Ice properties of single layer stratocumulus observed during M-PACE

Greg McFarquhar[1], Gong Zhang[1], Mike Poellot[2], Tim Tooman[3], Robert McCoy[3], Greg Kok[4], Andy Heymsfield[5] and Ann Fridlind[6]

[1]University of Illinois, Urbana, IL

[2]University of North Dakota, Grand Forks, ND

[3]Sandia National Labs, Livermore, CA

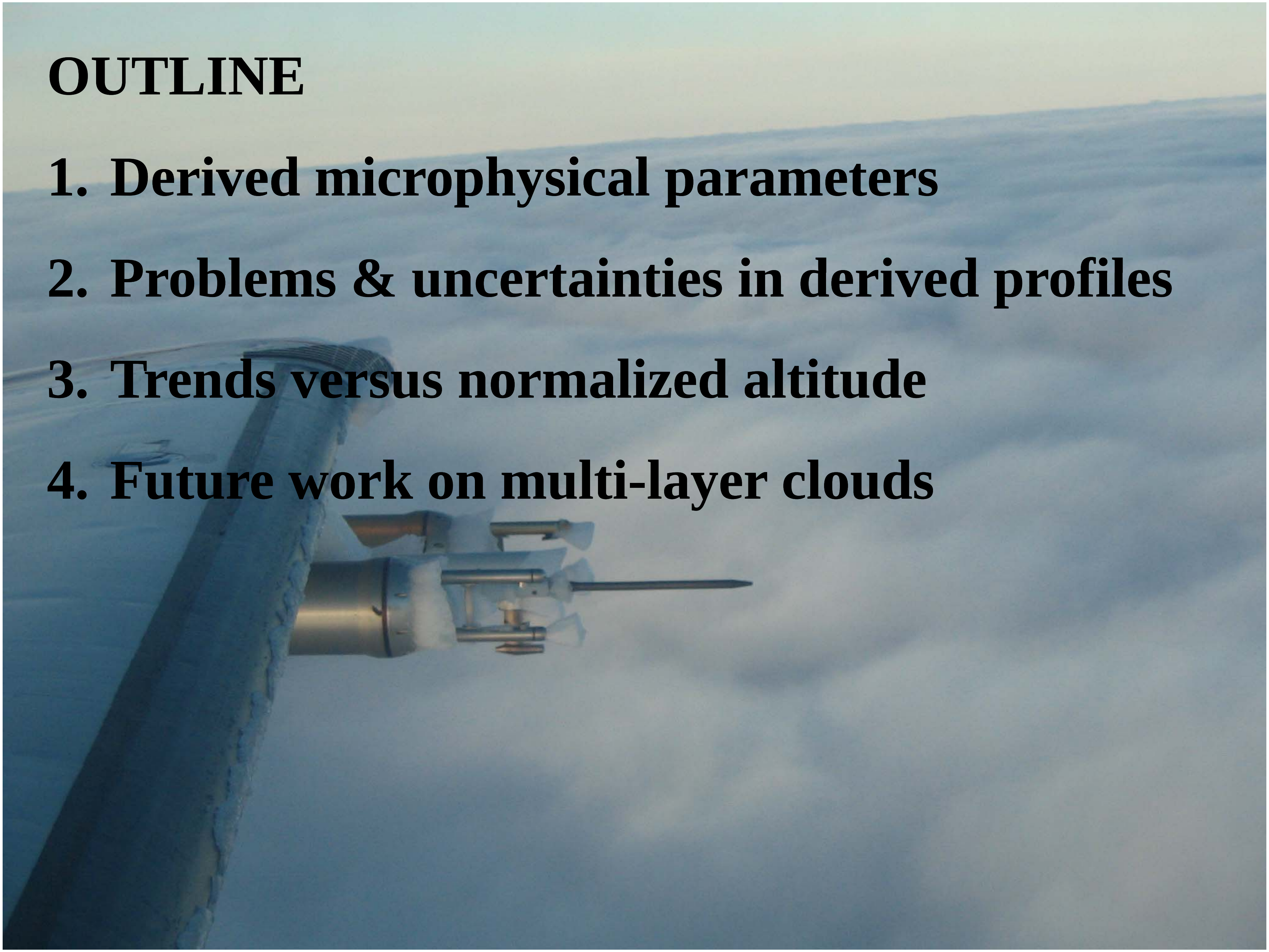
[4]DMT, Boulder, CO

[5]NCAR, Boulder CO

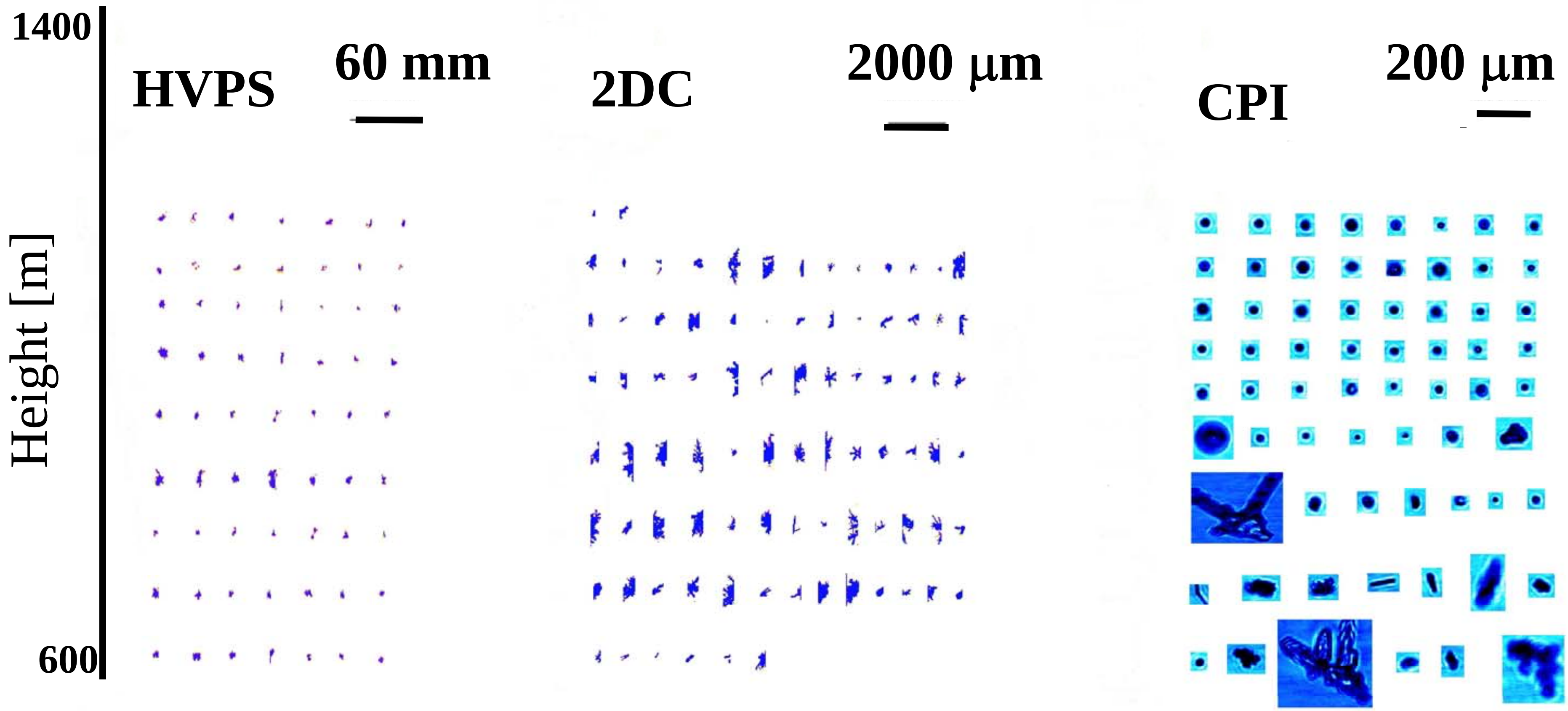
[6]NASA GISS, New York, NY

OUTLINE

1. Derived microphysical parameters
2. Problems & uncertainties in derived profiles
