On using Doppler cloud radar to study microphysics of ice clouds

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Motivation

- Ice cloud observations at SGP (1997-2010) with 35 GHz cloud radar (MMCR)
- For each height and finite time span, decompose Doppler velocity into V_t and w :

$$V_t = aZ^b \quad (1)$$

Kalesse, H. and Kollias, P., *J. Clim., 2013*

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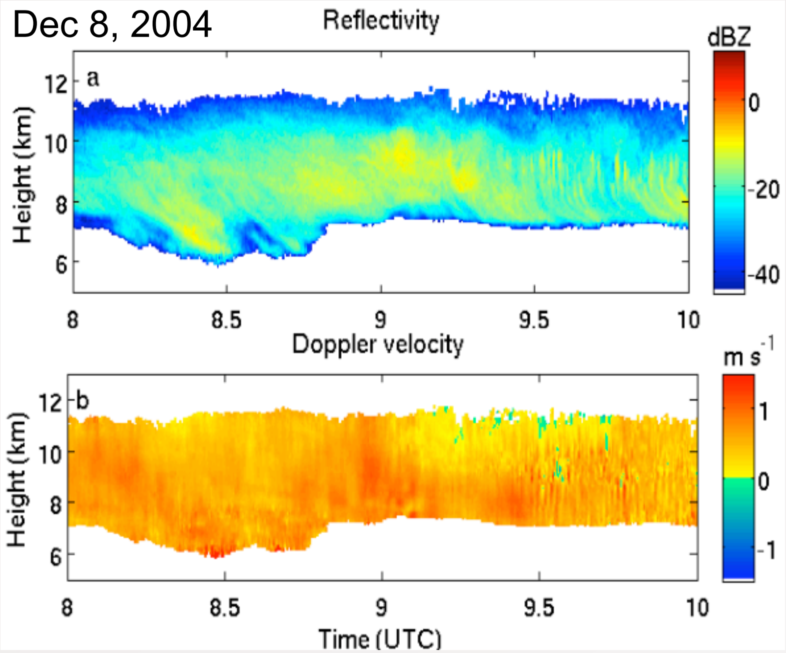
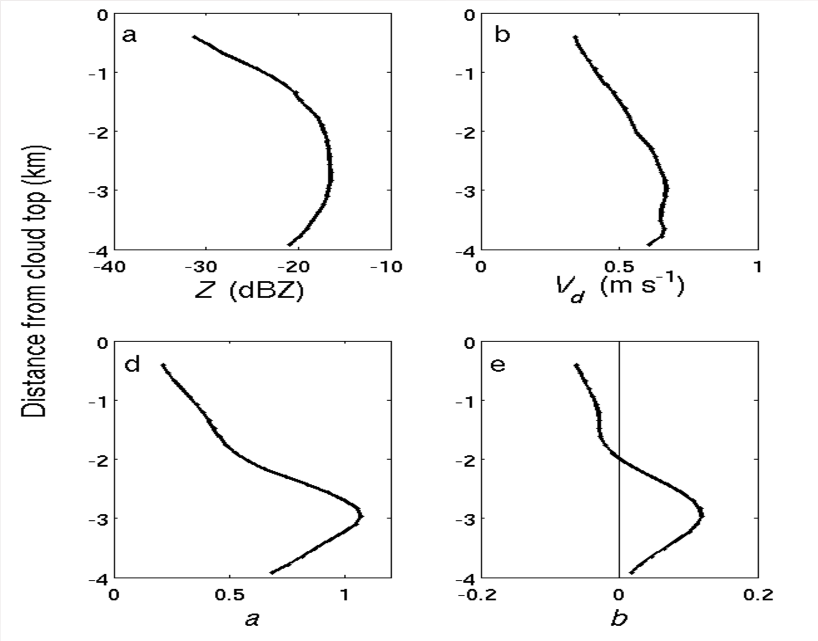
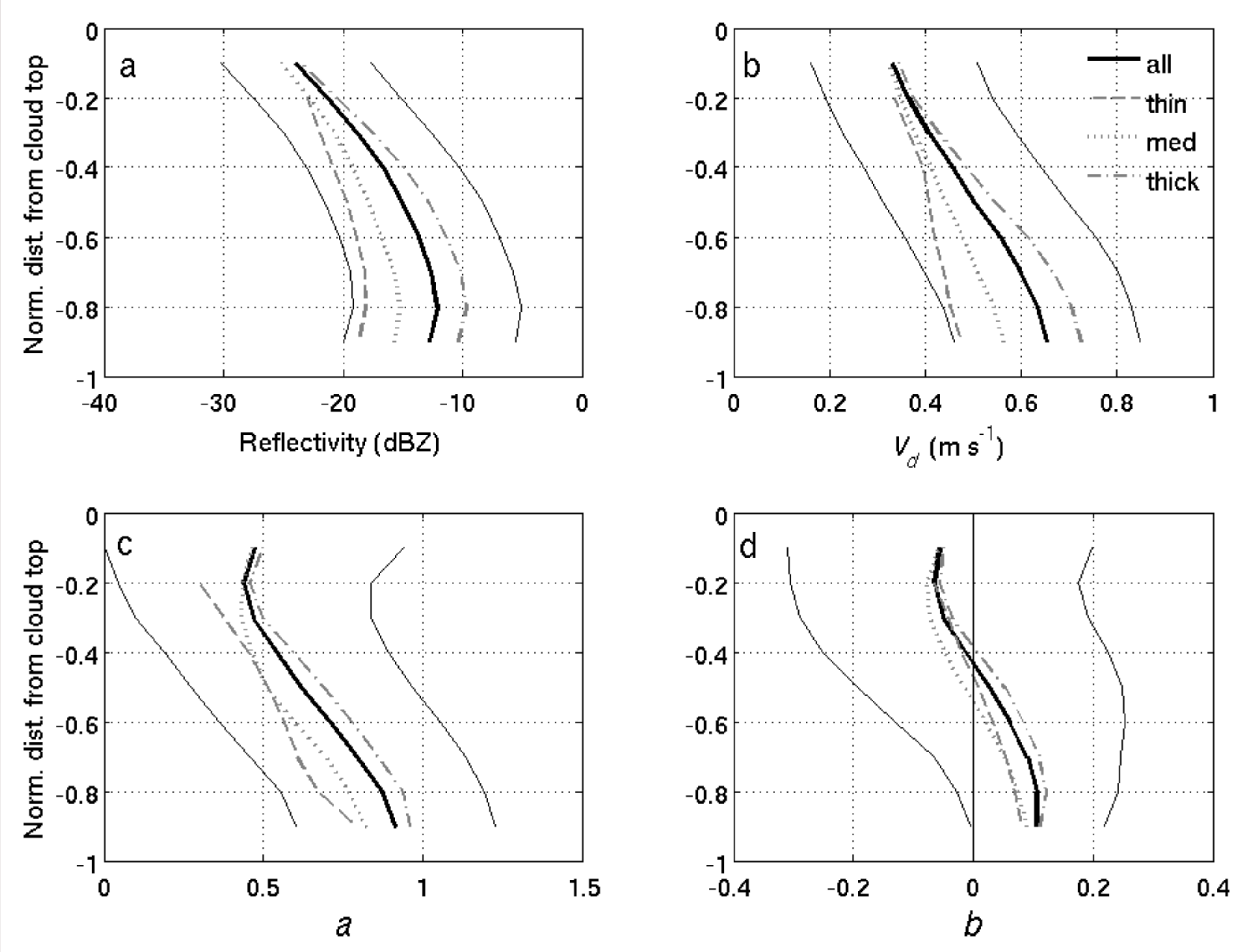
→ V_t-Z-relation varies with height (distance from cloud top):





