# Liquid water clouds – conditions for sub-adiabatic water content from long-term ground-based remote sensing observations

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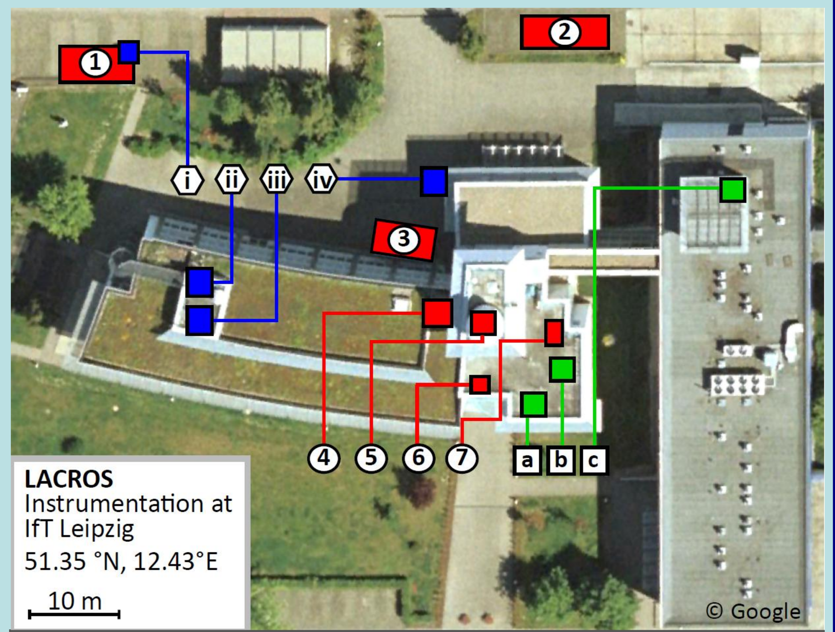
## Introduction

The vertical distribution of liquid water content (LWC) within a cloud is often assumed to follow an adiabatic increase with height. From observations it is known that in many cases show a sub-adiabatic behavior, due to entrainment or precipitation processes.

In this study, we take long-term ground-based cloud observations in the framework of the Cloudnet program (Illingworth et al., 2007) to assess the adiabaticity of liquid water clouds, using a combination of cloud radar, microwave radiometer and ceilometer.

## Cloud Net at LACROS

The detailed and continuous observation of microphysical cloud properties remains a challenging task. Within the last decade, the ground-based remote sensing instrumentation for cloud observation strongly improved. A set of similar instruments to perform this task became available at several places throughout Europe. Therefore, a common standard to derive cloud properties was developed within the CloudNet program (Illingworth et al. 2007).




**Active instrumentation**
① Cloud radar Mira-35
② Raman/HSR lidar BERTHA
③ Doppler lidar WiLi
④ Raman lidar MARTHA#
⑤ SAEMS#
⑥ Ceilometer CHM 15kx
⑦ Raman lidar Polly^XT

**Passive instrumentation**
ⓐ AERONET Sun photometer
ⓑ Microwave radiometer HATPRO
ⓒ All-sky imager

**In situ instrumentation**
ⓘ Optical disdrometer
ⓘⓘ Meteorological surface station
ⓘⓘⓘ Aerosol in-situ instrumentation
ⓘⓥ Sounding station Vaisala MW31

#: unmovable

Fig. 1: LACROS observatory at TROPOS in Leipzig

Following a target classification, algorithms for the retrieval of cloud liquid and ice water content as well as other cloud properties are applied. The observations are performed by a combination of a millimeter cloud radar, a lidar ceilometer and a passive microwave radiometer. Below, an example for a CloudNet target classification is shown (Fig. 2).

Since August 2011, all the instruments which are needed to apply the algorithms have been operating within the LACROS site in Leipzig (Fig. 1). For the present study, 664 days of observations were evaluated and all periods with pure liquid clouds were used (137766 periods of 30 seconds, i.e. around 8 % of the total measurement time).