3. Trends versus normalized altitude
4. Future work on multi-layer clouds



How do we go from raw data to something useful for comparing against models/retrievals?



Derived Parameters

- Cloud top (zt) and cloud base (zb)
- Cloud temperature
- Bulk microphysical parameters

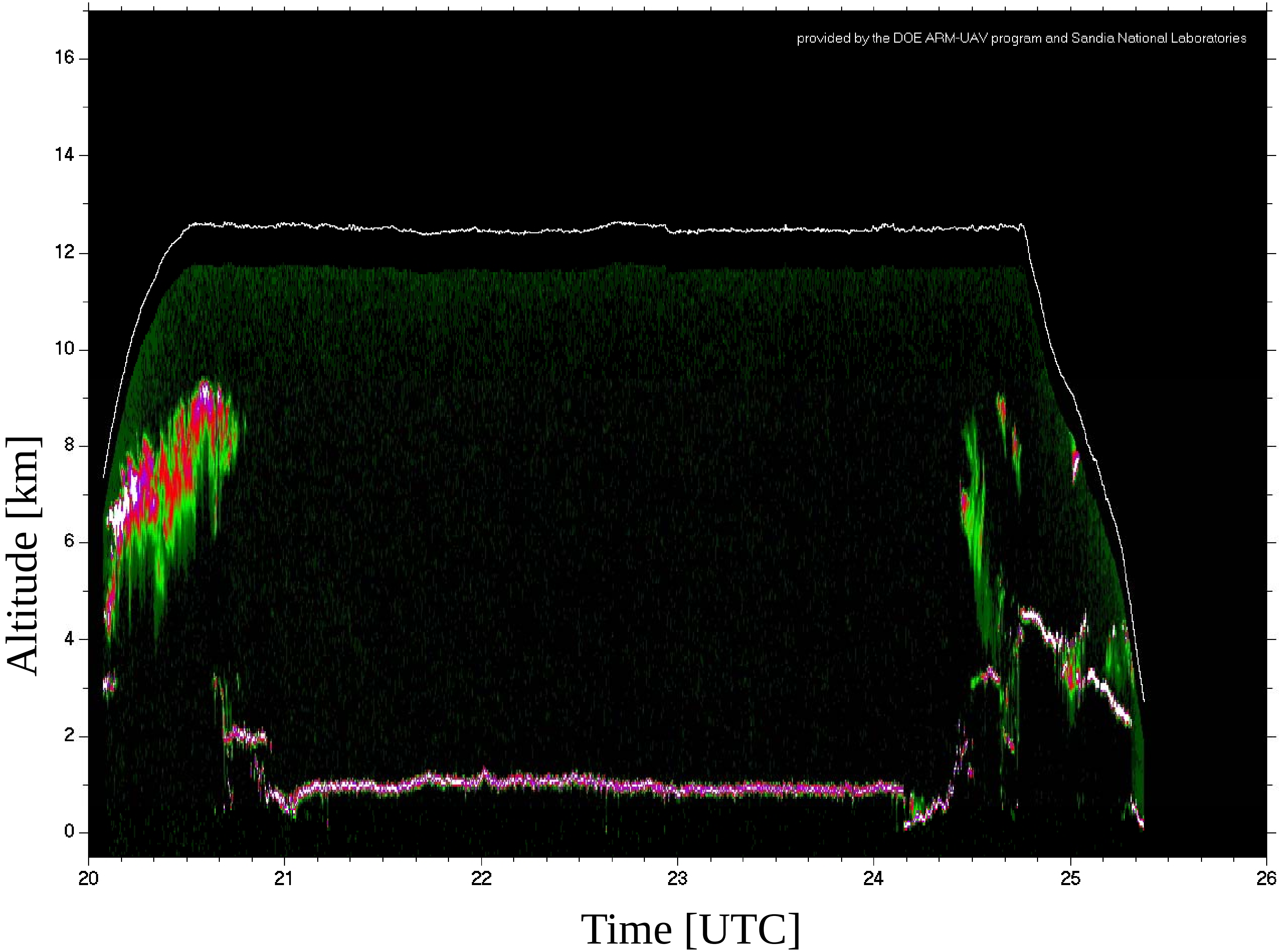
Liquid water content	LWC
Ice water content	IWC
Liquid water fraction	f_l=LWC/TWC
Effective radius of water drops	rew
Effective radius of ice (Fu 1996)	rei
Cloud droplet number concentration	Nw
Cloud ice crystal concentration	Ni

