The complexity of variational retrieval of liquid cloud properties

HD(CP)²
High definition clouds and precipitation for advancing climate prediction

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1) 1D-Var retrieval scheme

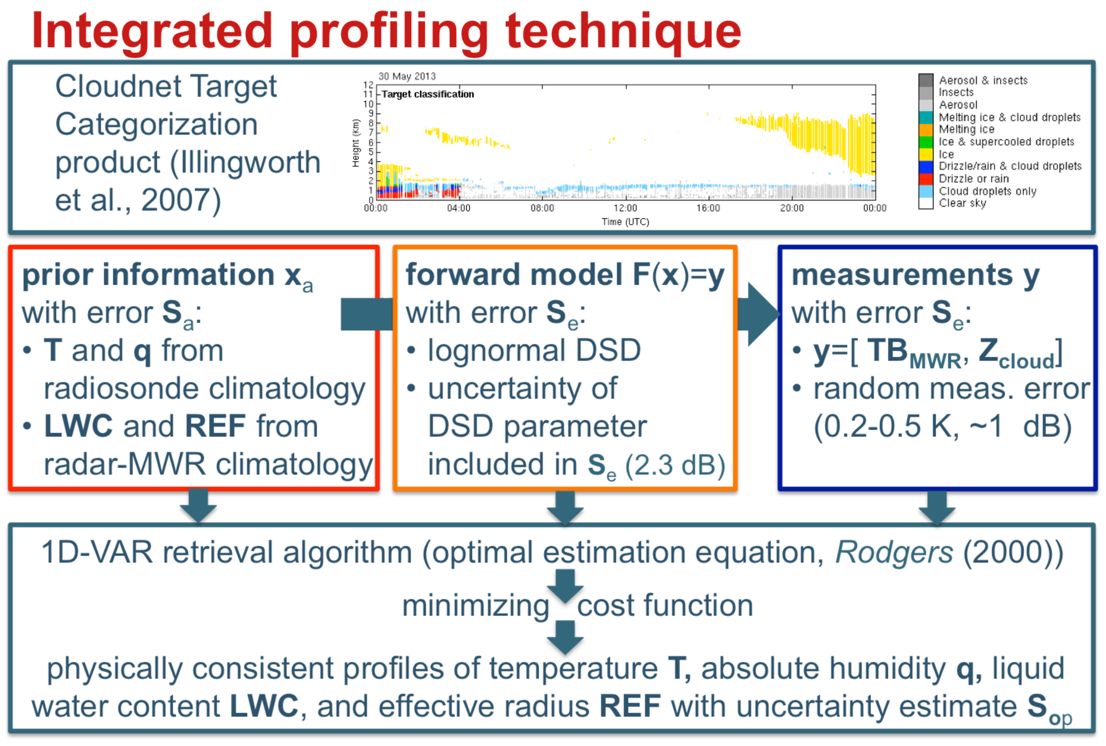

Figure 1. Schematic of the IPT. The IPT has been recently extended to also retrieve profiles of droplet effective radius (REF) including updated prior information on LWC and REF and a new forward model for Z.

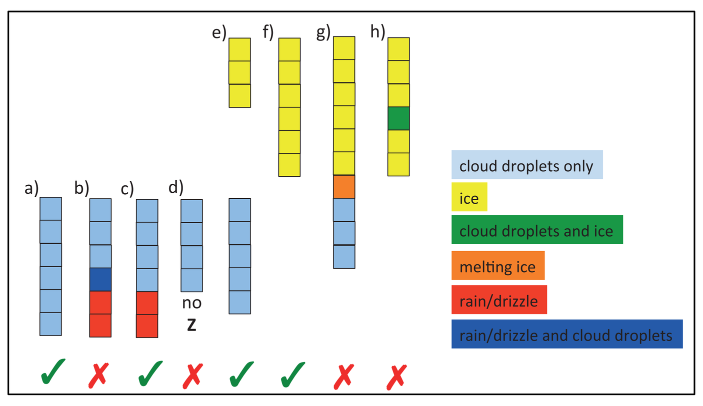

Figure 2. Examples for different possible Cloudnet cloud classifications in the atmospheric column where IPT currently is and is not applied .

