

This discussion paper is/has been under review for the journal Atmospheric Measurement Techniques (AMT). Please refer to the corresponding final paper in AMT if available.

# Ground-based remote sensing scheme for monitoring aerosol–cloud interactions

K. Sarna and H. W. J. Russchenberg

TU Delft Climate Institute, Faculty of Civil Engineering and Geotechnolgy, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, the Netherlands

Received: 13 October 2015 – Accepted: 4 November 2015 – Published: 17 November 2015

Correspondence to: K. Sarna (k.sarna@tudelft.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

A method for continuous observation of aerosol–cloud interactions with ground-based remote sensing instruments is presented. The main goal of this method is to enable the monitoring of cloud microphysical changes due to the changing aerosol concentration.

We use high resolution measurements from lidar, radar and radiometer which allow to collect and compare data continuously. This method is based on a standardised data format from Cloudnet and can be implemented at any observatory where the Cloudnet data set is available. Two example study cases were chosen from the Atmospheric Radiation Measurement (ARM) Program deployment at Graciosa Island, Azores, Portugal in 2009 to present the method. We show the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  for data divided into bins of LWP, each of  $10 \text{ gm}^{-2}$ . We explain why the commonly used way of quantity aerosol cloud interactions by use of an ACI index ( $\text{ACI}_{r,\tau} = \text{dln}r_e, \tau / \text{dln}\alpha$ ) is not the best way of quantifying aerosol–cloud interactions.

## 1 Introduction

Low-level water clouds are considered one of the main sources of uncertainties in climate change predictions. According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014), clouds and the effects of aerosol on their macro- and micro-structure continue to contribute to the largest uncertainty in the estimation and interpretation of the Earth’s energy budget. Low-level clouds impact mainly the shortwave radiation budget as it is mostly sensitive to the cloud albedo. The effect of aerosol concentration on cloud reflectance is often referred to as the Twomey effect (Twomey, 1974), albedo effect or first indirect effect. It is based on the close relation between the aerosol concentration below the cloud and the droplet concentration of a cloud formed above.

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The structure of this paper is following: first, we provide a description of the methodology for estimating the relationship between the aerosol concentration below the cloud base and the cloud droplet concentration and the droplet sizes in the cloud base region, as well as the combination of instruments and proxies used for the method. Then we show two example study cases from the ARM Mobile Facility at Graciosa Island at the Azores, Portugal. Finally, we discuss the possibilities of implementing this method over the network of cloud profiling observatories in Europe.

## 2 Quantifying interactions between aerosol and cloud

Very often in the literature the term aerosol–cloud interactions is associated with quantification of the impact of aerosol on cloud albedo. This relation was first postulated by Twomey (1974). Through experimental studies he showed that the number concentration of aerosol ( $N_a$ ) below the cloud is monotonically related to the cloud droplet number concentration ( $N_d$ ):

$$N_d \propto N_a^\gamma, \quad (1)$$

(Twomey and Warner, 1967). The aerosol number concentration and cloud droplet concentration are not directly proportional because the increased concentration of aerosol that can be activated into cloud droplets can lead to lowering of the maximum relative humidity that can be reached in the cloud base region. The value of  $\gamma$  varies between 0.7 and 0.8 between different experimental studies (Pruppacher and Klett, 2010; Twomey, 1974). Twomey (1977) further derived a theoretical relationship between the aerosol concentration and cloud albedo. He proposed that, since an increased aerosol concentration results in an increased number of cloud condensation nuclei (CCN) for cloud droplet formation, it will also lead to an increased cloud droplet concentration. If the amount of available water for the cloud formation is constant, by assuming a constant value of liquid water path (LWP), the increased cloud droplet concentration will

mean that the effective radius of cloud droplets ( $r_e$ ) is smaller. As the cloud droplet concentration and cloud effective radius influence the value of the cloud optical thickness ( $\tau_d$ ) it can be assumed that the optical thickness will be rising with the increase of the droplet concentration,

$$5 \quad \tau_d \propto N_d^{1/3} \quad (2)$$

(Twomey, 1974), and the decrease of the droplet radius:

$$r_e \propto \frac{\text{LWP}}{\tau_d}, \quad (3)$$

(Stephens, 1978).

10 Theoretical relationships between variables in Eqs. (1)–(3) led to the formulation of a relation between the aerosol optical thickness ( $\tau_a$ ), as  $\tau_a$  is a function of the aerosol number concentration ( $N_a$ ), and the effective radius of cloud droplets ( $r_e$ ):

$$r_e \propto \tau_a^{-\gamma/3}, \quad (4)$$

15 which is a basic theoretical relation used presently to quantify the effect described by Twomey. In order to empirically quantify the interactions between aerosol and cloud Feingold et al. (2001) introduced the indirect effect index (IE), later referred to as the ACI (Aerosol–Cloud Interactions),

$$\text{IE} = \text{ACI}_{r/\tau} = \left. \frac{d \ln r_e / \tau_d}{d \ln \alpha} \right|_{\text{LWP}} \quad 0 < \text{ACI}_{r/\tau} < 0.33, \quad (5)$$

20 where  $\alpha$  is an observed proxy of the amount of aerosol and varies between studies. It can include parameters such as aerosol number concentration ( $N_a$ ), aerosol optical thickness ( $\tau_a$ ) or Aerosol Index (AI), which is a product of  $\tau_a$  and Angström exponent.