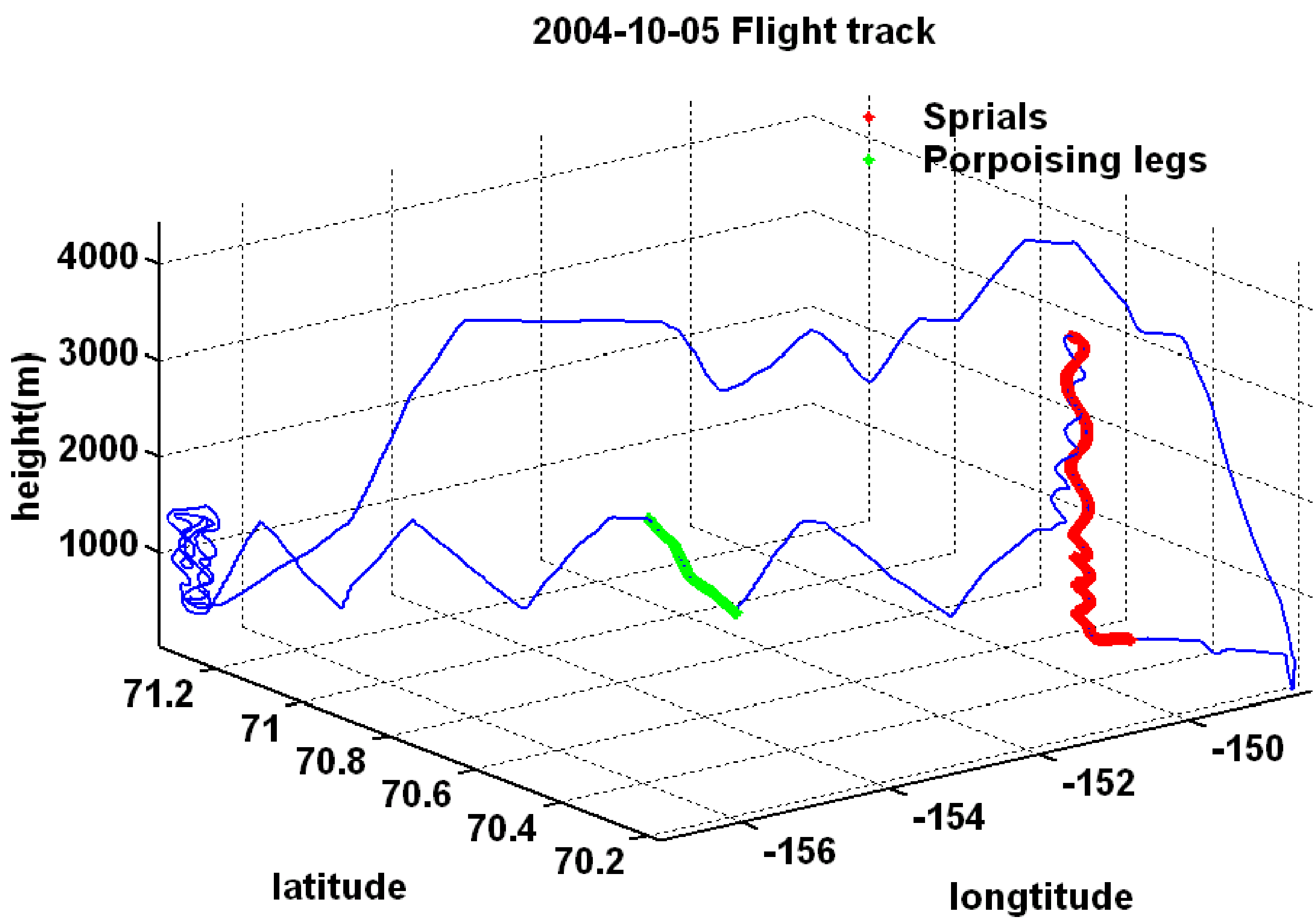
In-situ data on size, shape & phase → bulk parameters