2) Synthetic data study: retrieval performance

30 May 2013, 08-16 UTC (see Fig.1): create LWC and REF profiles („truth") based on observed LWP and Z values (Frisch et al. 1998; 2002) → simulate $\mathbf{TB_{MWR}}$ and $\mathbf{Z_{cloud}}$ „observations" → IPT LWC & REF → comparison to „truth"

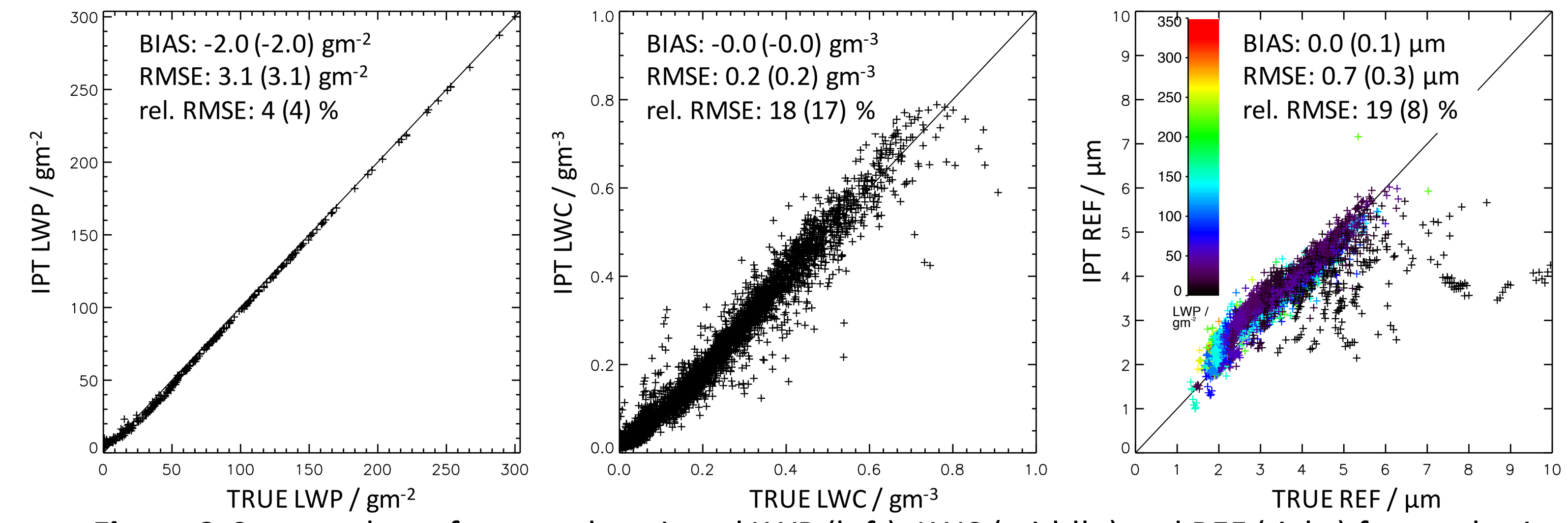

Figure 3. Scatter plots of true and retrieved LWP (left), LWC (middle) and REF (right) for synthetic case study on May 30, 2013 at JOYCE. *Values in () refer to profiles with LWP>10 gm*$^{-2}$.

3) Synthetic data study: error characterization and retrieval sensitivities

Theoretical retrieval error and degrees of freedom for signal

Table 1. IPT statistics for synthetic case on 30 May 2013, 8-16 UTC.

converged profiles	97 % (376 of 385)
theoretical retrieval uncertainties (mean±stddev)	
LWC	52±23%
REF	17±6%
degrees of freedom for signal (DOF) in profile of	
LWC (normalized by # cloud layers)	29±6%
REF (normalized by # cloud layers)	29±5%
temperature	2.3±0.01
absolute humidity	1.6±0.04

