquid water path from a

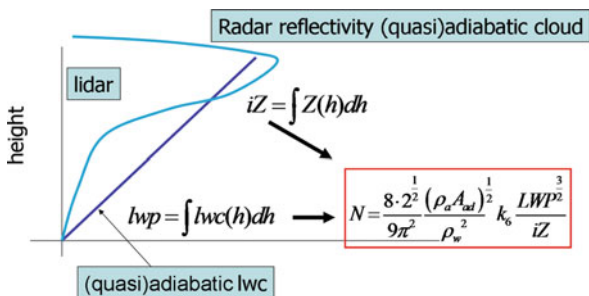


Fig. II.1.7 Schematics of the radar-radiometer technique for the cloud number concentration

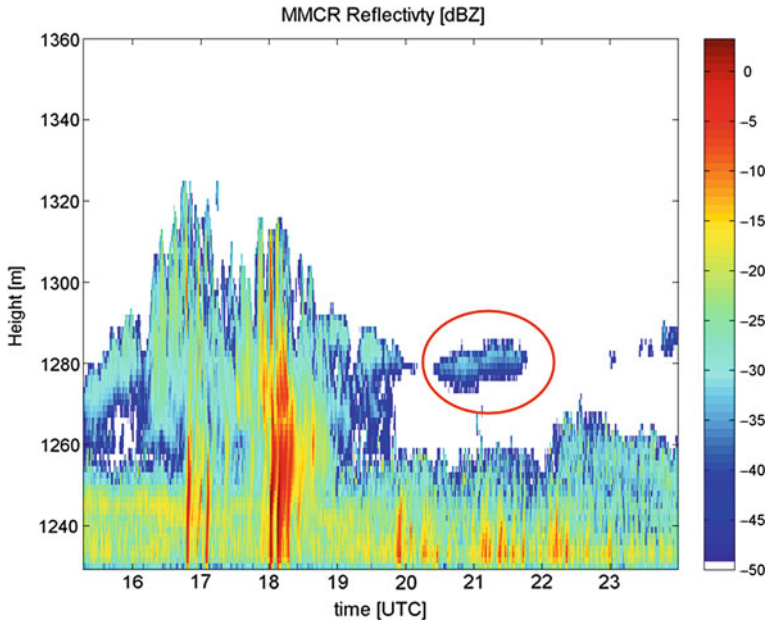


Fig. II.1.8 Time–height cross section of radar reflectivity [dBZ] from a millimeter-wave cloud radar