Uncertainties

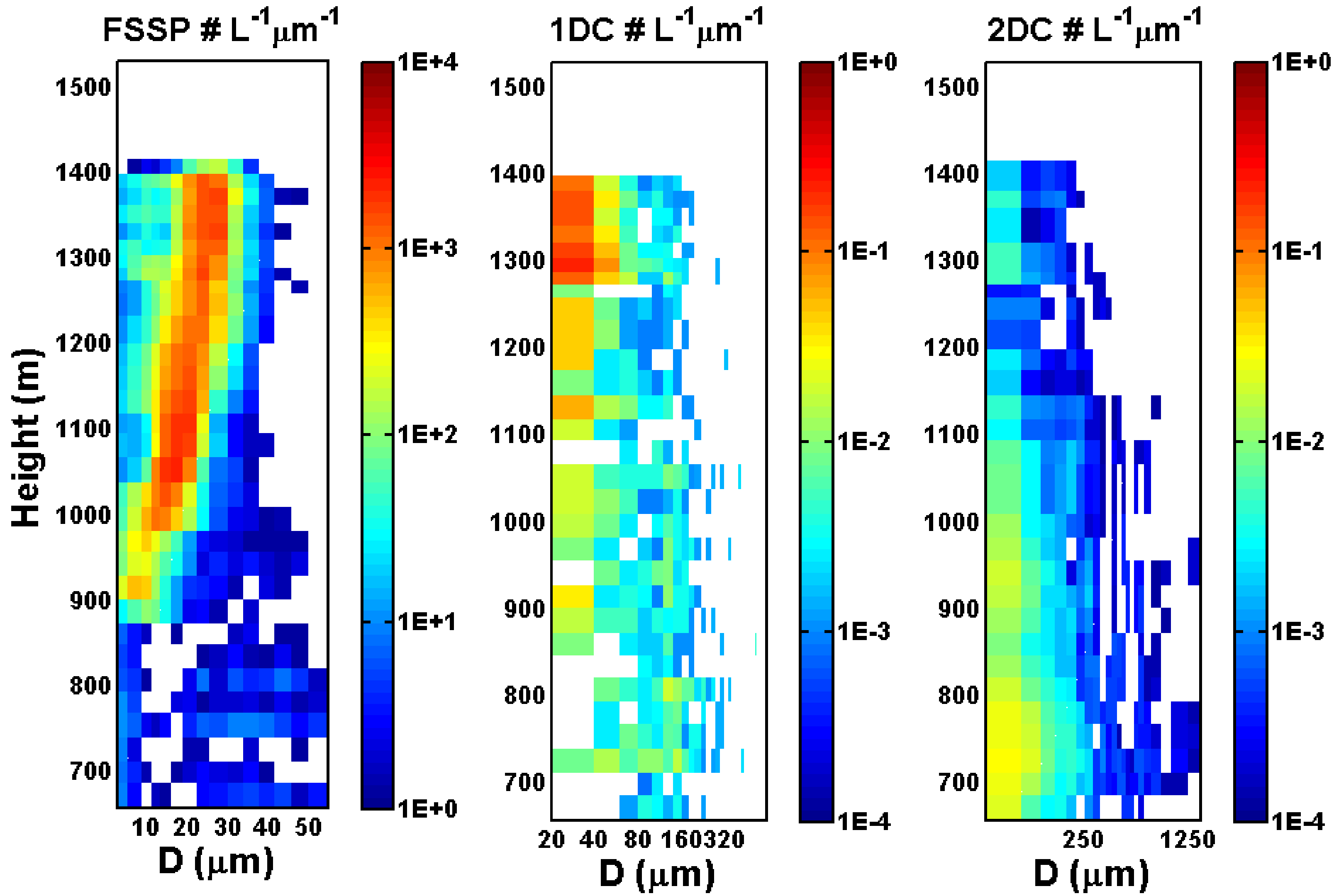
- **There is no ground-truth**
  - **assumptions & uncertainties in parameters derived from in-situ observations exist**
- **Some parameters have smaller/larger errors**
- **Arctic & mixed-phase clouds offer unique challenges & sometimes large uncertainties**

Example of single-layer mixed-phase cloud 10/12





- **Flight sampling strategy for M-PACE**
- **Analysis of 100 profiles from MPACE (including porpoises) completed, including multi-layer and single-layer clouds**