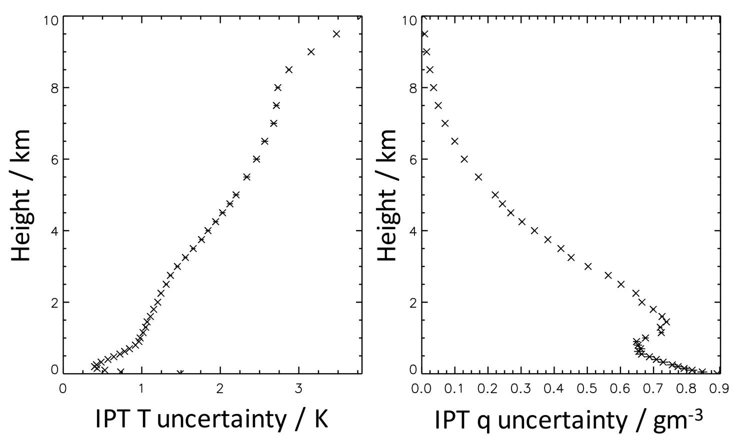

Figure 4. Theoretical retrieved temperature (left) and abs. humidity (right) error for synthetic case study on May 30, 2013 at JOYCE.

Are the retrieved profiles consistent with the measurements?

- X^2 test on $\delta\hat{\mathbf{y}} = \hat{\mathbf{y}} - \mathbf{y}$:
  $\delta\hat{\mathbf{y}}$ should be Gaussian distributed with zero mean and covariance $\mathbf{S}_{\delta\hat{y}} = \mathbf{S}_e\left(\mathbf{K}\mathbf{S}_a\mathbf{K}^T + \mathbf{S}_e\right)^{-1}\mathbf{S}_e$
- here: physically consistent solution in 98% of the converged cases (Fig. 5)

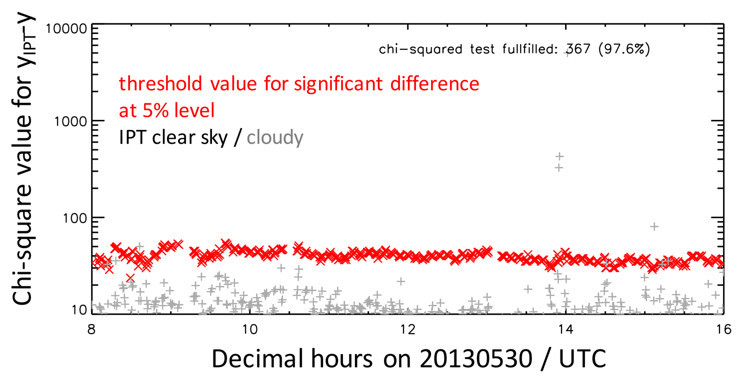

Figure 5. Time series of X^2 test on y_{IPT}-y for synthetic case study on May 30, 2013 at JOYCE.

Sensitivity to measurement noise

→ experiments with doubled TB and Z noise
→ experiment with correlated TB noise (correlations based on typical observed values)

	standard noise	2x TB noise	2x Z noise	correlated TB noise
DOF				
T	2.3	1.9	2.3	2.4
q	1.6	1.3	1.6	1.6
LWC (%)	29.0	28.4	28.8	29.0
REF (%)	28.8	28.7	28.6	28.8
IPT uncertainty				
LWC (gm^{-3})	0.06	0.07	0.06	0.06
REF (µm)	0.6	0.6	0.6	0.6

Table 2. DOF and theoretical retrieval uncertainty for REF and LWC for modified measurement error covariance matrices $\mathbf{S}_e$.

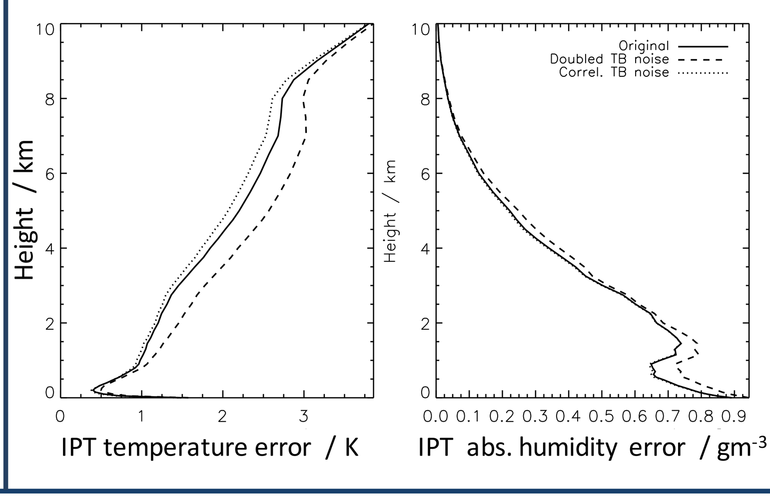

Figure 6. Theoretical retrieved temperature (left) and abs. humidity (right) erros for synthetic case study on May 30, 2013 at JOYCE, when TB noise is doubled (dashed line) and correlated TB noise is assumed (dotted line).