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



It is important to note that in order to derive Eq. (2) Twomey made a series of assumptions. He restricted his analysis to homogeneous clouds with a thin optical thickness where cloud droplet number concentration and aerosol optical thickness can be considered directly proportional to an increasing pollution. The assumption about aerosol optical thickness meant that he considered all components in the aerosol to increase together and at the same proportion. Further, he assumed that absorption is not greatly modified when the cloud forms and therefore the increase in the cloud nuclei concentration is proportional to the absorption optical thickness of the aerosol. The combination of these assumptions greatly minimises the amount of observational study cases where the relation from Eq. (2) can be applied. Another important, and often omitted, factor is that the cloud droplet concentration ( $N_d$ ) is modified by mixing, collision and coalescence, evaporation and coagulation within the cloud. However, at the area close to the cloud base, where the cloud is at the early formation stage, the initial  $N_d$  is determined by the amount of nuclei able to activate into cloud droplets at or below the maximum supersaturation in the cloudy air (Twomey and Warner, 1967). This means that the number concentration of aerosol to the number concentration of cloud droplets should be related below the cloud base. Cloud droplet concentration can be related with the cloud reflectance and albedo only under an assumption that the cloud is homogeneous and its properties do not change from the cloud base to the cloud top. The relation from the Eq. (5) is derived from the cloud reflectance and under all the above mentioned assumptions its transition to other parameters and actual observations is not straightforward.

In this study we focus on the aerosol–cloud interactions as an approximation of the nucleation process without relating it to the cloud albedo. We design a method that enables monitoring daily the microphysical process between aerosol and clouds. To avoid the ambiguity of the ACI empirical form (Eq. 5), we quantify the relation between cloud and aerosol properties with statistical parameters making only the assumption that the aerosol number concentration in the cloud base region is monotonically related to the cloud droplet concentration (Eq. 1) and that the increase of the cloud droplet concen-



be satisfied by ground-based remote sensing instruments which are at the core of this monitoring scheme.

As a microphysical process, aerosol–cloud interactions should be observed in the same air column, at a high temporal resolution. We used the Cloudnet dataset, which provides a set of high quality measurements from radar, lidar and a microwave radiometer (Hogan and O'Connor, 2004). Additionally, each pixel of the data set is categorised in terms of the presence of liquid droplets (cloud, rain or drizzle), ice, insects or aerosol. This categorisation allows us to construct an algorithm that can be applied to specific targets only.

### 3.2 Aerosol and cloud properties proxies

Clouds are formed when aerosol particles are activated into cloud droplets. Activation is a change from stable to unstable growth due to the increase of the ambient humidity. Haze droplets grow through the peak of the Köhler curve (Köhler, 1936) and are transformed into cloud droplets. When a higher concentration of the aerosol particles is present, the competition for the excess water vapour will be greater and thus, the resulting cloud droplets will be smaller (Lamb and Verlinde, 2011).

In low level liquid water clouds, in particular Stratocumulus, the number of the activated droplets is approaching the concentration of the aerosol accumulation mode (particles between 0.1 and 1  $\mu\text{m}$ ), making that concentration itself the primary determinant of the cloud droplet concentration (e.g., Martin et al., 1994; Lu et al., 2007). Based on an adiabatic cloud parcel model representing the hygroscopic growth of CCN and droplet condensation, Feingold (2003) concluded that aerosol number concentration ( $N_a$ ) contributes most significantly to aerosol effects on clouds. Other aerosol parameters, such as size, breadth of the aerosol size distribution and its chemical composition are of a secondary importance.

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





of the measurements is difficult to estimate as the internal processing algorithms are proprietary. A single value of 0.5 dB is used for all pixels (Hogan and O'Connor, 2004).

### 3.2.2 Cloud droplets size and number concentration

Aerosol–cloud interactions are described as the response of the microphysical properties of the cloud to the change of the aerosol number concentration. The cloud properties that we are specifically interested in are the cloud droplet size and the number concentration of the droplets. Both these variables are obtained through a retrieval of cloud microphysical properties from measurements.

For retrieval of the cloud droplet concentration ( $N_d$ ) and the cloud droplet effective radius ( $r_e$ ) from cloud radar and MWR observations we apply a method according to Frisch et al. (2002). Assuming that  $N_d$  and gamma cloud droplet distribution with a fixed distribution shape ( $\nu$ ) are constant with height, the  $r_e$  can be derived from the Radar Reflectivity Factor ( $Z$ ) and the MWR retrieved LWP:

$$r_e(h) = \left( \frac{(\nu + 2)^3}{(\nu + 3)(\nu + 4)(\nu + 5)} \right)^{\frac{1}{3}} \left( \frac{\pi \rho_w \sum_{i=1}^n Z^{\frac{1}{2}}(h_i) \Delta h}{48 \text{LWP}} \right)^{\frac{1}{3}} Z^{\frac{1}{6}}(h), \quad (7)$$

where  $\rho_w$  is the density of liquid water ( $10^6 \text{ gm}^{-3}$ ),  $\Delta h$  is the the length of the radar range gate,  $Z(h_i)$  is the reflectivity factor at the  $i$ th radar measured gate and  $n$  represents the number of the in-cloud radar-measured gates. The cloud droplet number concentration ( $N_d$ ) is calculated from the following formula:

$$N_d = \left( \frac{(\nu + 3)(\nu + 4)(\nu + 5)}{\nu(\nu + 1)(\nu + 2)} \right) \left( \frac{6 \text{LWP}}{\pi \rho_w \sum_{i=1}^n Z^{\frac{1}{2}}(h_i) \Delta h} \right). \quad (8)$$

Both of those retrieved properties have been evaluated against other methods in Knist (2014). The comparison of different retrieved microphysical cloud properties reveals

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



that  $r_e$  is the most robust parameter. The estimated uncertainties in  $r_e$  are about 10–15% and in  $N_d$  around 40–60%. In both proxies the uncertainties are due to observational errors and algorithm assumptions. Following Knist (2014), the gamma cloud droplet distribution shape parameter is set to 8.7. This value is obtained from the ratio between the third and second moment of the droplet distribution and has been found in reanalysis of the in-situ observations of Stratocumulus clouds (Brenquier et al., 2011).

Similarly to the aerosol proxy, we compare the  $r_e$  at a set distance from the cloud base. We set this distance at 85 m above the cloud base detected from the lidar measurements, as the lidar can detect the cloud base height more precisely than the radar. The distance of 85 m ensures that the cloud is detected by both instruments.