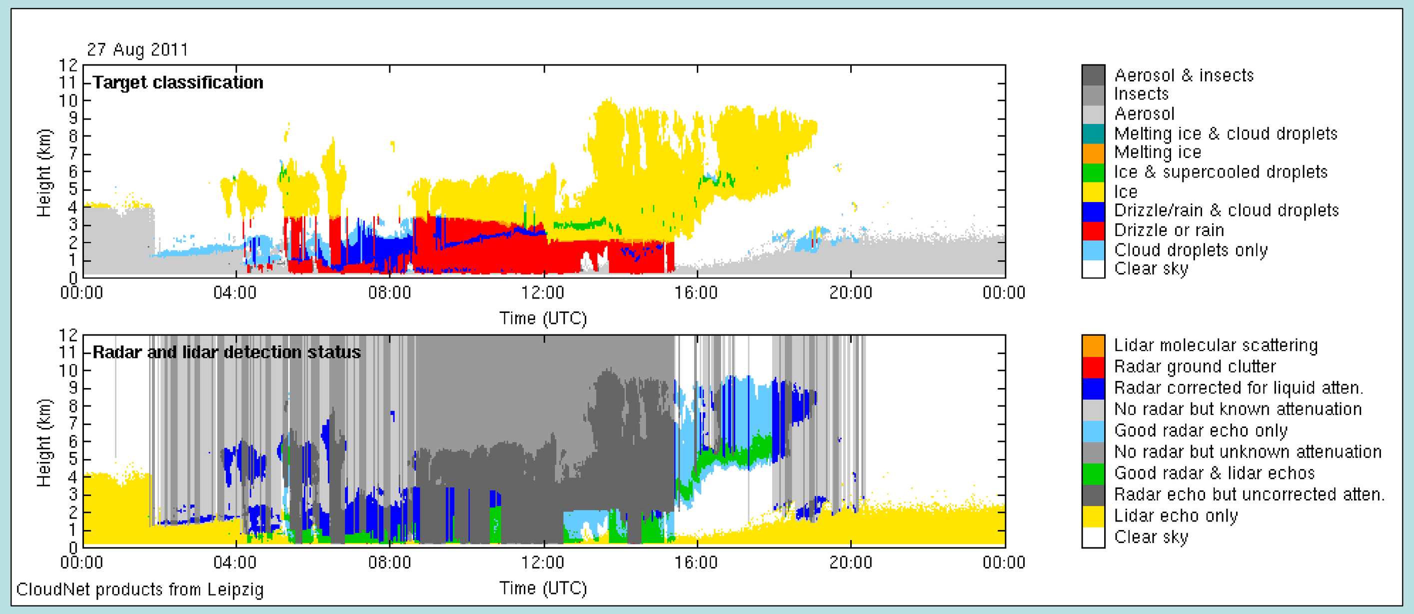



Fig. 2: Example for CloudNet target classification for Leipzig (27 August 2011)

## LWC retrieval

The knowledge about the microphysical properties of clouds is crucial for the understanding of radiative effects, like indirect aerosol effects.

By ground-based remote sensing, the liquid water path (LWP) can be derived, which is the vertical integral of the liquid water content (LWC) over the atmospheric column:

$$LWP = \int LWC(z)dz$$

$$LWC = \frac{4}{3}\varrho_w \pi \int n(r) r^3 dr$$

The liquid water content depends on the 3rd moment of the drop size distribution.

The challenge to retrieve cloud liquid water content (LWC) from ground-based remote sensing observations lies in the non-linear relationship between the radar reflectivity Z and the LWC. Since the drop size distribution is not known, the LWC cannot be directly inferred.

Cloud radars give a good view of the vertical cloud structure, but the quantitative information on the LWC is limited. Passive microwave radiometers (MWR) can determine the integrated liquid water (LWP) with a high accuracy, but cannot give the vertical distribution of LWC. However, knowing the temperature and humidity profiles as well as the cloud boundaries, an adiabatic cloud liquid water profile following Brenguier (1991) can be derived. This adiabatic LWC can then be scaled with the LWP observed by a microwave radiometer to determine the subadiabatic factor (adiabaticity) $f_{ad}$.

The liquid water content can then be written as: $LWC(z) = f_{ad}\Gamma_{ad} z$

It is known that real clouds are often subadiabatic because of entrainment processes and non-adiabatic layers. However, in many satellite-derived cloud products, adiabatic LWC or a constant sub adiabatic factor are assumed. To assess the influence of atmospheric conditions on adiabaticity, this study has been performed using Cloudnet data.