Effect of inappropriate forward model assumptions

How large is the retrieval error if the true DSD differs from the assumed one? → simulate TB and Z „observations" for typically observed DSDs but assume fixed lognormal DSD (σ_x=0.38) in IPT
→ true DSDs are assumed to be lognormal or modified gamma with σ_x=0.38 and v_{gam}=8.7 being varied in 10% steps up to ±30% and ±70%

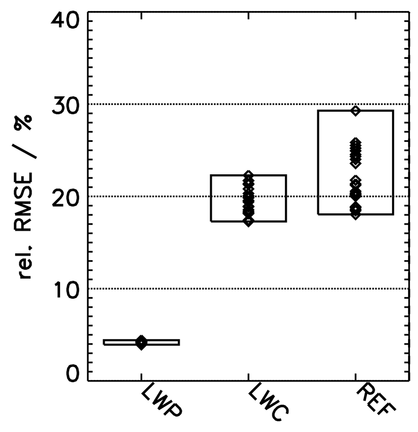

Figure 7. Spread of rel. RMSE of LWP, LWC and REF due to differences in the assumed and true DSD.

4) IPT application at JOYCE

Measurement biases and impact on IPT results

- often large discrepancies between simulated and observed TBs: are the MWR TBs biased?
  → spectral consistency check of MWR TBs in clear-sky cases: are TB differences of two channels in expected range?

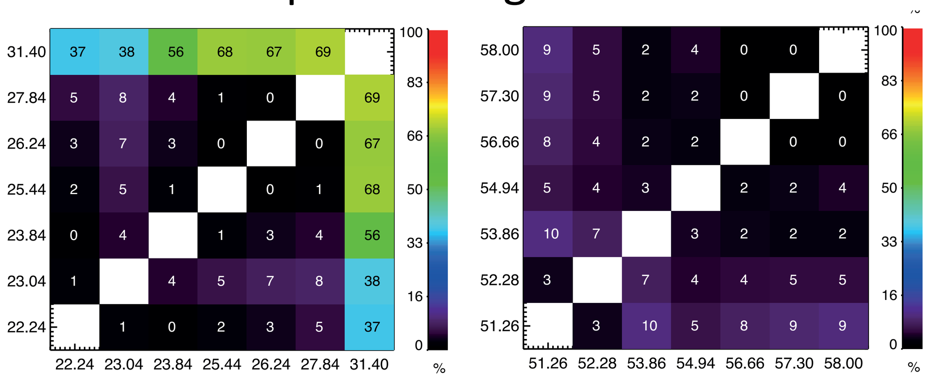

Figure 9. Percentage of tested days (268) in 2013 where the difference of TB pairs in the K band (left) and V band (right) are not within the calculated 2-sigma range (see Fig. 8).