### 3.2.3 Relation between aerosol and cloud proxies

The strong relation between aerosol concentration and cloud droplet concentration (Eq. 1) is postulated both by theory and observations. We expect to see an inverse relationship between the aerosol concentration and cloud droplets size. With the increase of the aerosol concentration, the cloud droplet size is expected to decrease while at the same time the cloud droplet concentration is expected to increase.

Applying those relations to the proxies of cloud and aerosols we use in this method we should observe a decrease of the cloud droplet effective radius ( $r_e$ ) with the increase of the integrated attenuated backscatter (ATB). The cloud droplet number concentration ( $N_d$ ) should be increasing with the increasing value of the integrated attenuated backscatter (ATB).

### 3.3 Data selection criteria

Clouds are complicated systems with many processes taking place at the same time. Hence, singling out a small microphysical process is difficult. Analysed data need to be limited by implementing a number of filters. Firstly, this monitoring scheme applies only to liquid water clouds on top of the boundary layer in well-mixed conditions. This

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



limitation ensures that the cloud is not decoupled from the boundary layer and the aerosol background below the cloud (Feingold et al., 2006). Secondly, we can only consider data when no precipitation is present, including drizzle, as it can obscure the formative stage of a cloud (Feingold et al., 2003). We use the Cloudnet categorisation data for the classification of the observed targets. Thirdly, only data with a changing aerosol background is analysed. The assumption of aerosol–cloud interactions is that the variation in the aerosol concentration affects the variation in the cloud properties. Thus, both aerosol and cloud parameters need to vary to observe the impact of aerosol on cloud. This scheme relies on measurements from three separate instruments. Only profiles where all three instruments provide good quality data can be analysed.

Some larger scale factors, such as boundary layer dynamics or variations in temperature, pressure or humidity, can influence changes in the cloud. We ensure similar meteorological conditions by analysing aerosol and cloud properties on a daily basis. This minimises the influence of variations in general weather conditions. To further minimise the impact of these factors on the calculation of aerosol–cloud interactions, due to some daily variations, we apply a constraint on LWP. It's prime role is to isolate the aerosol activation process from different interactions that can happen at the same time. Daily datasets are divided into profiles where the value of LWP is similar. We divide the data into bins of LWP of  $10 \text{ g m}^{-2}$ , as creating smaller bins is difficult due to the limited data points. LWP should be above  $30 \text{ g m}^{-2}$  and below  $150 \text{ g m}^{-2}$ . Values below  $30 \text{ g m}^{-2}$  are disregarded because of the uncertainty of LWP calculated from MWR, which is around  $15 \text{ g m}^{-2}$  (Turner et al., 2007). The values above  $150 \text{ g m}^{-2}$  are excluded to avoid precipitating clouds.

The analysis of an aggregated dataset grouped by varying meteorological regimes would be a good way of getting a better understanding of aerosol–cloud interactions drivers. Such a study can be made with the method presented here but is beyond the scope of this manuscript.







## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



standard deviation of  $230 \text{ cm}^{-3}$  and mean value of  $550 \text{ cm}^{-3}$ . Note that values of  $N_d$  over  $2500 \text{ cm}^{-3}$  (around 02:00 UTC) were excluded from the analysis. Values of  $r_e$  range between 2.5 and  $7.5 \mu\text{m}$ , with a mean radius  $4.7 \mu\text{m}$  and a standard deviation of  $0.95 \mu\text{m}$ . ATB in the selected period has a mean value of  $1.4 \times 10^{-3} \text{ sr}^{-1}$  and a standard deviation of  $0.25 \times 10^{-3} \text{ sr}^{-1}$ . It should be noted that on 29 November ATB is higher, but, even accounting for the uncertainty of ATB, the variation is smaller than on 3 November.

Suitable data from 29 November 2009 are divided into bins based on the value of the LWP which ranges from 30 to  $90 \text{ gm}^{-2}$ . Data was divided into 6 separate bins, each covering  $10 \text{ gm}^{-2}$ . Figure 6 presents relation between the integrated attenuated backscatter ATB and cloud droplet effective radius  $r_e$  together with the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$ , corresponding to each bin.

Examination of the correlation coefficient,  $r$ , and the coefficient of determination,  $r^2$  reveals that on average both of these statistical values are lower on 29 November than on 3 November, even though the total number of observations is higher on that day. The possible explanation for this is that the cloud base was more than 1500 m a.g.l.. This may suggest that the impact of the aerosol background below the cloud is smaller. Also, as we indicated before, the variation in the aerosol background is smaller. If the aerosol background below the cloud is more stable separating cloud microphysical process within the cloud might be more difficult. Also, it was indicated by Feingold (2003) that other aerosol parameters than  $N_a$ , such as the size distribution and composition, are of a greater importance when the aerosol loading is higher. Note that for the case from 29 November 2009 the correlation coefficient for the LWP bin from 80 to  $90 \text{ gm}^{-2}$  is actually positive. This suggest that at this LWP cloud droplets grow through different process, such as collision and coalescence, and the activation of aerosol into cloud droplets is a secondary process.

Figure 8 presents the relation between the integrated attenuated backscatter, ATB, and the cloud droplet number concentration,  $N_d$ , together with the corresponding Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,

$r^2$ . Again it can be clearly observed that the cloud droplet number concentration increases with the increase of aerosol concentration (represented by ATB). Data from 29 November shows less scatter than on 3 November, but the correlation coefficient is lower.

### 4.3 Comparison of example study cases

Table 2 summarises statistical parameters, including the number of observations within each LWP bin, for both study cases presented here. Values of the correlation coefficient  $r$  are generally higher for the value of LWP in the range from 30 to 70  $\text{g m}^{-2}$ . This suggests that aerosol–cloud interactions connected to the droplet activation play a more important role in the lower values of LWP and that supposedly drizzle can obscure the process of the activation of aerosol into cloud droplets.