What do profiles of V_t-Z-relation (parameters a, b) tell us about microphysical regimes?

Application to ice cloud climatology - mean profiles



Ice cloud depth categories:

< 1.5 km (thin)
1.5 – 3 km (med)
> 3 km (thick)

Sensitivity test:

t = 20/30/60/120 min
dH = 45 m, 135 m

- Large standard variation (grey solid line)
- Principal Component Analysis - Find modes explaining most of observed variance

Estimation of *a, b* from parameterized microphysical relations

- <u>Symbol fill – microphys. param.:</u>

Hogan et al., 2006 : solid
Field et al., 2007 : stars
Heymsfield & Donner, 1990 : empty

- <u>Colors – mass- and velocity-dimensional relations:</u>

Morrison and Gettelman, 2008: blue
Wilson and Ballard, 1999 : red
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- <u>Symbols shape - PSD widths:</u>

σ = 0.2: square
σ = 0.5: triangle

- <u>Symbol size - temperatures:</u>

-60 °C : small
-45 °C : medium
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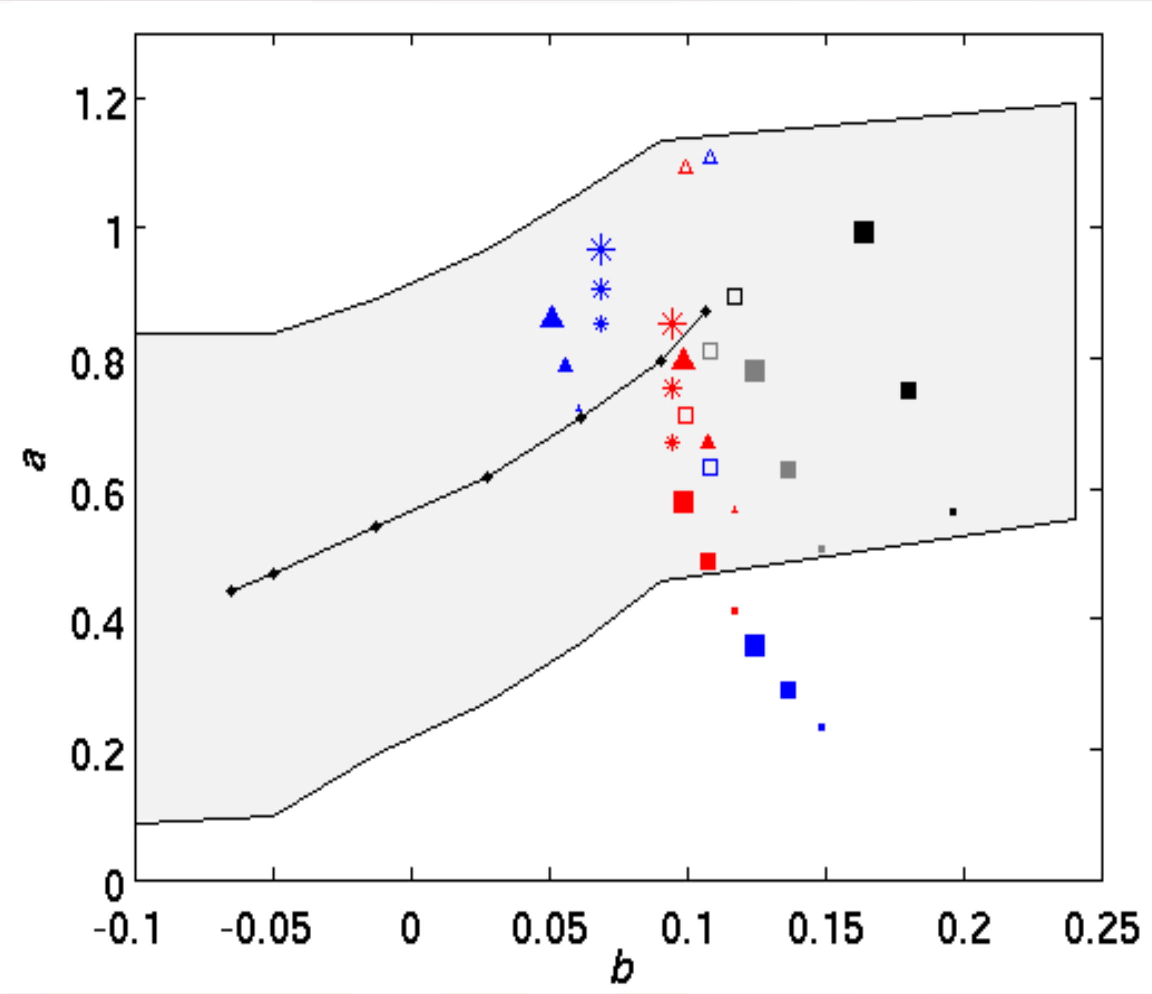

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- *b < 0 ?*

→ explanation of radar-derived *b* using microphysical considerations

Microphysical considerations

Rate of change dD/dt for given microphysical process: $$\frac{dD}{dt} = xD^y \quad (2)$$

Rate of mass growth for vapor diffusion:

$$\frac{dm}{dt} = 4\pi s_i H_i(T,p) C f_{ven} \xrightarrow[m = \frac{\pi}{6}\rho_w D^3]{m = a_m D_s^{b_m} \quad (3)} \frac{dD}{dt}$$