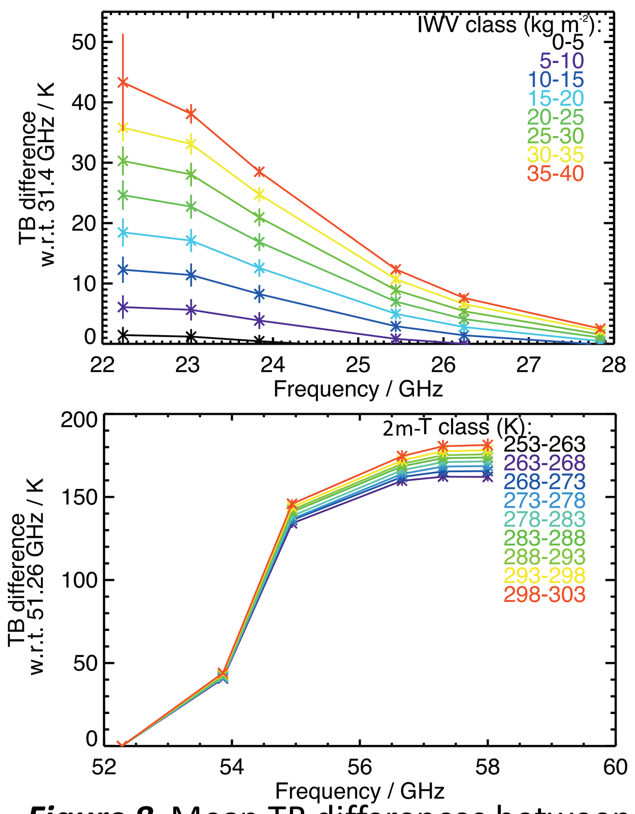

Figure 8. Mean TB differences between the lowest MWR K band frequencies and 31.4 GHz channel (top) and between highest MWR V band frequencies and 51.26 GHz channel (bottom) based on forward calculations of 7,761 clear-sky De Bilt radiosondes.

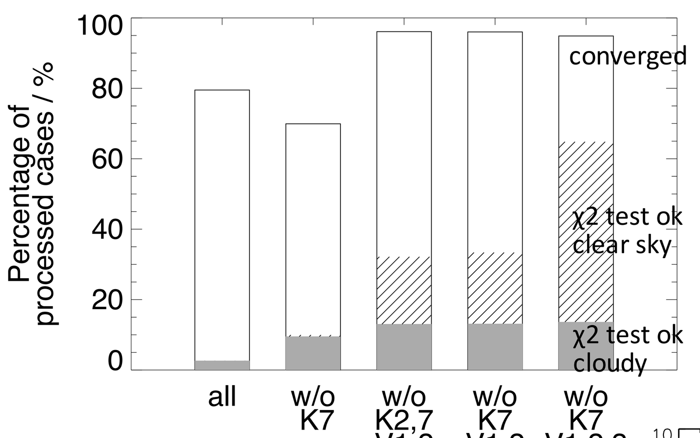

Figure 10. Convergence and χ2 test statistic for 11 days (18,996 profiles) in 2013 at JOYCE for IPT results using all MWR frequencies (all) and excluding in varying combinations 23.04 GHz (K2), 31.4 GHz (K7), 51.26 GHz (V1), 52.28 GHz (V2) and 53.86 GHz (V3).

Table 3. DOF for T, q, LWC and REF profiles and theoretical retrieval errors for REF and LWC for IPT including all MWR frequencies and without 31.4 GHz and 51.26-53.86 GHz.

	all frequencies	w/o K7, V1,2,3
DOF		
T	2.3	2.0
q	1.6	1.4
LWC (%)	29.0	28.0
REF (%)	28.8	28.3
IPT uncertainty		
LWC (gm^{-3})	0.06	0.08
REF (µm)	0.6	0.6

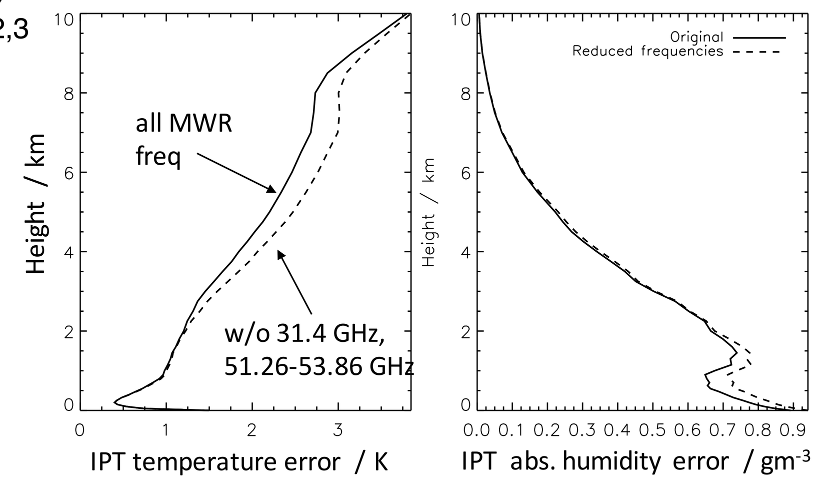

Figure 11. Theoretical retrieved temperature (left) and abs. humidity (right) errors for synthetic case study on May 30, 2013 at JOYCE using all MWR frequencies (solid line) and disregarding 31.4 and 51.26-53.86 GHz (dashed line).

