Retrieval of Cirrus Cloud Ice Water Content (IWC) Profile from Ground-Based Remote Sensing Using the Synergy of Lidar and Multi-Spectral Infrared Radiometry

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Objective:

Improve knowledge about the microphysical properties of cirrus clouds

Instrumentation:

Thermal Infrared (TIR) Radiometer: type CLIMAT CE332, developed by CIMEL (Sicard et al. (1999, *Opt. Eng.*), Legrand et al. (2000, *J. Atmos. Oceanic Technol.*), Brogniez et al. (2003, *J. Atmos. Oceanic. Technol.*))

→ 3 wavelengths in the TIR: 8.7, 10.8 and 12.0 µm

Micro-pulse Lidar with elastic backscatter, type: CAML-CE370, developed by CIMEL

→ wavelength 532 nm

Method:

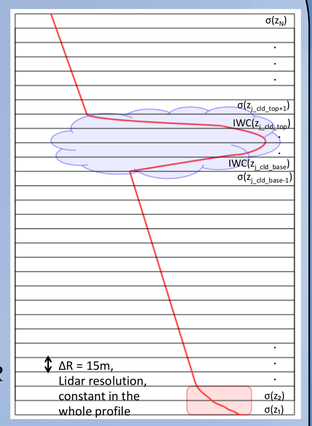
Development of a retrieval algorithm for extinction/IWC profiles based on Optimal Estimation:

$$y = F(x) + e$$

- **y**: measurement vector: measured Lidar profile: red line
- **x**: state vector: contains the quantities to be retrieved → profile of extinction outside the cloud, IWC inside cloud
- **e**: uncertainties arising from Forward Model and measurements
- **F**: Forward Model: Lidar equation:

$$F(\hat{x}_j, \hat{b}_j) = \ln(\beta_m(z_j) + k(z_j)\hat{x}(z_j)) - 2\sum_{l=1}^{N-1}[\bar{\sigma}_{m,l} + \eta\bar{x}_l]\Delta R$$

backscatter-to-extinction ratio



Cirrus cloud: $k = \omega_0 \cdot P(180°)$

→ single scattering albedo and phase function at 180° obtained from microphysical model of Baran et al. (2014, *Quart. J. Roy. Meteor. Soc.*)

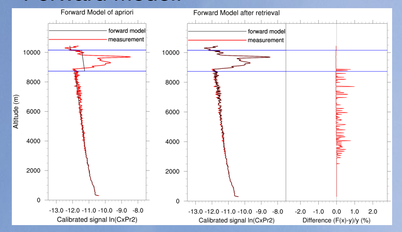
Multiple scattering factor η: 0.75 for cirrus, otherwise 1

Errors on non-retrieved parameters η, k and ßm are taken into account

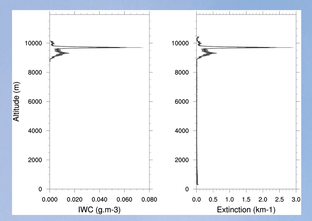
First Step: Lidar Only Algorithm

Example profile measured on November 30, 2016 at 18.18 UTC with a cirrus cloud between 8.7 and 10.2 km altitude:

Forward Model:



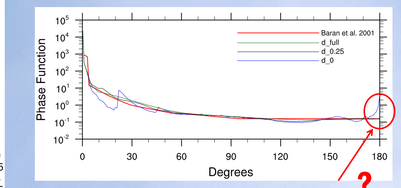
Retrieval result:



Errors on non-retrieved parameters: η (25%), k (25%) and ßm (2%)

Retrieval results for time period between 15 and 24 UTC, November 30, 2016:

The retrievals strongly depend on the backscatter-to-extinction ratio and hence on the microphysical model:



Zhou and Yang (2015, *Opt. Exp.*): Phase function at 180° is 1.5 to 2 times larger than value at 175°

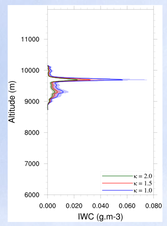
Test: multiply k with different factors κ: $k = \omega_0 \cdot P(180°) \cdot \kappa$

→ the IWP changes:

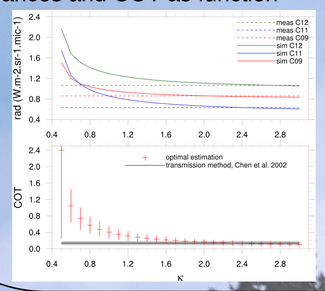
κ = 1.0: 10.41 g.m⁻²

κ = 1.5: 6.03 g.m⁻²

κ = 2.0: 4.26 g.m⁻²



Radiances and COT as function of κ:



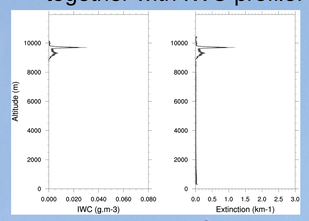
TIR sensitive to IWP

→ can be used to constrain amount of ice in the cloud (IWC) and hence backscatter-to-extinction ratio

Second Step: Synergy Algorithm

Integration of TIR in Optimal Estimation framework:

→ add 3 TIR radiances to the measurement vector and retrieve factor κ together with IWC profile:



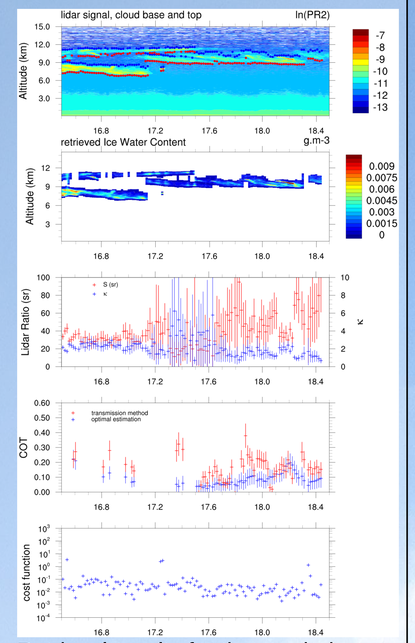
Result for example profile measured on November 30, 2016 at 18.18 UTC

→ IWC considerably smaller than from Lidar only algorithm (IWP = 4.47 g.m⁻²)

→ retrieved κ: 1.92 ± 0.41

Forward Model TIR: **LIDORT** (Spurr et al. (2001, *J. Quant. Spec. Rad. Trans.*))

Errors on non-retrieved parameters taken into account in the retrievals: surface emissivity (2%), surface temperature (0.5%), temperature profile (0.5% for each layer), water vapor profile (10% for each layer), ozone profile (2% for each layer)



Retrieval results for time period between 16.5 and 18.5 UTC on November 30, 2016

→ success of retrieval seems to be limited for very thin clouds

Conclusion:

We developed an algorithm combining Lidar and TIR in a common Optimal Estimation framework:

→ Lidar only retrievals strongly depend on assumptions for the backscatter-to-extinction ratio (microphysical model)

→ we showed that TIR radiances are sensitive to the IWP and can be used to constrain the IWC and hence the microphysics

→ **New Synergy Algorithm:** Retrieval of a correction factor for the backscatter intensity of ice crystals as well as an IWC profile consistent with both TIR and Lidar measurements