a_m, b_m from Mitchell, 1996
C: capacitance

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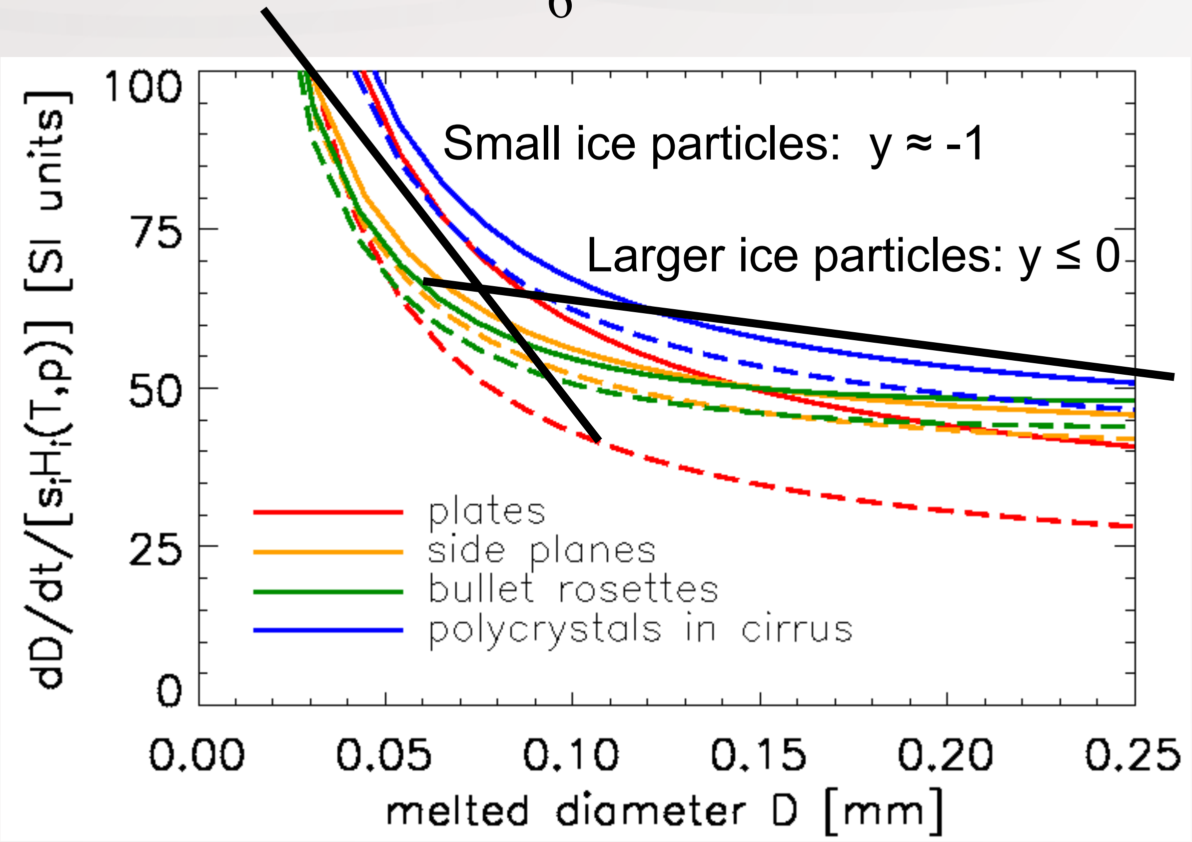

Microphysical considerations

Velocity-size relation: $u = a_{u,s} D_s^{b_{u,s}} = a_u D^{b_u}$ (4)

→ Parameter *b* in $V_t = aZ^b$ can be expressed in terms of b_u (4) and *y* (2) for given PSD shape

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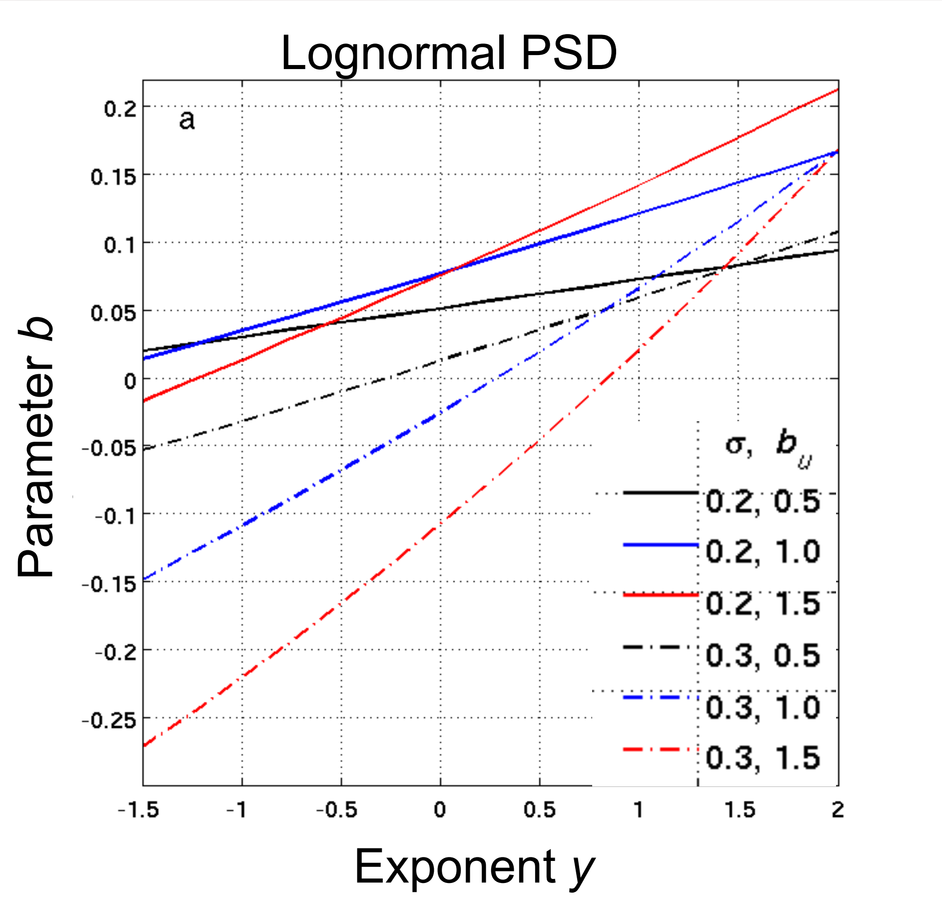