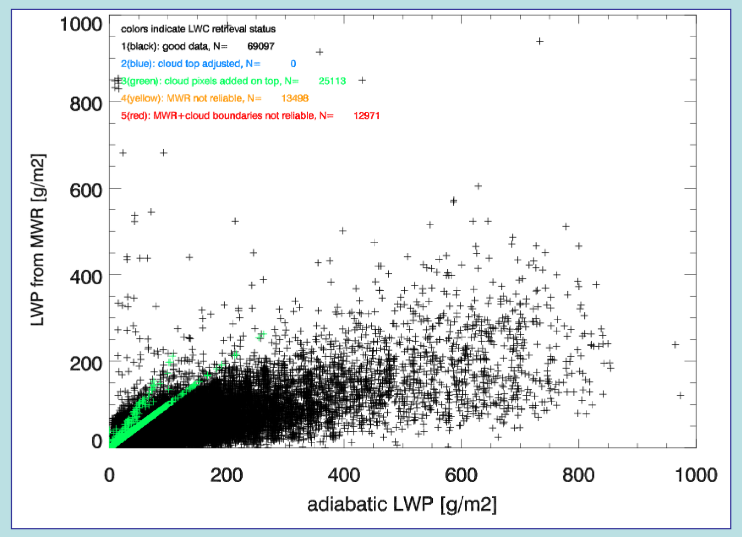



Fig. 3: adiabatic LWP vs scaled (measured) LWP for whole dataset from LACROS observations.
Note the overestimation of LWP by adiabatic assumption.

It turns out that especially in cases with thicker clouds, the adiabatic LWC was too high compared to the observed (Fig. 3). Even if only one-layer clouds are taken into account, the overestimation of the LWC is still significant (Fig. 4).