Results of a one-year IPT aplication at JOYCE

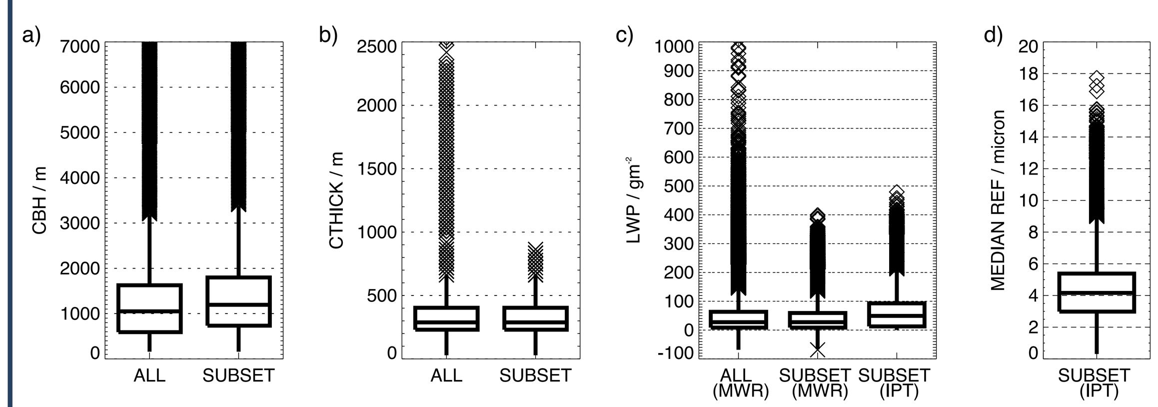

Figure 12. Boxplots of cloud base height (a), geometrical cloud thickness (b), LWP (c) and median REF of cloud profile (d) for all single-layer non-drizzling water clouds (SL WC) in 2013 (ALL) and for the SL WC subset captured by the IPT (SUBSET).

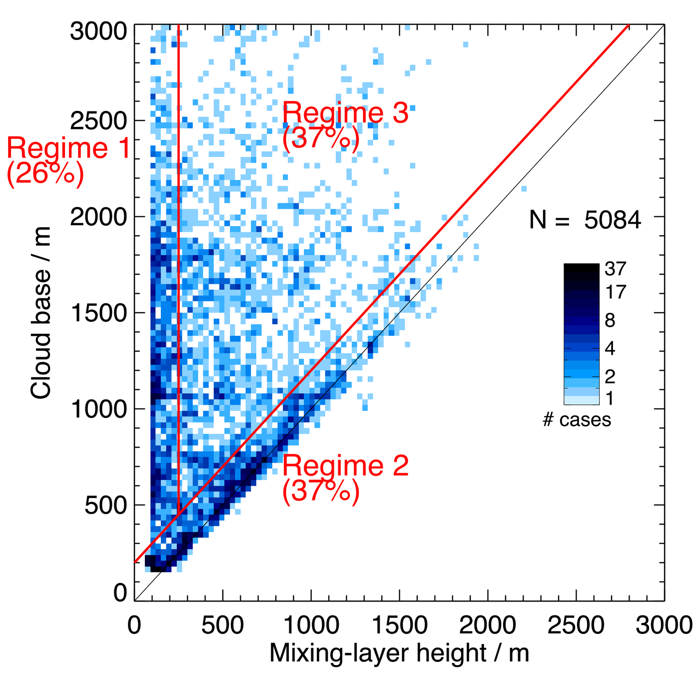

Figure 13. 2D-histogram of mixing-layer height (m) and cloud base height (m) of single-layer water clouds at JOYCE in 2013. In total, 5,796 cases are included which have been attributed to 3 different regimes.