As we mentioned before, due to using daily data it is necessary to check if the sample in each bin can give a representative value of the correlation coefficient. In order to test that we use a student's  $t$  test. For all bins on 29 November and bins of LWP between 30 and 80  $\text{g m}^{-2}$  on 3 November presented correlations are significant at 99 % level. For the bins between 90 and 100 LWP on 3 November presented correlations are significant at 95 % probability level. For the last bin (between 100 and 110 LWP) the correlations are only significant at 90 % probability level due to a very small sample size.

## 5 Summary and outlook

In this paper we present a method for observing interactions between aerosol and clouds. This method enables continuous monitoring of cloud microphysical responses to the changing aerosol background through a use of high resolution ground-based remote sensing instruments. This scheme is developed on the base of a standardised data format from Cloudnet. We used the Cloudnet cloud categorisation product to

### Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





the aerosol and cloud properties when the parameters are compared at a set height dependent on the cloud base height.

The method we developed is based on a synergy of widely available, high resolution remote sensing instruments. It enables monitoring the interactions of aerosols and clouds. Although the data needs to comply with restrictive criteria, the use of a Cloudnet data format and the categorisation product makes data selection possible in close to real-time. We showed that using the integrated value of the attenuated backscatter from lidar enables the monitoring of aerosol–cloud interactions. The measurements from radar, lidar and microwave radiometer are collected continuously and can therefore provide a continuous estimate of effects of aerosol concentration on cloud properties. This framework of measurements can be implemented at any observatory where the Cloudnet dataset is available and can be integrated into a Cloudnet framework as one of the products. The software developed for this methodology is available under GNU General Public License (Sarna, 2015). Monitoring aerosol–cloud interactions in the same manner over multiple regions will allow for more studies of these phenomena and will result in a better understanding of the interactions between aerosol and clouds.

*Acknowledgements.* The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement 262254.

We acknowledge the Cloudnet project (European Union contract EVK2-2000-00611) for providing the Cloudnet Target Categorisation dataset, which was produced by the Department of Meteorology from the University of Reading using measurements from the US Department of Energy as part of the Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) Climate Research Facility at Graciosa, Azores.

The authors would like to acknowledge Christine Knist and thank her for providing the cloud microphysical properties dataset used in this study.

## AMTD

8, 11953–11986, 2015

### Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



IPCC (Ed.): Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2014. 11954

Kaufman, Y. J., Koren, I., Remer, L. A., Rosenfeld, D., and Rudich, Y.: The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, *P. Natl. Acad. Sci. USA*, 102, 11207–11212, doi:10.1073/pnas.0505191102, 2005. 11955

Kim, B.-G., Miller, M. A., Schwartz, S. E., Liu, Y., and Min, Q.: The role of adiabaticity in the aerosol first indirect effect, *J. Geophys. Res.*, 113, D05210, doi:10.1029/2007JD008961, 2008. 11955

Knist, C. L.: Retrieval of liquid water cloud properties from ground-based remote sensing observations, PhD thesis, TU Delft, Civil Engineering and Geosciences, Geoscience and Remote Sensing, Delft, the Netherlands, 2014. 11962, 11963

Kovalev, V. A.: Solutions in LIDAR Profiling of the Atmosphere, John Wiley & Sons, Hoboken, NJ, USA, 2015. 11961

Köhler, H.: The nucleus in and the growth of hygroscopic droplets, *T. Faraday Soc.*, 32, 1152–1161, doi:10.1039/TF9363201152, 1936. 11960

Lamb, D. and Verlinde, J.: Physics and Chemistry of Clouds, Cambridge University Press, Cambridge, UK, 2011. 11960

Lu, M.-L., Conant, W. C., Jonsson, H. H., Varutbangkul, V., Flagan, R. C., and Seinfeld, J. H.: The Marine Stratus/Stratocumulus Experiment (MASE): aerosol–cloud relationships in marine stratocumulus, *J. Geophys. Res.*, 112, D10209, doi:10.1029/2006JD007985, 2007. 11960

Lu, M.-L., Feingold, G., Jonsson, H. H., Chuang, P. Y., Gates, H., Flagan, R. C., and Seinfeld, J. H.: Aerosol–cloud relationships in continental shallow cumulus, *J. Geophys. Res.*, 113, D15201, doi:10.1029/2007JD009354, 2008. 11955

Martin, G. M., Johnson, D. W., and Spice, A.: The measurement and parameterization of effective radius of droplets in warm stratocumulus clouds, *J. Atmos. Sci.*, 51, 1823–1842, doi:10.1175/1520-0469(1994)051<1823:TMAPOE>2.0.CO;2, 1994. 11960, 11966

McComiskey, A. and Feingold, G.: The scale problem in quantifying aerosol indirect effects, *Atmos. Chem. Phys.*, 12, 1031–1049, doi:10.5194/acp-12-1031-2012, 2012. 11955

McComiskey, A., Feingold, G., Frisch, A. S., Turner, D. D., Miller, M. A., Chiu, J. C., Min, Q., and Ogren, J. A.: An assessment of aerosol–cloud interactions in marine stratus clouds based on

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



surface remote sensing, *J. Geophys. Res.*, 114, D09203, doi:10.1029/2008JD011006, 2009. 11955

Münkel, C., Eresmaa, N., Räsänen, J., and Karppinen, A.: Retrieval of mixing height and dust concentration with lidar ceilometer, *Bound.-Lay. Meteorol.*, 124, 117–128, doi:10.1007/s10546-006-9103-3, 2006. 11961

O'Connor, E. J., Illingworth, A. J., and Hogan, R. J.: A technique for autocalibration of cloud lidar, *J. Atmos. Ocean. Tech.*, 21, 777–786, doi:10.1175/1520-0426(2004)021<0777:ATFAOC>2.0.CO;2, 2004. 11961

Pruppacher, H. R. and Klett, J. D.: *Microphysics of Clouds and Precipitation*, Springer, Dordrecht, Netherlands, 2010. 11956