Fazit: *b* ≤ 0 possible → Empirical relations in microphysical parameterizations could be adjusted to better represent conditions near cloud top.

→ Kalesse, H., P. Kollias, W. Szyrmer, *accepted by JGR, 2013*

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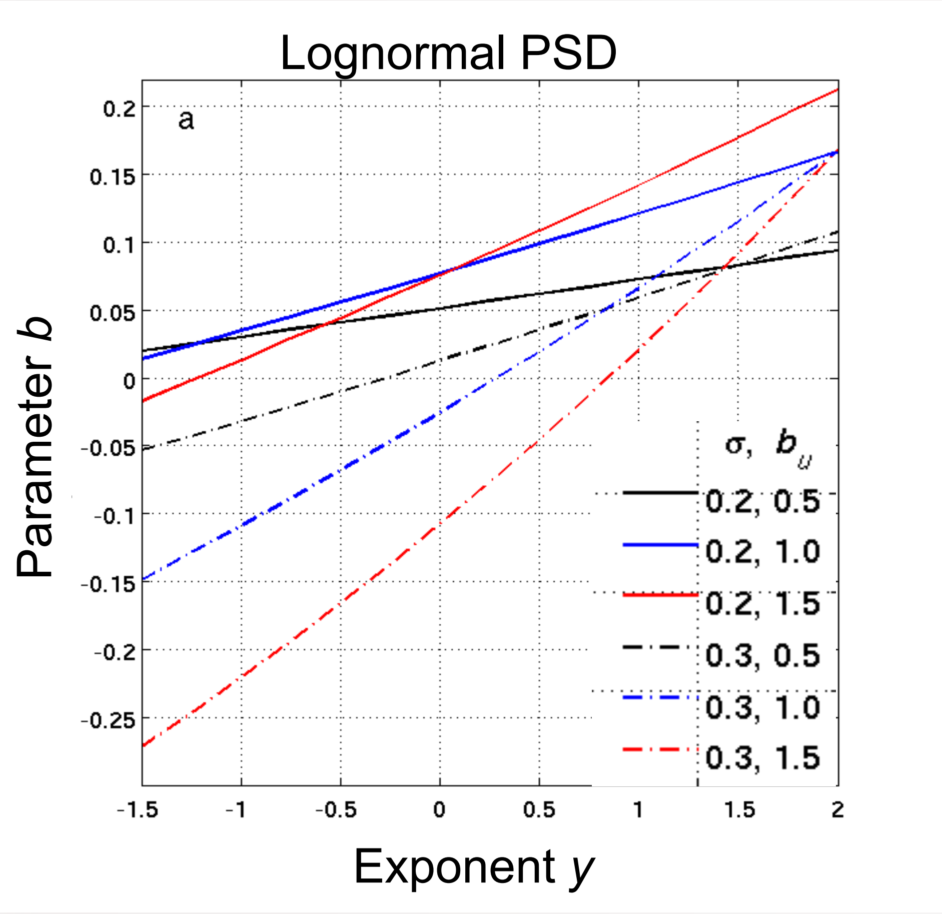

- *b* can be expressed in terms of PSD moments:

$$b = \frac{d \ln M_{6+b_u}}{d \ln M_6} - 1$$

- *b*>0 (<0): larger moments grow more rapidly (slowly) than reflectivity-corresponding moment
- nucleation + deposition: growth of small particles more rapid than of larger ones → *b* ≤ 0
- aggregation: rate of growth via agg. larger for bigger particles → *b* > 0
- riming: rate of growth via riming larger for bigger particles (y ≈ 2→) *b* > 0

Fazit: *b* ≤ 0 possible → Empirical relations in microphysical parameterizations could be adjusted to better represent conditions near cloud top.