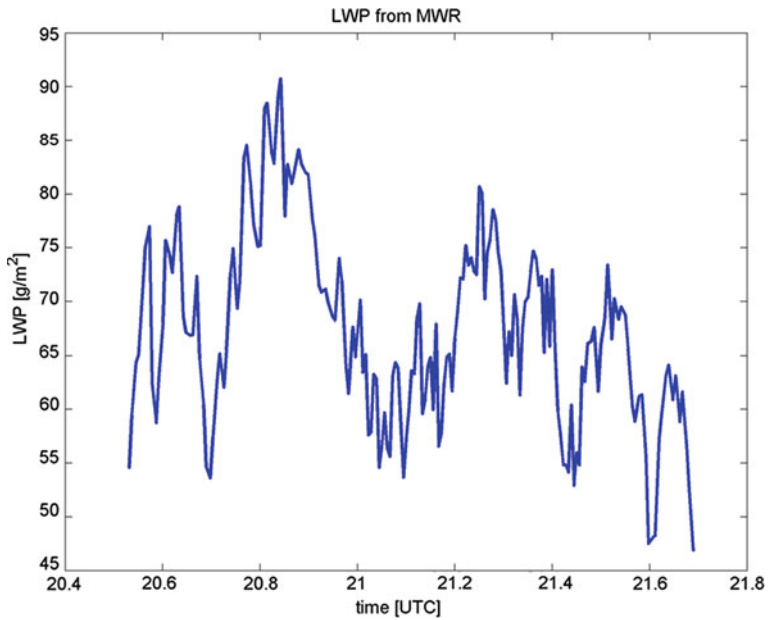


Fig. II.1.9 Liquid water path estimated by a microwave radiometer

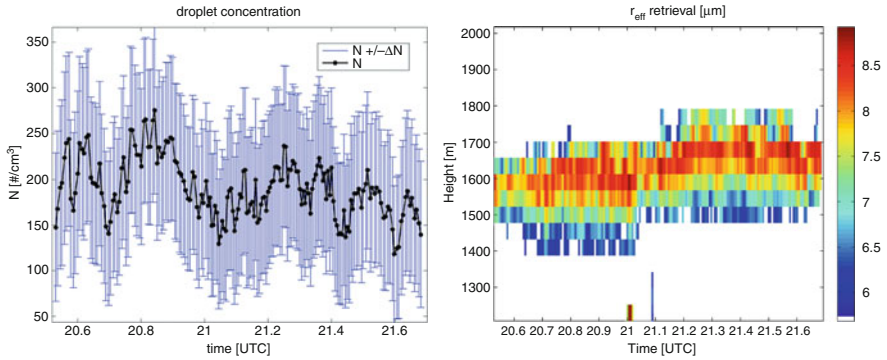


Fig. II.1.10 Droplet concentration (*left*) and effective radius (*right*) as retrieved by the combined approach

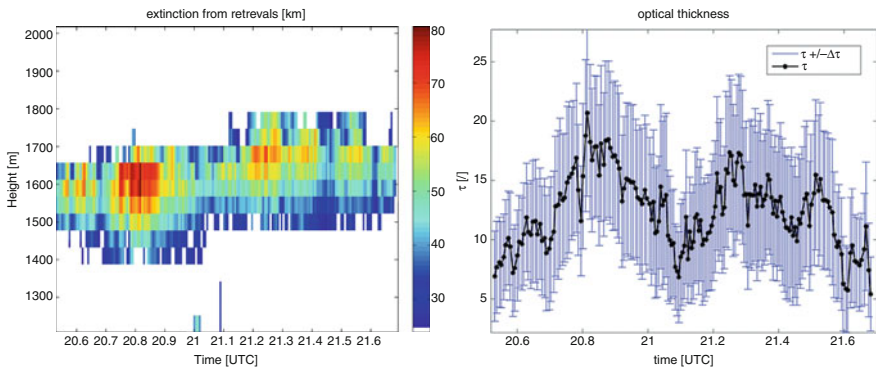


Fig. II.1.11 Extinction profile (*left*) and optical thickness (*right*) as retrieved by the combined approach

microwave radiometer. And out of these two we get the number concentration. Using the number concentration and the assumed cloud model, we can calculate the effective radius and other microphysical properties (Figs. II.1.10 and II.1.11).

When we integrate the extinction profile in Fig. II.1.11, we get the cloud optical thickness. This is the parameter relevant for climate studies. It tells how the cloud is affecting the radiation balance.

4 Zooming in on the Microstructure of Precipitation: The Shape and Size of Raindrops and Ice Crystals

Most rain originates from ice crystals aloft. The physical process is understood in qualitative terms, but quantification is very difficult. Ice crystals occur in a large variety of shapes and sizes, and each category is differently effective in the process