Connection of single-layer water clouds to boundary layer dynamics

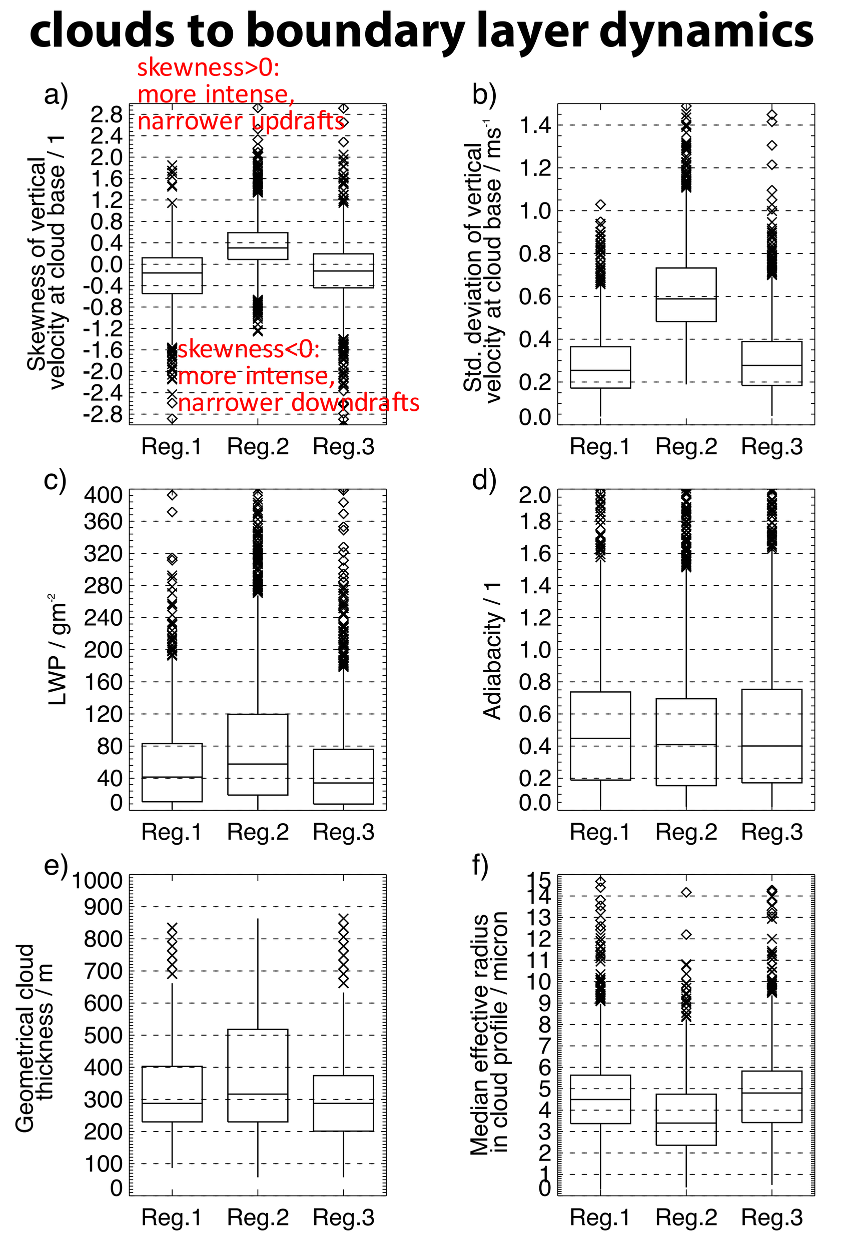

Figure 14. Boxplots of skewness of vertical velocity (a) and standard deviation of vertical velocity (b) at cloud base, LWP (c), adiabacity(d), geometrical cloud thickness (e) and median REF of cloud profile (f) for the SL WCs of the identified 3 cloud regimes.

6) Conclusions & Outlook

- IPT provides physically consistent results
- theoretical unc. for LWC and REF: 52 and 17%
- results less sensitive to measurement uncertainties, but deviations of assumed DSD from true one may increase REF error up to 30%
- X^2 test on y_{IPT}-y essential quality check
- bias free measurements crucial
  → IPT to be used as a further quality check!
- in combination with wind lidar information, analysis of single-layer water clouds and their relation to boundary layer dynamics possible:
- water clouds which follow MLH development are driven by surface heating, contain more water, are less adiabatic, have a larger geometrical thickness and smaller REF than clouds being disconnected from MLH
  → do we find similar results from LES simulations?