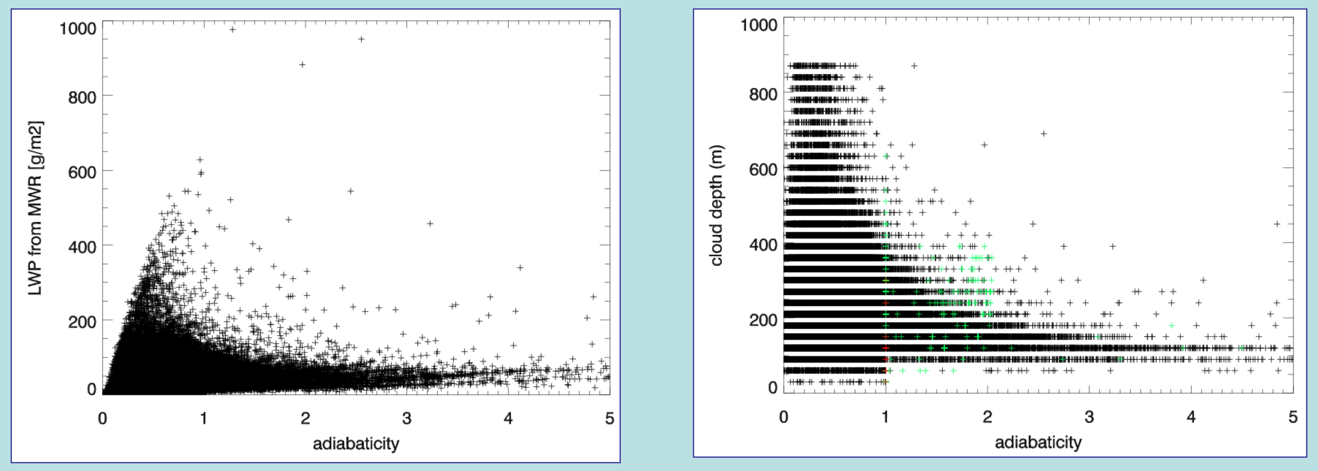
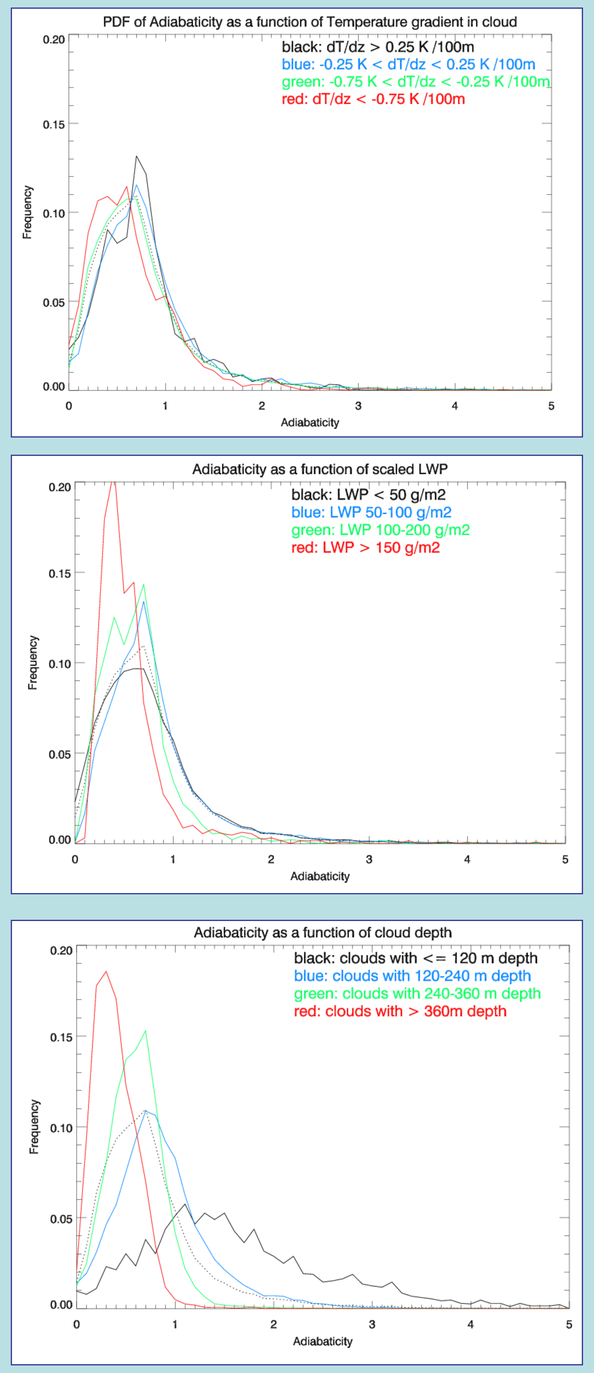



Fig. 4: left: adiabaticity as a function of observed LWP. right: adiabaticity depending cloud depth

## Atmospheric influences on cloud adiabaticity




After detailed investigation of the dataset it turns out that the following conclusions can be drawn: Thick clouds (>200m cloud depth) tend to be largely subadiabatic with fad between 0.3 and 0.5 whereas shallow clouds are closer to the adiabatic state. Also clouds with high observed LWP values are less following the adiabatic assumption.

In turn, the cloud temperature has only little effect, neither does the temperature gradient or the vertical velocity within the cloud. (Fig. 5 and 6)