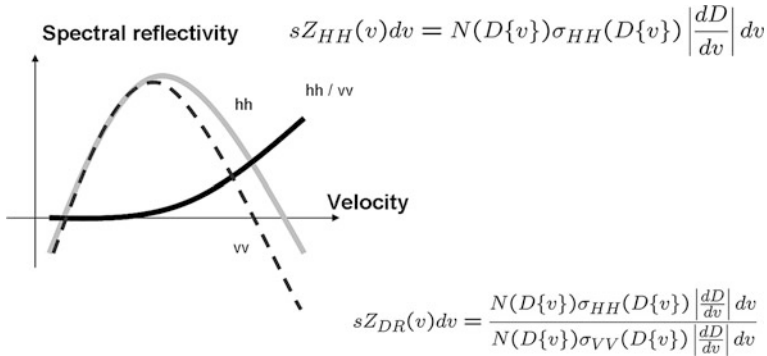


Fig. II.1.12 Introducing the spectral differential reflectivity Zdr

of aggregation, coalescence, or breakup. The need for high quality observations is high. We herewith describe a new technique that combines Doppler and polarization radar measurements to derive the microphysical properties of ice crystals, before they melt into raindrops (Fig. II.1.12).

Spherical particles do not change the polarization of radar waves, whereas oblate particles scatter horizontally polarized waves better than vertically ones. The fall speed of differently shaped particles may also differ. A clear case is rain: small drops are spherical and have a low fall speed, and large particles are oblate with a large fall speed. This leads to the concept of the spectral differential reflectivity: the polarization dependence of radar waves per class of occurring velocities. A Doppler–polarimetric radar can measure this quantity.

Figure II.1.13 is an example of a Doppler–polarimetric radar observation of rain-fall. The left panel shows the velocity distribution of the reflectivity as function of height. The right panel shows the corresponding spectral differential reflectivity. Between 1,600 and 2,000 m we can see an enhanced reflectivity. This is the bright band due to melting ice. Above it there is ice and below rainfall. The velocity spectrum is narrow in the ice region, which indicates that the particles have similar fall

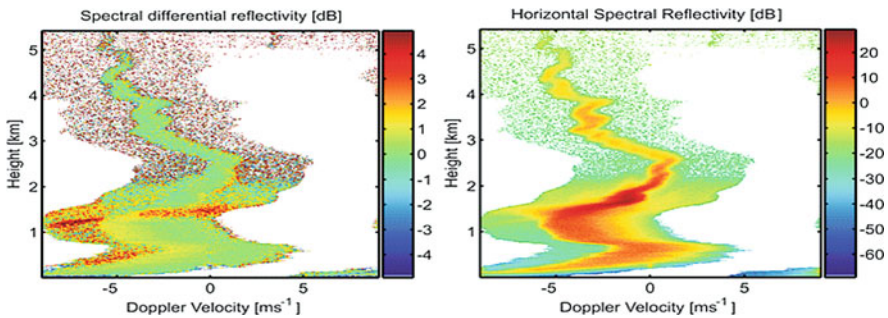
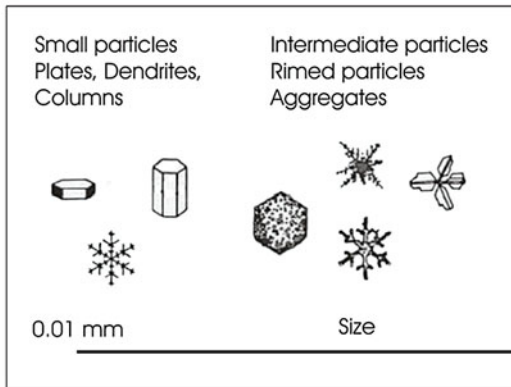


Fig. II.1.13 Examples of polarimetric spectrogram

Precipitation above the melting layer consists of many different ice particles



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Fig. II.1.14 Size and shape of precipitating ice particles existing in clouds above the melting layer

speeds. Right panel shows that the shape of the particles can change quite a bit in the process of melting.

The retrieval of ice crystal information from such data is not easy. We have to construct a microphysical model that includes the variety of sizes and shapes (Fig. II.1.14) and relate this to the expected radar observables. In the inverse approach we can then derive the microphysical properties from the measurements.

Figure II.1.15 shows some of the results. The radar reflection is given as function of velocity for different types of ice particles. It is clear that plates and aggregates dominate for low velocities. This implies that we can only infer these types from the observations.