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Thank you for your attention!

Doppler velocity decomposition technique

V_t-Z-H-t technique (adapted from Protat and Williams, 2011)

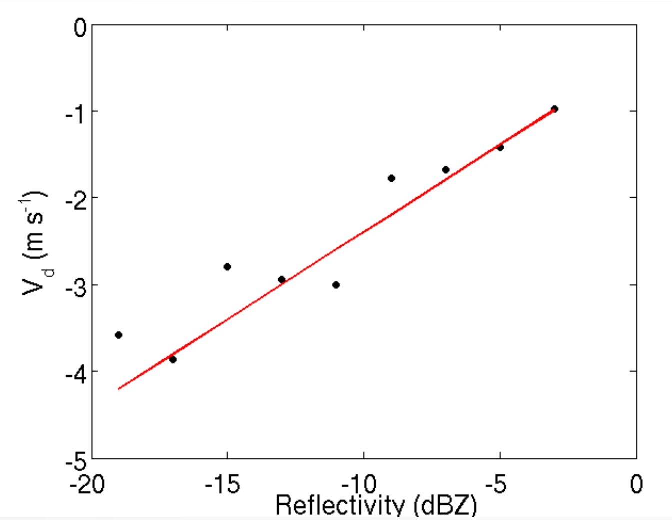
- Consider 20-60 min period of V_d at particular height
- Assumptions: as above (mean $w < V_t$, mean w = 0 m s^{-1} → mean V_d = mean V_t)
- For each time period and height H, extract empirical power law relation:

$$V_t = aZ^b$$

- Use a,b to determine V_t at 10s resolution
- Determine w at 10s resolution:

$$w = V_d - aZ^b$$

- Air density correction of $V_t \rightarrow V_{t,0}$
- Result: w, V_t, $V_{t,0}$ at 10s resolution
- Outperforms techniques 1. & 2. (Protat and Williams, 2011)
- Averaging time: 20min (best trade-off as found in sensitivity test)
- Linear regression coefficients a, b



Comparison of profile-averaged *a, b* with other studies

Data set	**Power-law coefficient *a***	**Power-law coefficient *b***
Heymsfield, 1977 (midlat)	0.59 - 0.67	0.06 - 0.1
Orr and Kropfli, 1999 (midlat)	0.19 - 0.52	-0.01 - 0.44
Protat, 2003 (midlat)	0.29 - 0.7	0.05 - 0.18
This study*, all ice clouds (midlat)	0.65 ± 0.42	0.03 ± 0.19
This study*, thin clouds	0.53 ± 0.41	0.01 ± 0.19
This study*, medium clouds	0.64 ± 0.42	0.03 ± 0.19
This study*, thick clouds	0.72 ± 0.4	0.06 ± 0.2