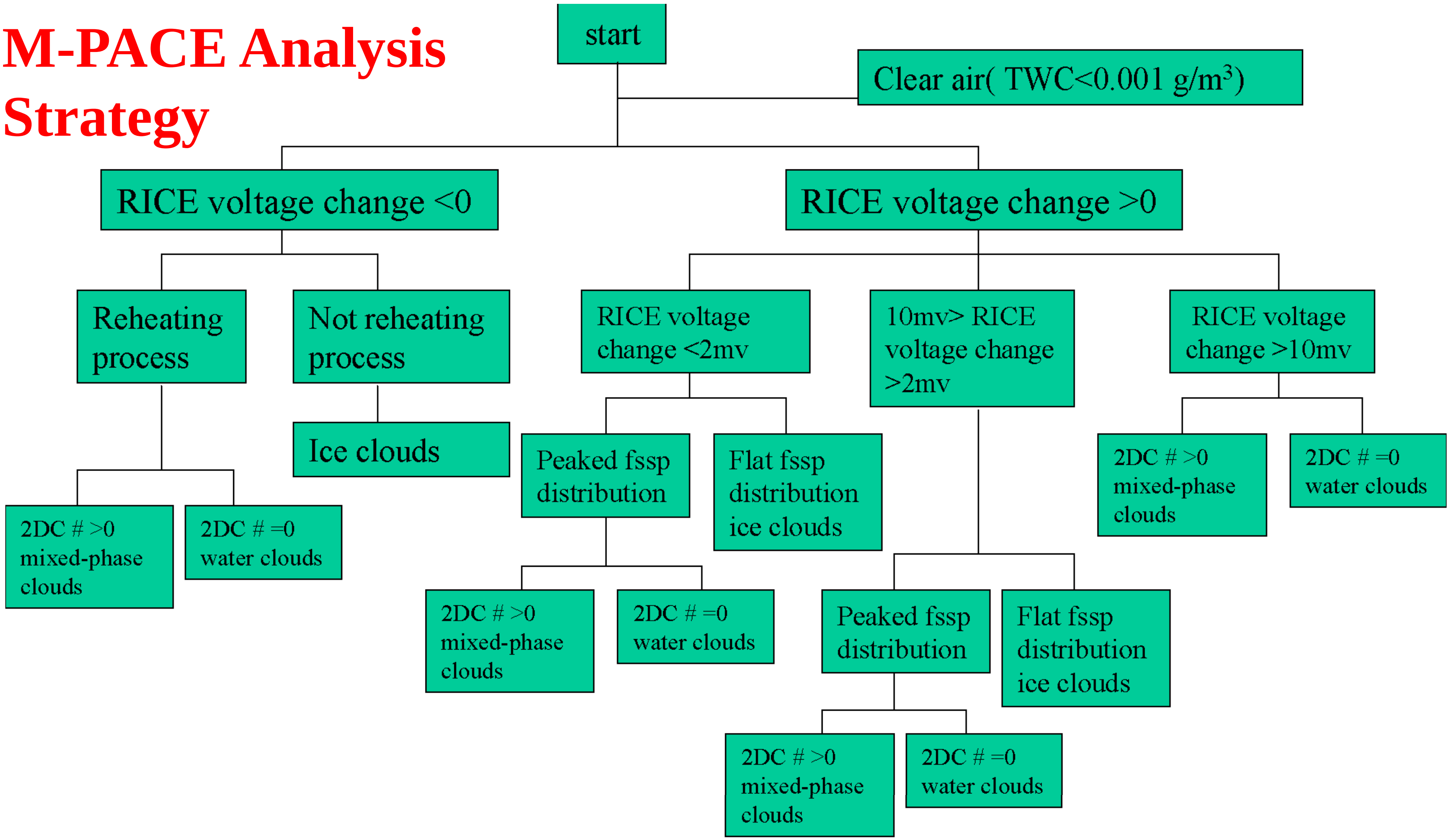


Spiral from Oct. 10: 1) cloud base ~ 900 m (from lidar)