Rémillard, J., Kollias, P., Luke, E., and Wood, R.: Marine boundary layer cloud observations in the Azores, *J. Climate*, 25, 7381–7398, doi:10.1175/JCLI-D-11-00610.1, 2012. 11965, 11967

Sarna, K.: ACI monitoring: first release, doi:10.5281/zenodo.32033, Computer Software, 2015. 11971

Stephens, G. L.: Radiation profiles in extended water clouds. II: Parameterization schemes, *J. Atmos. Sci.*, 35, 2123–2132, doi:10.1175/1520-0469(1978)035<2123:RPIEWC>2.0.CO;2, 1978. 11957

Sundström, A.-M., Nousiainen, T., and Petäjä, T.: On the quantitative low-level aerosol measurements using ceilometer-type lidar, *J. Atmos. Ocean. Tech.*, 26, 2340–2352, doi:10.1175/2009JTECHA1252.1, 2009. 11961

Turner, D. D., Vogelmann, A. M., Johnson, K., Miller, M., Austin, R. T., Barnard, J. C., Flynn, C., Long, C., McFarlane, S. A., Cady-Pereira, K., Clough, S. A., Chiu, J. C., Khaiyer, M. M., Liljegren, J., Lin, B., Minnis, P., Marshak, A., Matrosov, S. Y., Min, Q., O'Hirok, W., Wang, Z., and Wiscombe, W.: Thin liquid water clouds: their importance and our challenge, *B. Am. Meteorol. Soc.*, 88, 177–190, doi:10.1175/BAMS-88-2-177, 2007. 11964

Twohy, C. H., Petters, M. D., Snider, J. R., Stevens, B., Tahnk, W., Wetzal, M., Russell, L., and Burnet, F.: Evaluation of the aerosol indirect effect in marine stratocumulus clouds: droplet number, size, liquid water path, and radiative impact, *J. Geophys. Res.*, 110, D08203, doi:10.1029/2004JD005116, 2005. 11955

Twomey, S.: Pollution and the planetary albedo, *Atmos. Environ.*, 8, 1251–1256, doi:10.1016/0004-6981(74)90004-3, 1974. 11954, 11956, 11957

**Monitoring  
aerosol–cloud  
interactions**K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Twomey, S.: The influence of pollution on the shortwave albedo of clouds, *J. Atmos. Sci.*, 34, 1149–1152, doi:10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2, 1977. 11956
- Twomey, S. and Warner, J.: Comparison of measurements of cloud droplets and cloud nuclei, *J. Atmos. Sci.*, 24, 702–703, doi:10.1175/1520-0469(1967)024<0702:COMOCD>2.0.CO;2, 1967. 11956, 11958
- 5 Widener, K. B. and Mead, J. B.: W-Band ARM cloud radar-Specifications and design, in: Fourteenth ARM Science Team Meeting Proceedings, Albuquerque, NM, USA, available at: [http://www.arm.gov/publications/proceedings/conf14/extended\\_abs/widener2-kb.pdf](http://www.arm.gov/publications/proceedings/conf14/extended_abs/widener2-kb.pdf), 2004. 11965
- 10 Wiegner, M., Madonna, F., Biniotoglou, I., Forkel, R., Gasteiger, J., Geiß, A., Pappalardo, G., Schäfer, K., and Thomas, W.: What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET, *Atmos. Meas. Tech.*, 7, 1979–1997, doi:10.5194/amt-7-1979-2014, 2014. 11961

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

**Table 1.** Cloud and aerosol properties measured or derived from the observations at the Graciosa Island, Azores.

Measured Quantity	Definition	Instrument(s)
Cloud Liquid Water Path	LWP [ $\text{g m}^{-2}$ ]	MWR
Radar Reflectivity Factor	$Z$ [dBZ or $\text{m}^6 \text{m}^{-3}$ ]	WACR
Cloud Droplet Effective Radius	$r_e$ [ $\mu\text{m}$ ] (see Eq. 7)	WACR/MWR
Cloud Droplets Number Concentration	$N_d$ [ $\text{cm}^{-3}$ ] (see Eq. 8)	WACR/MWR
Attenuated Backscatter Coefficient	ATB [ $\text{m}^{-1} \text{sr}^{-1}$ ]	Vaisala CT25K

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)

[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Table 2.** The statistical parameters calculated between  $\ln(r_e)$  and  $\ln(ATB)$ , namely Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  and the number of observations within the LWP bins,  $n$ , for two study cases from Graciosa Island at the Azores (3 and 29 November 2009).

LWP bin	3 November 2009			29 November 2009		
	$r$	$r^2$	$n$	$r$	$r^2$	$n$
30 < LWP < 40	−0.76	0.58	71	−0.36	0.13	54
40 < LWP < 50	−0.80	0.65	43	−0.56	0.32	63
50 < LWP < 60	−0.70	0.49	56	−0.68	0.47	67
60 < LWP < 70	−0.50	0.25	95	−0.64	0.41	98
70 < LWP < 80	−0.33	0.11	62	−0.31	0.10	98
80 < LWP < 90	−0.27	0.07	44	0.57	0.32	39
90 < LWP < 100	−0.53	0.28	16	–	–	–
100 < LWP < 110	−0.47	0.22	8	–	–	–

## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

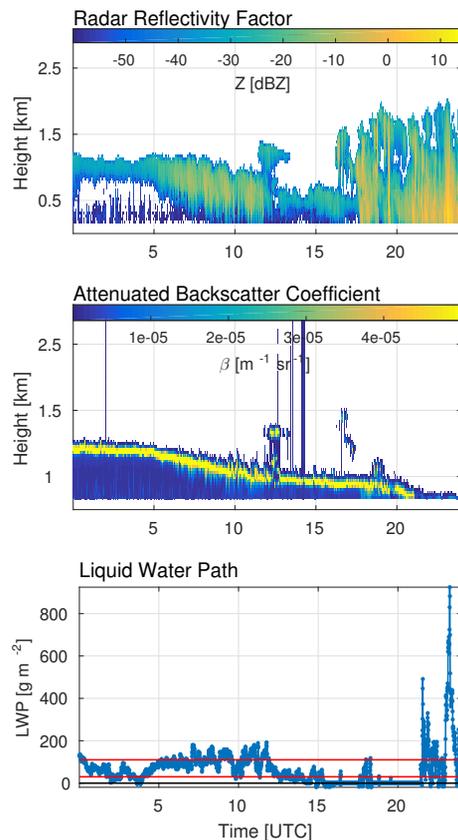
Printer-friendly Version

Interactive Discussion



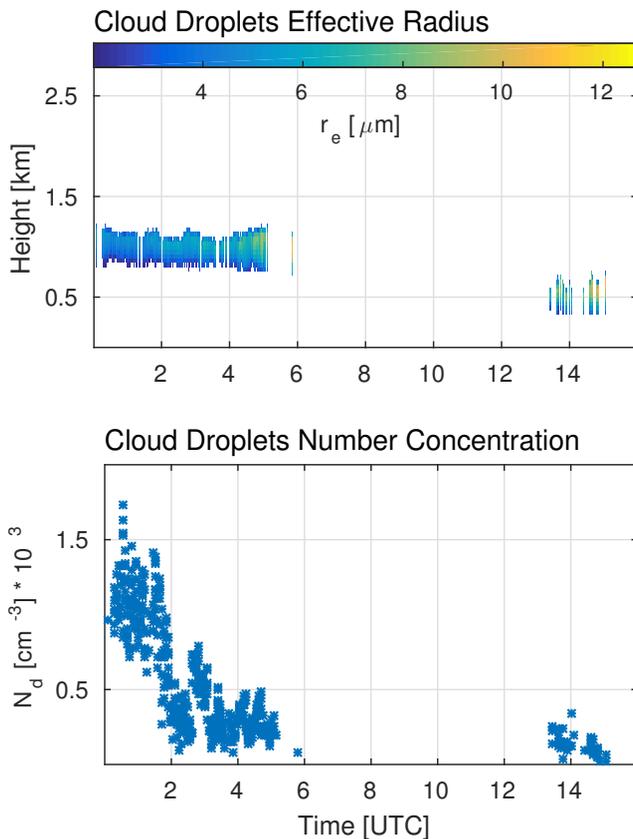
**Table 3.** The statistical parameters calculated between  $\ln(N_d)$  and  $\ln(ATB)$ , namely the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  and the number of observations,  $n$ , for two study cases from Graciosa Island at the Azores (3 and 29 November 2009).

3 November 2009			29 November 2009		
$r$	$r^2$	$n$	$r$	$r^2$	$n$
0.57	0.33	395	0.40	0.16	419

**Monitoring  
aerosol–cloud  
interactions**K. Sarna and  
H. W. J. Russchenberg

**Figure 1.** The time-height cross section of the Radar Reflectivity Factor from WACR, the Attenuated Backscatter Coefficient from Vaisala CT25K and the Liquid Water Path from MWR for a full day of measurements on 3 November 2009.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



**Figure 2.** The time-height cross section of the Cloud Droplet Effective Radius ( $r_e$ ) calculated from WACR and MWR measurements (Eq. 7) and the Cloud Droplet Number Concentration ( $N_d$ ) calculated from Eq. (8) from 3 November 2009. Data is only retrieved in the time steps when the data selection criteria are met.

**Monitoring  
aerosol–cloud  
interactions**

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

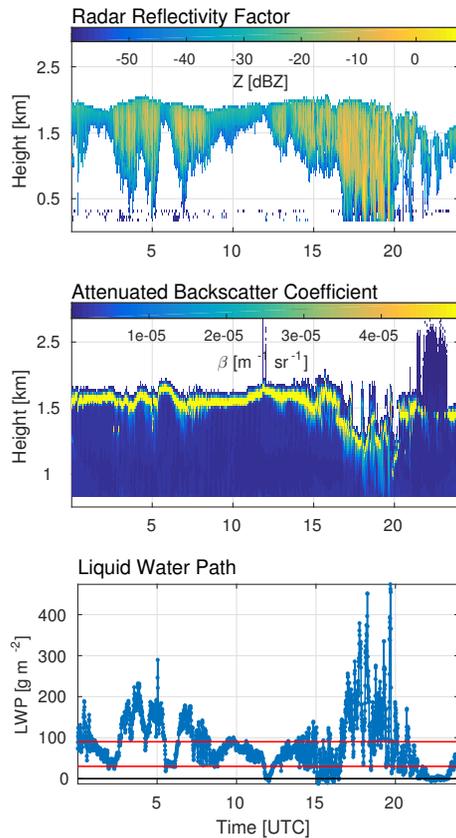
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Figure 3.** The time-height cross section of the Radar Reflectivity from WACR, the Attenuated Backscatter Coefficient from Vaisala CT25K and the Liquid Water Path from MWR for a full day of measurements on 29 November 2009.