* Mean and standard deviation over profiles

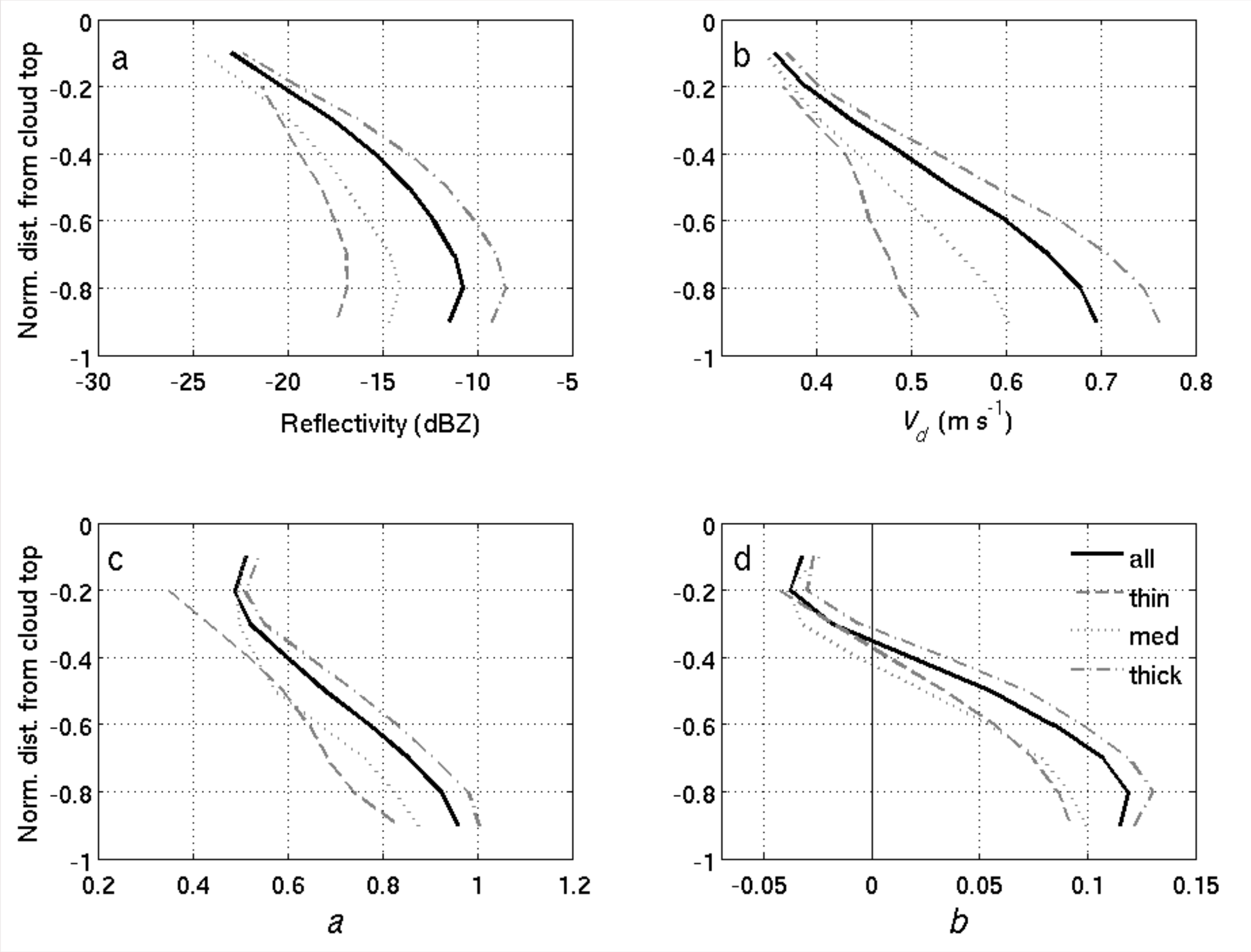
Estimation of *a, b* from parameterized microphysical relations

- V_t-Z-powerlaw:
  … relation between two bulk quantities controlled mainly by the larger particle regime of particle size distribution (PSD) and is thus associated to higher moments
- Relations between other bulk quantities have been developed
- Derive parameters *a*, *b* from other relations:
  - Choose three selected microphysical relations:
    1. *IWC*-Z relation* (Hogan et al., 2006)
    2. relations between any order PSD moment and 2nd moment* (Field et al., 2007)
    3. relation between mass-weighted fall speed and *IWC* (Heymsfield & Donner, 1990)

    * with *T*-dependent coefficients

  - Calculate the expected parameters *a* and *b* of V_t-Z-powerlaw
    - Two-moment normalization (M_3,M_6), liquid-equivalent diameter *D*, lognormal PSD
    - Four different assumptions on particle mass- and velocity dimensional relations:
      1. Thompson et al., 2008 (WRF)
      2. Morrison and Gettelman, 2008 (CAM3)
      3. Wilson and Ballard, 1990 (MetUM)
      4. Heymsfield et al., 2013 (observational study of small ice particles)
- Compare with radar-based observations

Results of Principal Component Analysis



Ice cloud depth categories:

< 1.5 km (thin)

1.5 – 3 km (med)