2) Precipitating ice throughout cloud & beneath cloud

3) Liquid throughout cloud, strong growth throughout cloud

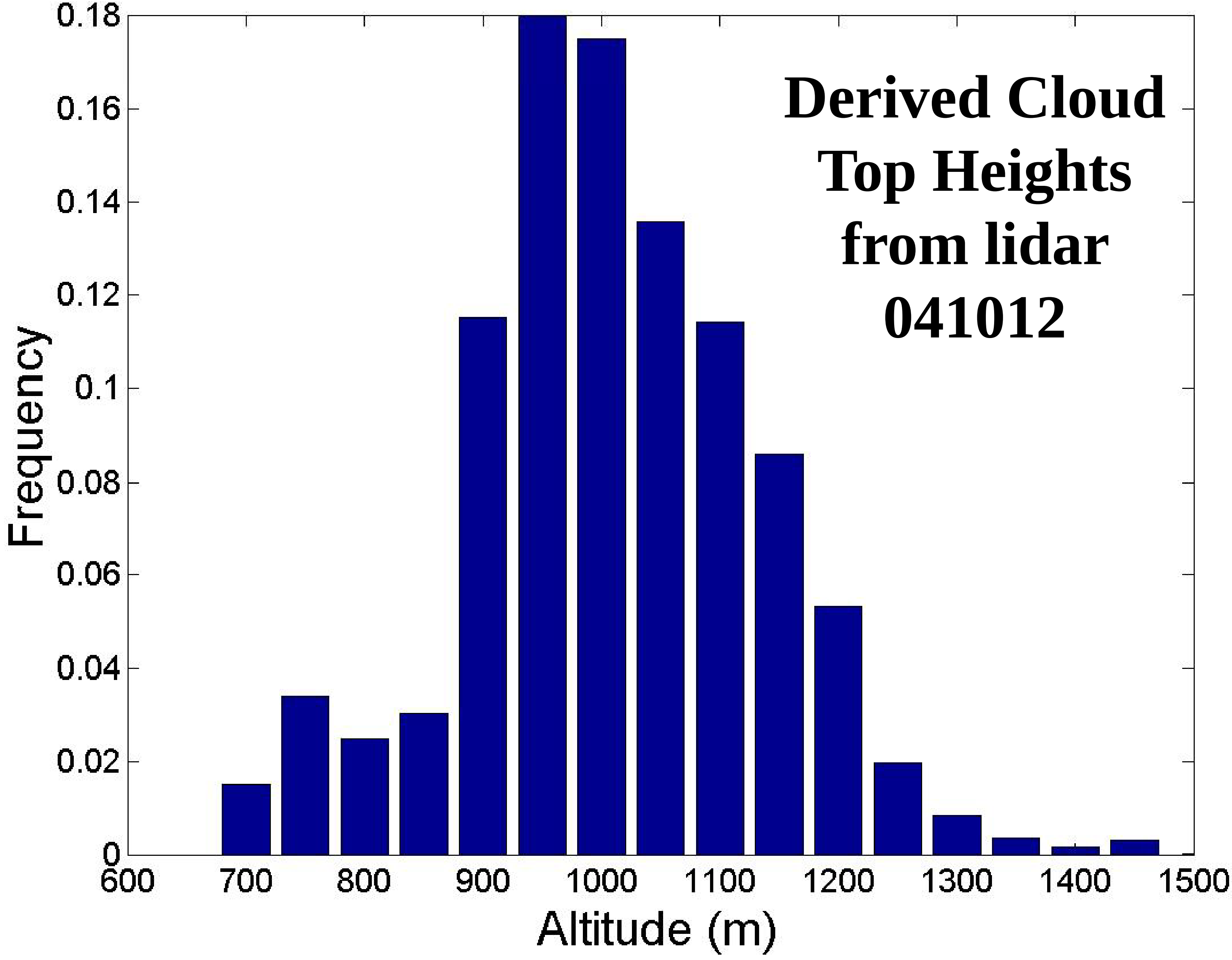
M-PACE Analysis Strategy

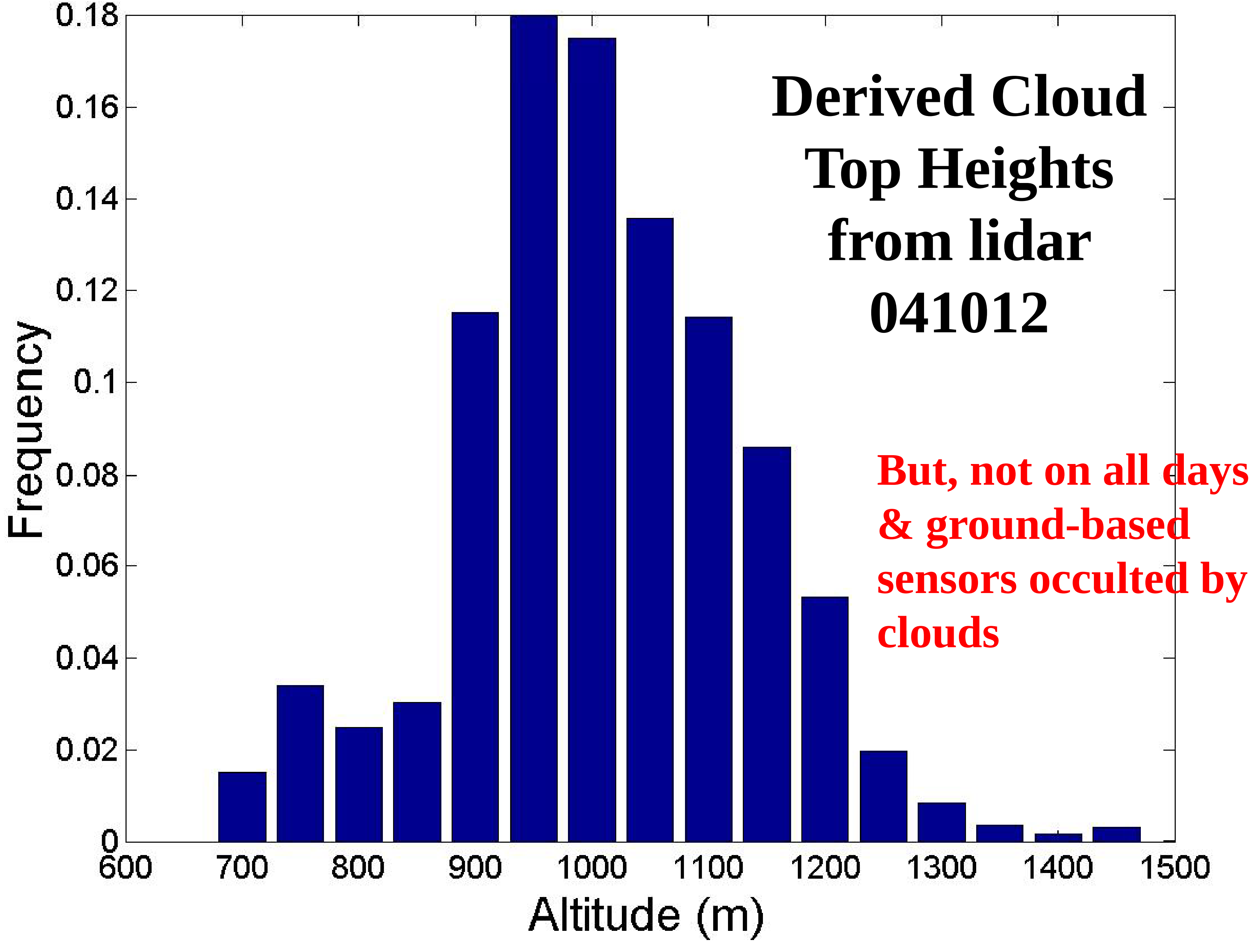