What we get then is information like the ones in Fig. II.1.16: the equivolumetric diameter and number concentration as function of time for aggregates and plates. Note the large difference between the two different habits.

With the data in Fig. II.1.16 we can do a consistency check: if we use the numbers to calculate the reflectivity, does it correspond to the observations?

$$Z = \frac{|K|^2}{|K_r|^2} \int_{D=0}^{\infty} N(D) D^6 dD$$

The computed reflectivity is shown in Fig. II.1.17; time dependence of obtained reflectivity shows good correlation with the measured reflectivity.

Fig. II.1.15 Radar reflection as function of velocity for different types of ice particles

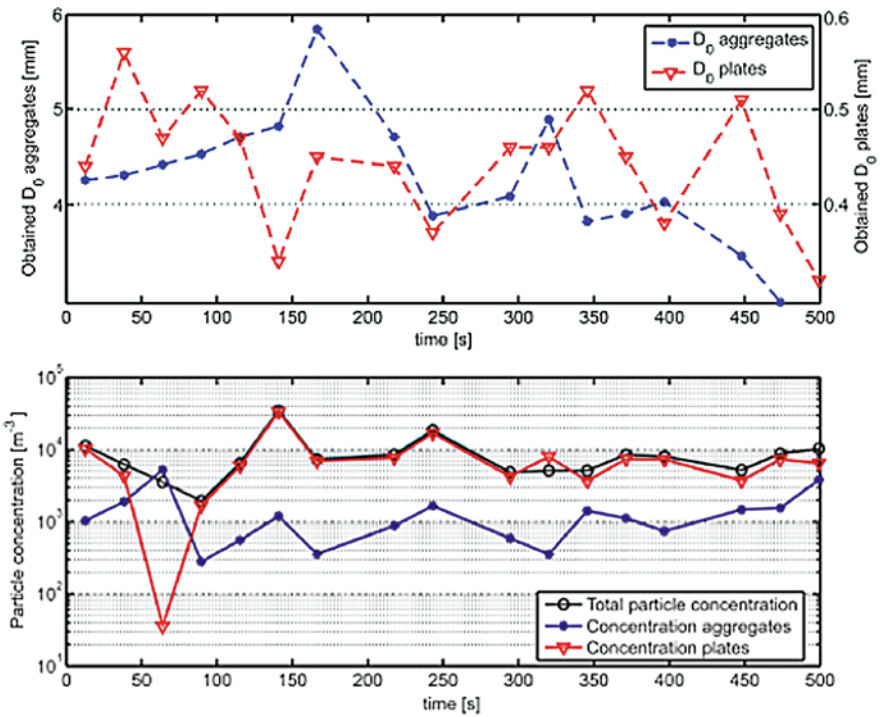
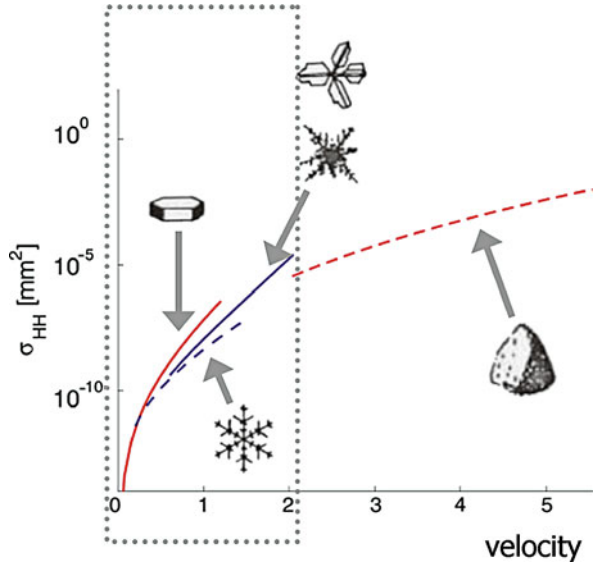


Fig. II.1.16 Retrieved time series: Equivolumetric diameter (*top*) and particle concentration (*bottom*)