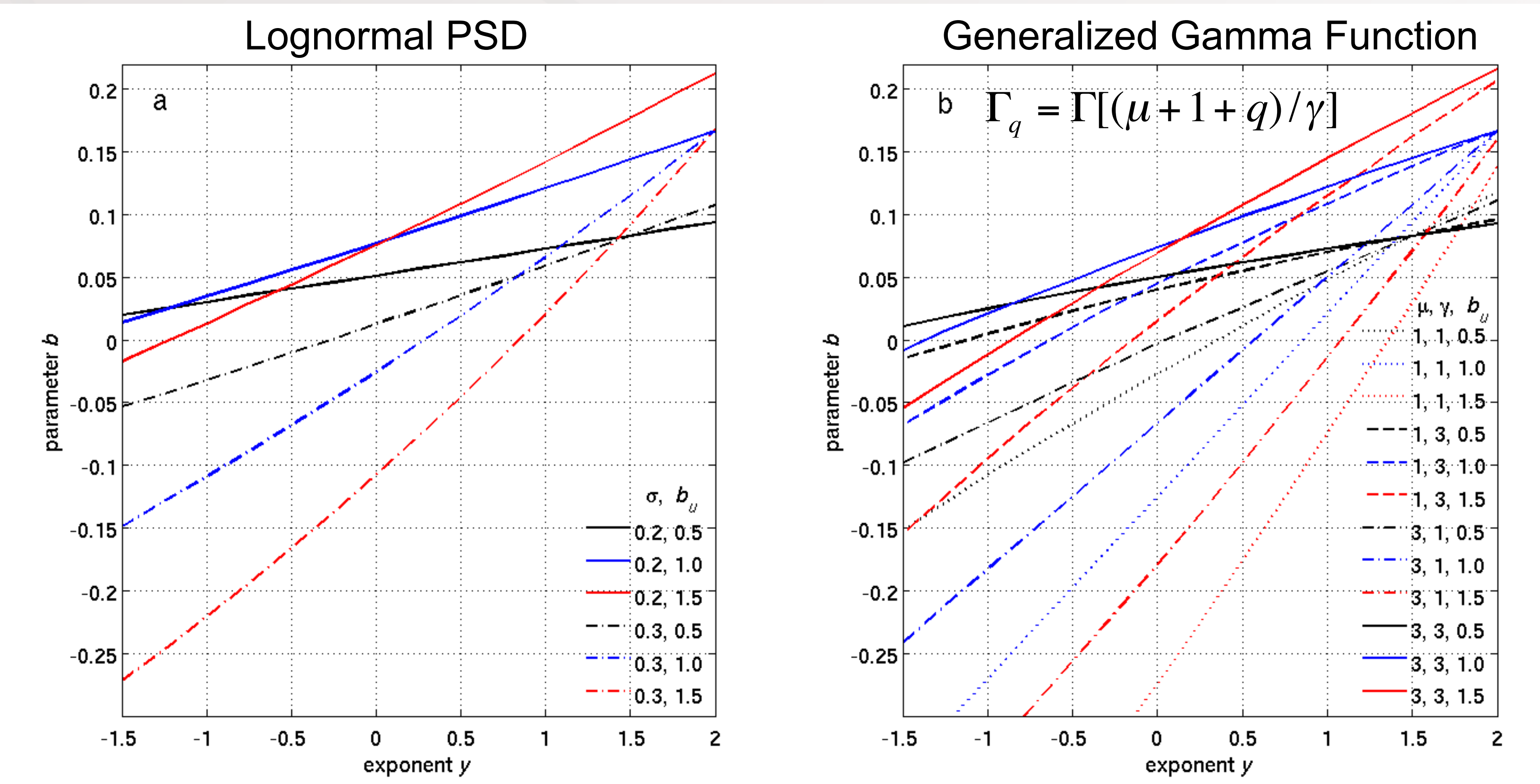
> 3 km (thick)

- First principal component mode explains 89% of observed variance
- PCA profiles similar to mean profiles

Microphysical considerations

Velocity-size relation: $u = a_{u,s} D_s^{b_{u,s}} = a_u D^{b_u}$ (4) , with (3) follows $b_u = 3\frac{b_{u,s}}{b_m}$, $a_u = a_{u,s}\left(\frac{\pi\rho_w}{6a_m}\right)^{\frac{b_{u,s}}{b_m}}$

Parameter b in (1) can be expressed in terms of b_u and y for given PSD shape



Microphysical considerations

$V_t = aZ^b$ (1), with $u = a_{u,s} D_s^{b_{u,s}} = a_u D^{b_u}$ $\quad b_u = 3\frac{b_{u,s}}{b_m}$ $\quad a_u = a_{u,s}\left(\frac{\pi\rho_w}{6a_m}\right)^{\frac{b_{u,s}}{b_m}}$: $V_t = a_u \frac{M_{6+b_u}}{M_6}$ (2)

$Z = \mu \cdot 10^{18} M_6 = \mu_e M_6$ (3) with $\mu = \left(\frac{\rho_w}{\rho_i}\right)^2 \left(\frac{|K_i|}{|K_w|}\right)^2$ Density
Dielectric constant

(2) and (3) into (1): $M_{6+b_u} = \frac{a}{a_u}\mu_e^b M_6^{1+b}$

Therefore, for given sets of (*a*,*b*) and (a_u, b_u): $b = \frac{d\ln M_{6+b_u}}{d\ln M_6} - 1$