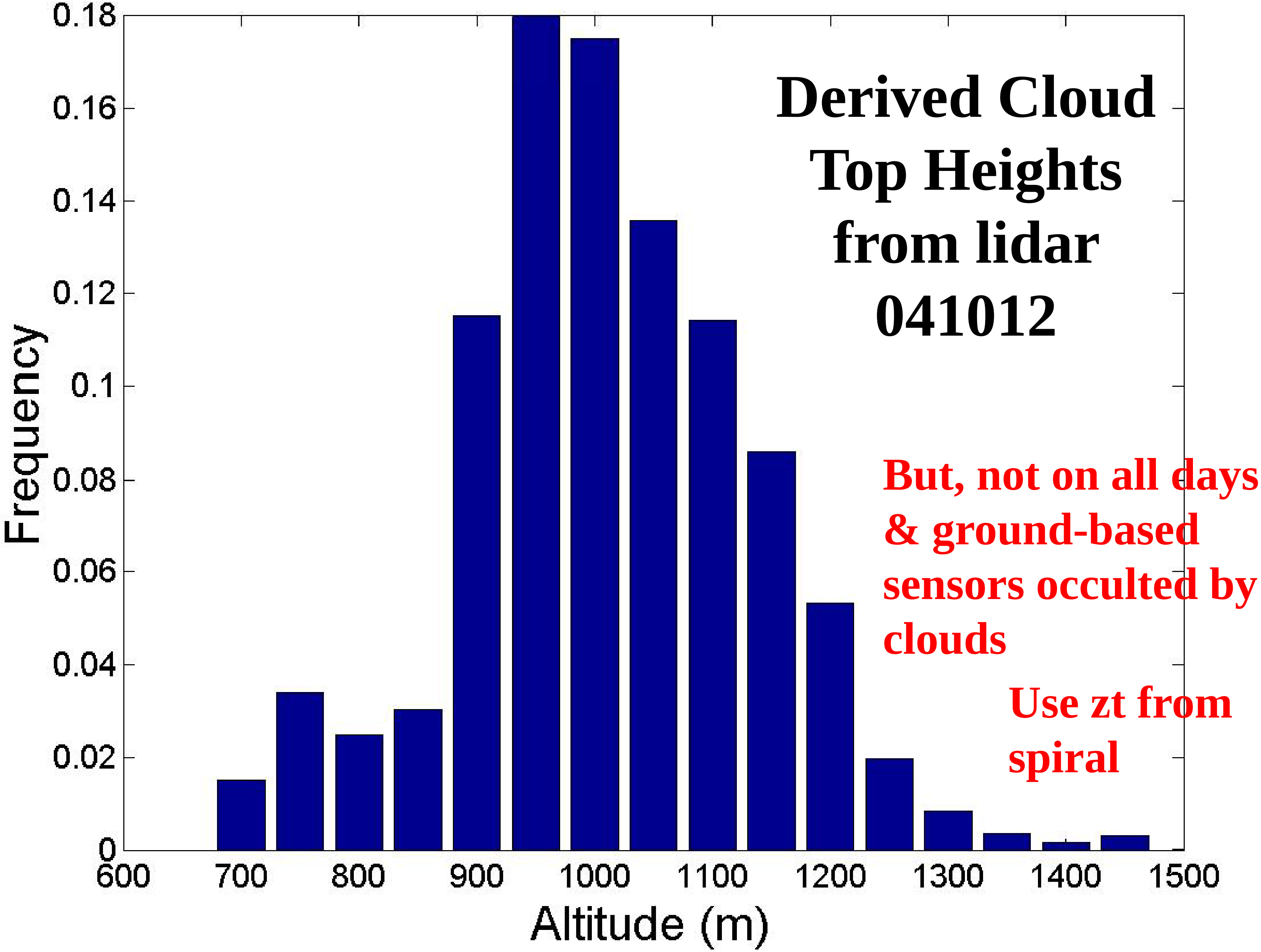
1. **Identify phase**
2. **Calculate SDs for ice/water components (FSSP, 1DC, 2DC, HVPS)**
3. **Calculate bulk properties (SDs, King probe, CVI, RICE)**