**Monitoring aerosol–cloud interactions**

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

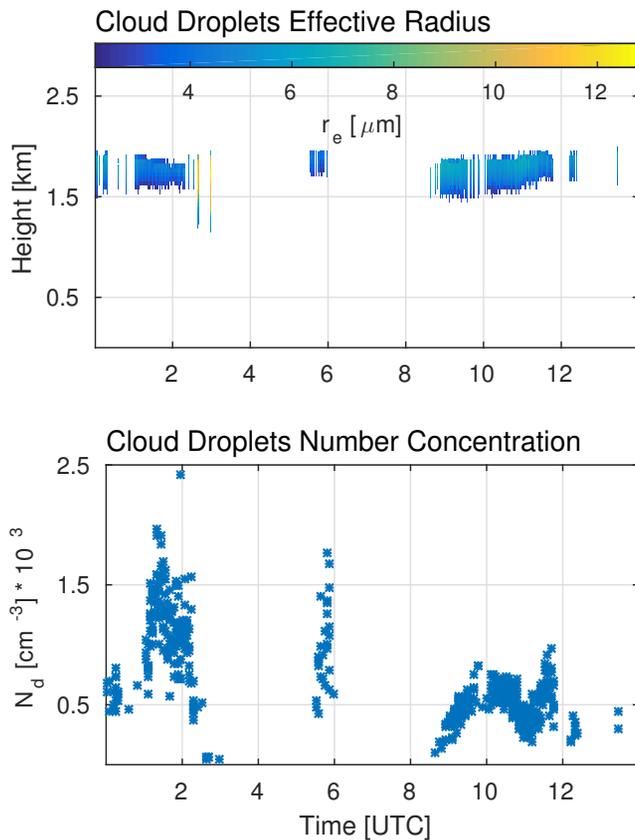
Back Close

Full Screen / Esc

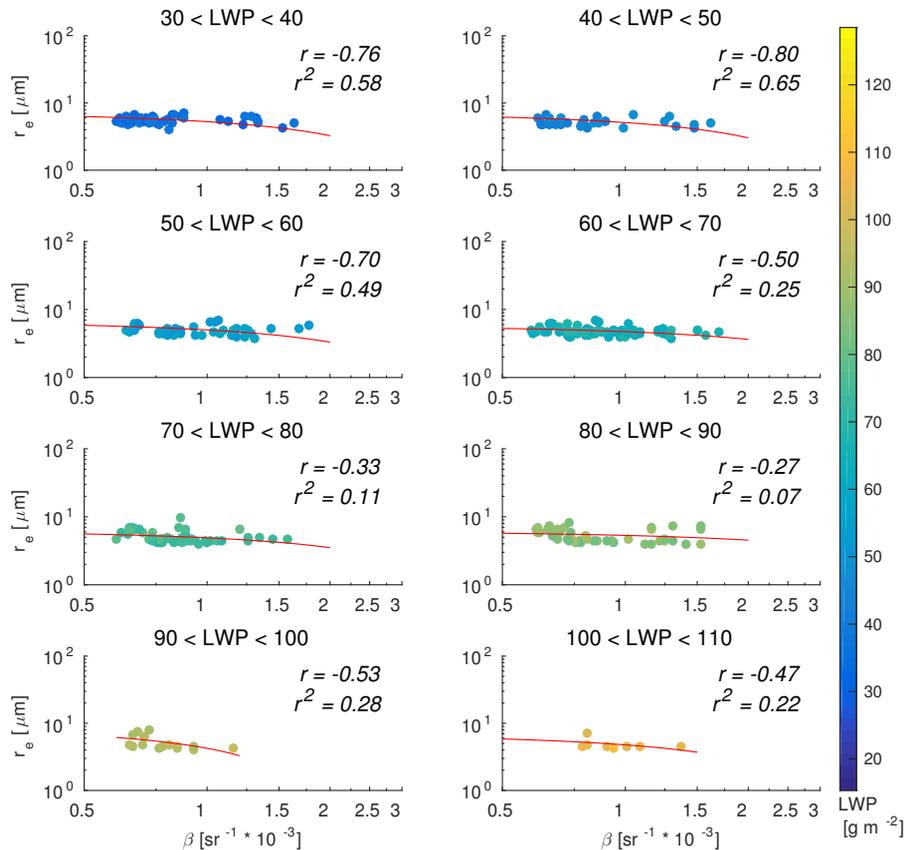
Printer-friendly Version

Interactive Discussion





**Figure 4.** The time-height cross section of the Cloud Droplet Effective Radius ( $r_e$ ) derived from the WACR and MWR (Eq. 7) and the Cloud Droplet Number Concentration ( $N_d$ ) calculated from Eq. (8) from 29 November 2009. Data is only retrieved in the time steps when the data selection criteria are met.



**Figure 5.** The values of the effective radius  $r_e$  derived from WACR and MWR measurements are plotted vs. the integrated attenuated backscatter ATB measured by Vaisala CT25K on 3 November 2009. Data are sorted by the values of LWP from MWR. Every panel shows the corresponding value of the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  and the regression line (red) for that LWP bin.

**Monitoring aerosol–cloud interactions**

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Monitoring aerosol–cloud interactions