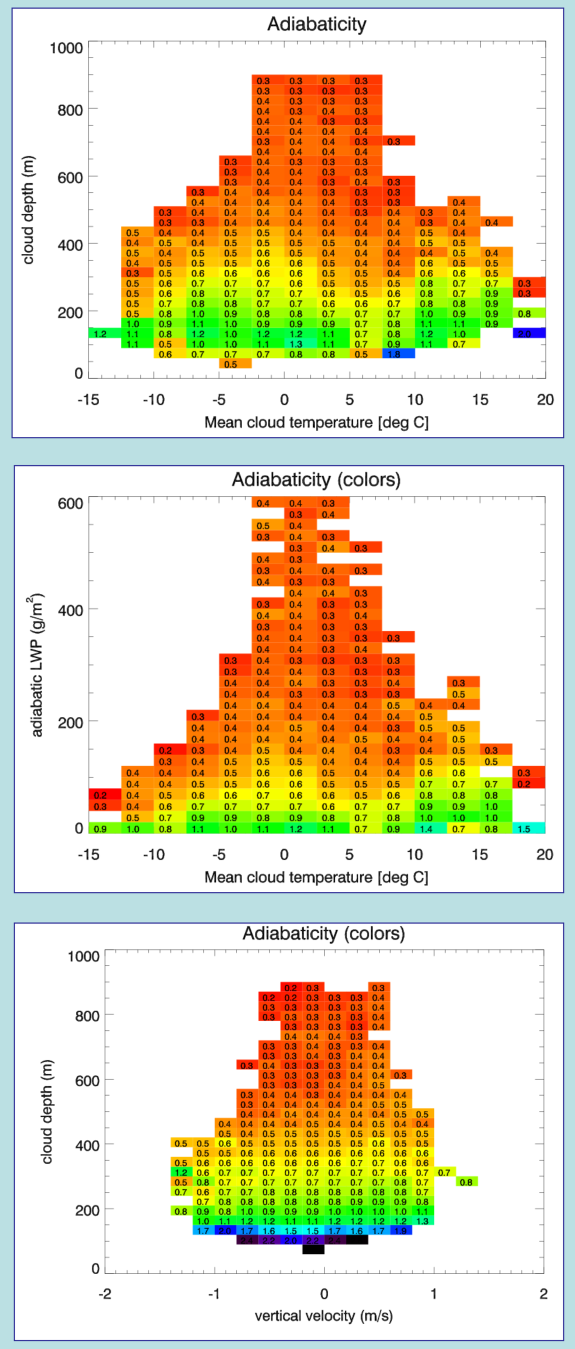
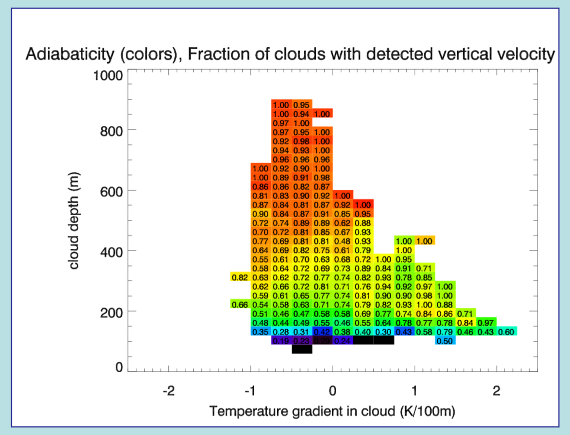



Fig. 5 (left): Probability density functions of adiabaticity as a function of (a) Temperature gradient in cloud, (b) scaled LWP, and (c) cloud depth

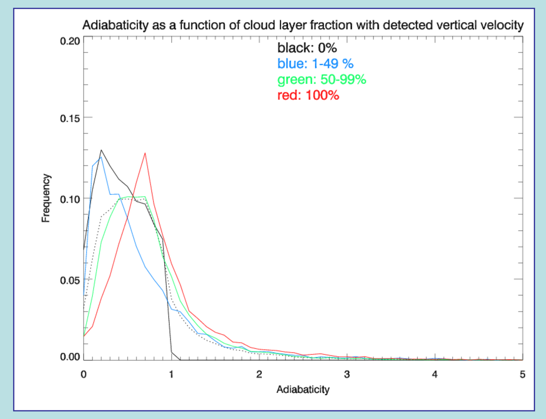
Fig. 6 (right): Mean adiabaticity (in colors) as a function of different atmospheric quantities. Mean values are valid for the respective bin.




It has to be taken into account that the CloudNet algorithm has problems to detect the properties of shallow clouds with small droplets accurately. (Fig 7,8)

Fig. 7 (left): Fraction of clouds with detected vertical velocity

Fig. 8 (right): Derived adiabaticity as function of cloud layers with detected vertical velocity




## Discussion and Outlook

- Deeper clouds tend to have a lower adiabaticity and also for very low cloud base heights, the LWC is largely overestimated by the adiabatic approach. Adiabatic assumption is best for shallow clouds.
- Sub-adiabatic LWC is relatively frequent, but satellite and ground-based retrievals often use an adiabatic cloud model for LWC calculations
- Case-studies of satellite comparisons show similar results
- Comparison with modified adiabatic approaches

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