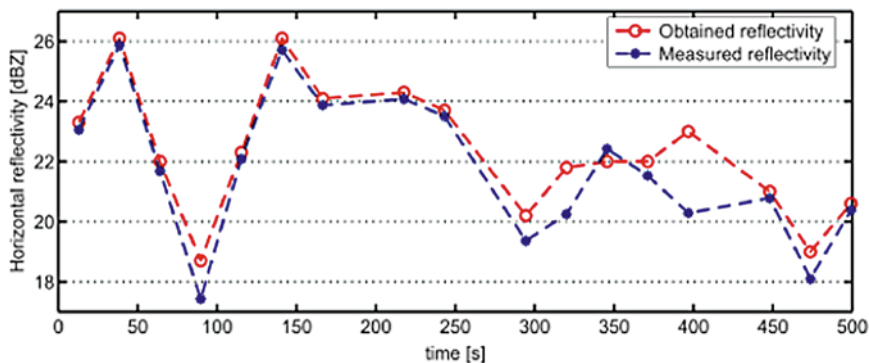


Fig. II.1.17 Time series of equivalent obtained and measured reflectivity

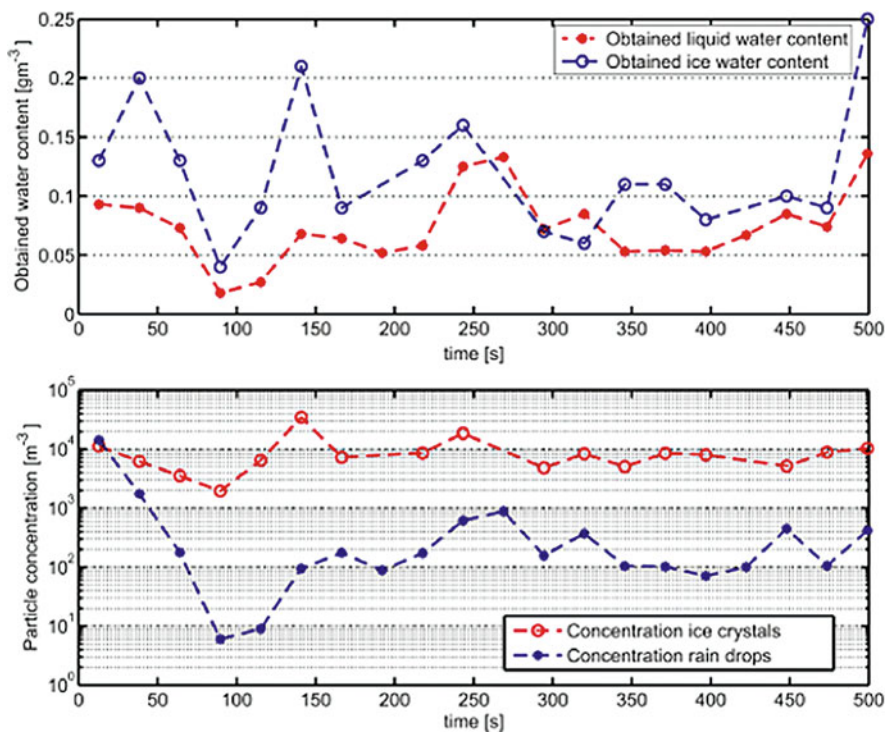


Fig. II.1.18 Ice water content and liquid water content (top) and particle concentrations of ice crystals and rain (bottom). Trends in radar observables comparable above and below the melting layer

Finally, we can calculate the ice water content and number concentration of rainfall droplet and ice crystals, as illustrated in Fig. II.1.18:

$$\text{IWC} = \int_{D=0}^{\infty} N(D)m(D)dD$$

With these observations we can now study the rainfall process. For instance look into questions like: how stationary is the mass flow through the melting layer? How does the number concentration change during melting? Does it correspond to common assumptions in models?