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

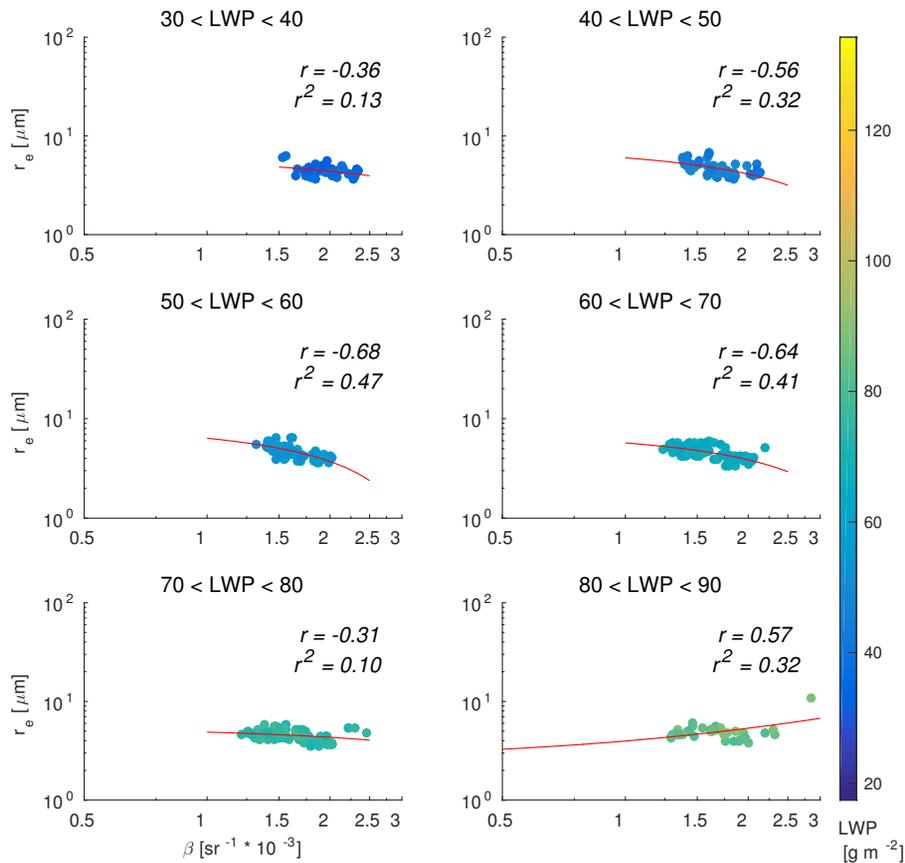
Back

Close

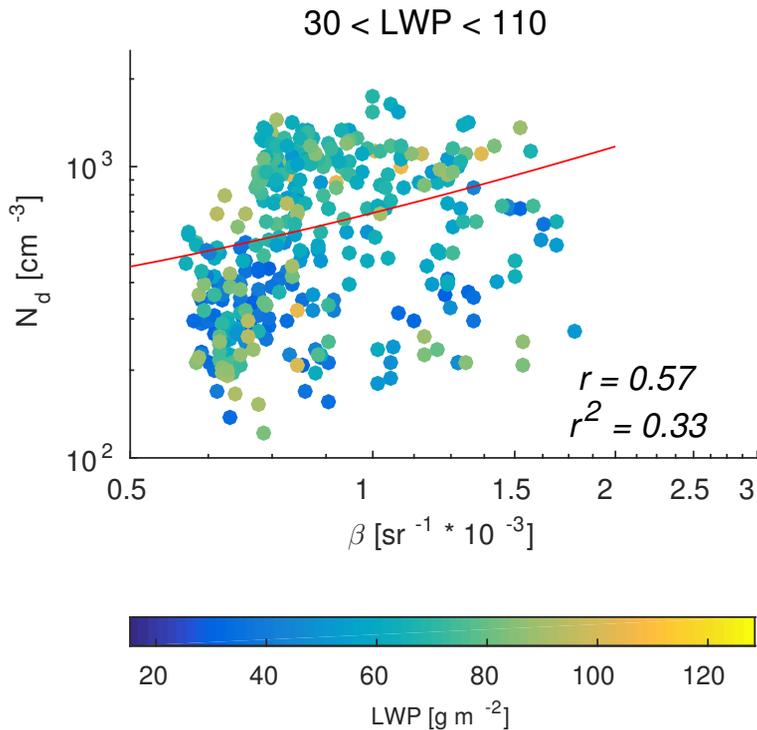
Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Figure 6.** The values of the effective radius  $r_e$  derived from WACR and MWR measurements are plotted vs. the integrated attenuated backscatter ATB measured by Vaisala CT25K on 29 November 2009. Data are sorted by the values of LWP from MWR. Every panel shows the corresponding value of the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  and the regression line (red) for that LWP bin.



**Figure 7.** The cloud droplet number concentration  $N_d$  derived from WACR and MWR measurements with Eq. (8) is plotted vs. the integrated attenuated backscatter ATB measured by Vaisala CT25K on 3 November 2009. Corresponding value of the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  and the regression line (red) is presented.

**Monitoring aerosol–cloud interactions**

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

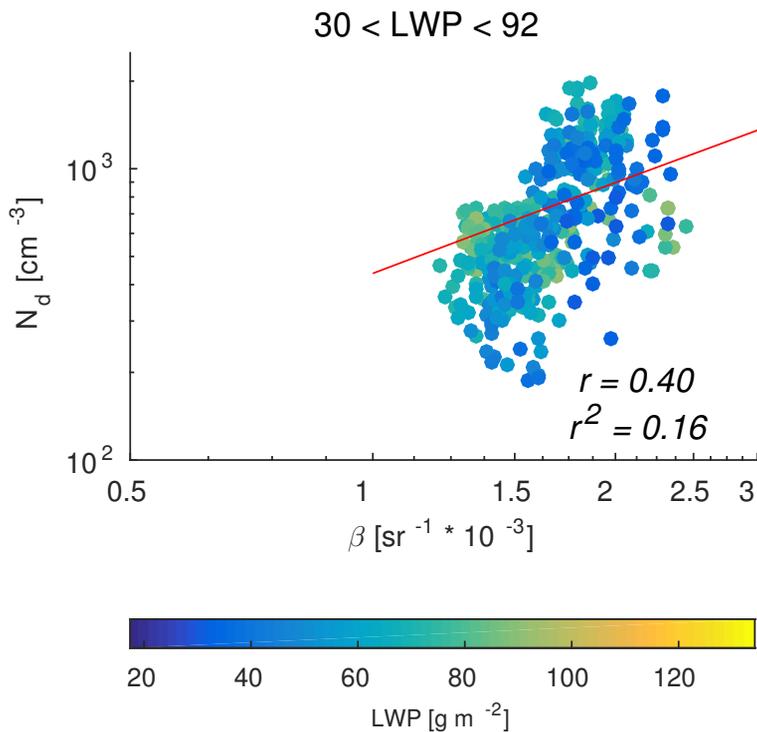
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Figure 8.** The cloud droplet number concentration  $N_d$  derived from WACR and MWR measurements with Eq. (8) is plotted vs. the integrated attenuated backscatter ATB measured by Vaisala CT25K on 29 November 2009. Corresponding value of the Pearson Product–Moment Correlation Coefficient,  $r$ , and the Coefficient of Determination,  $r^2$  and the regression line (red) is presented.

**Monitoring  
aerosol–cloud  
interactions**

K. Sarna and  
H. W. J. Russchenberg

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