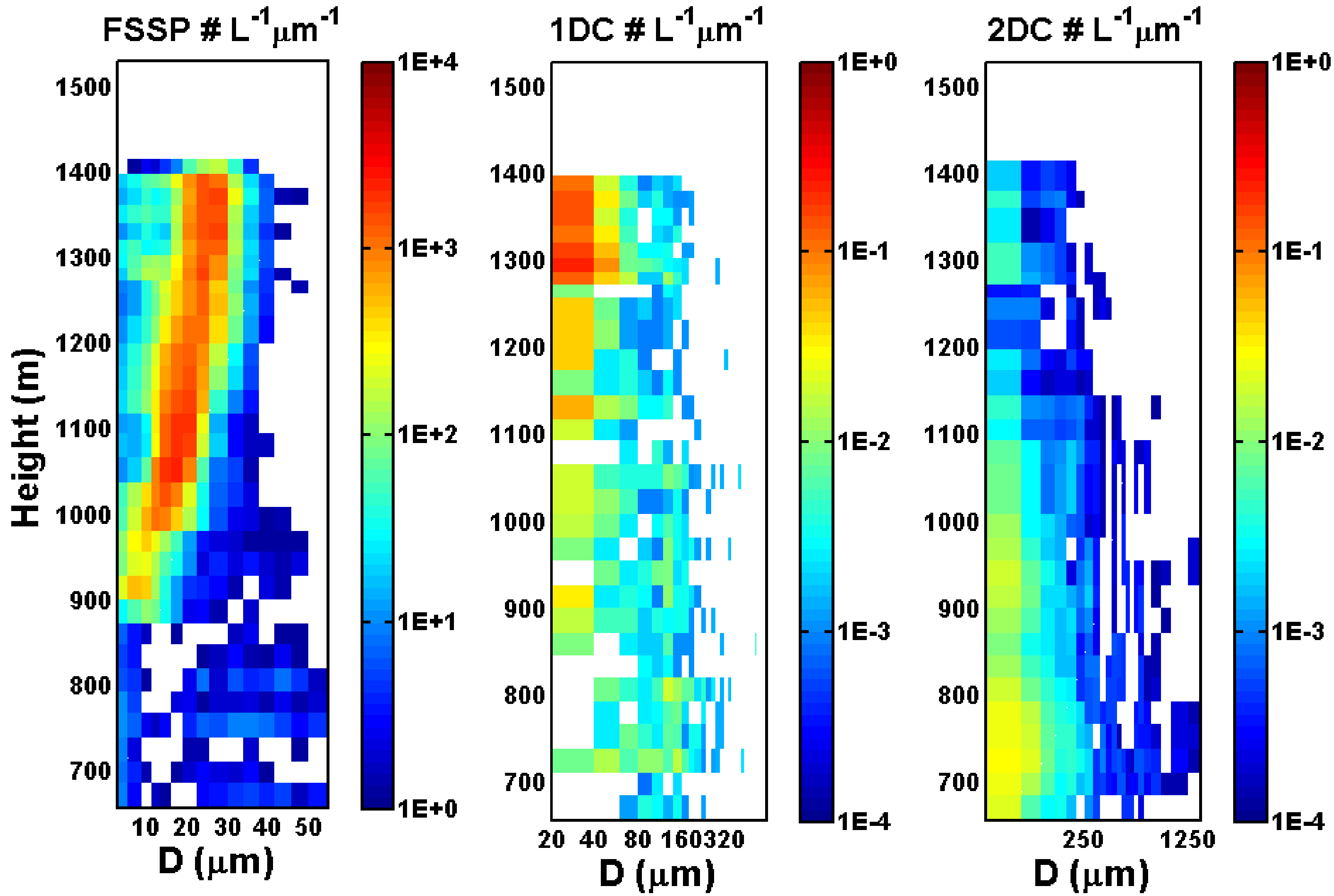
Problems/Uncertainties in M-PACE Data

1. Estimate cloud base & cloud top

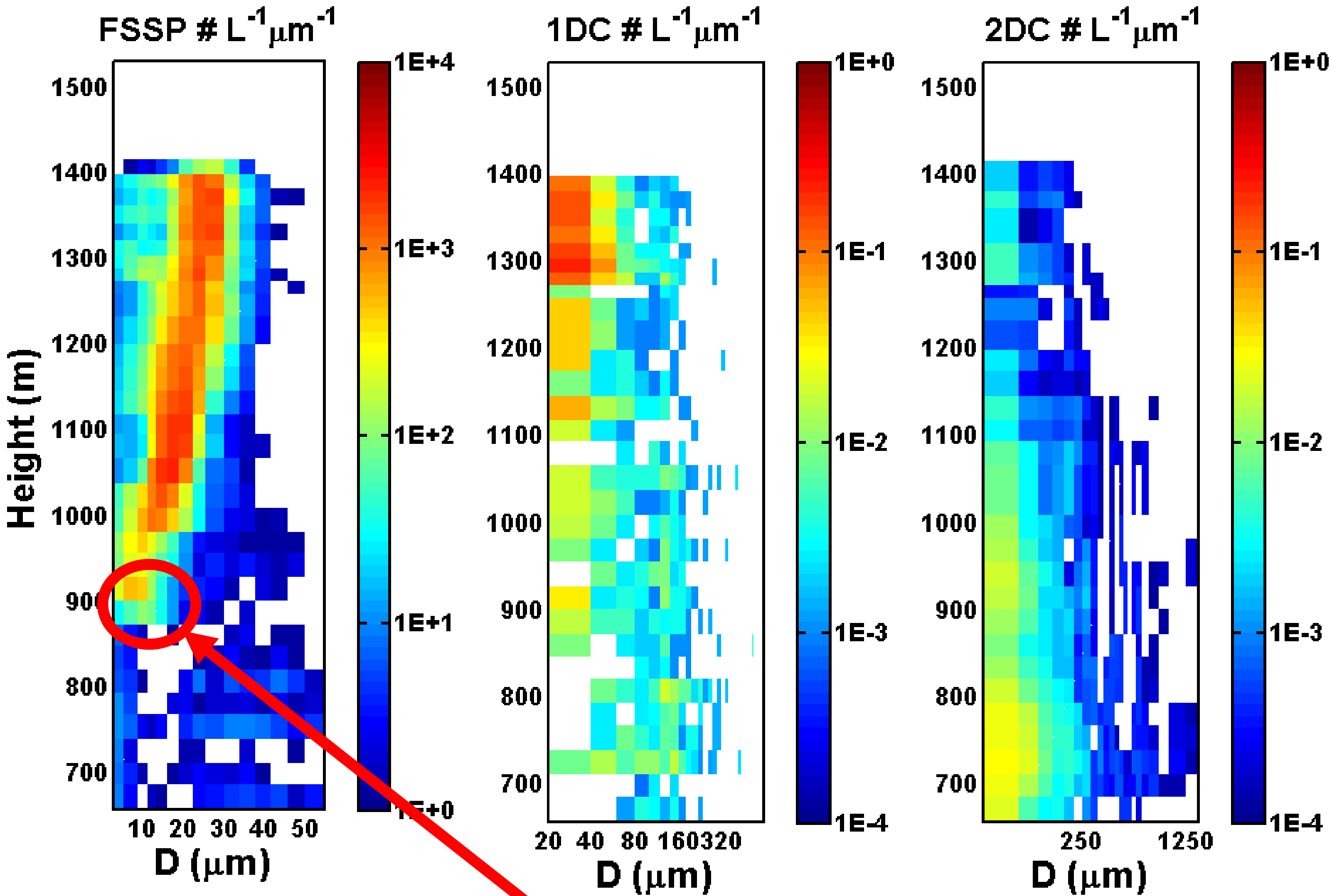

Derived Cloud
Top Heights
from lidar
041012
Frequency
Altitude (m)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
600
700
800
900
1000
1100
1200
1300
1400
1500


0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Frequency
600
700
800
900
1000
1100
1200
1300
1400
1500
Altitude (m)
Derived Cloud Top Heights from lidar 041012
But, not on all days & ground-based sensors occulted by clouds


Derived Cloud Top Heights from lidar 041012
But, not on all days & ground-based sensors occulted by clouds
Use zt from spiral
Frequency
Altitude (m)
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
600
700
800
900
1000
1100
1200
1300
1400
1500

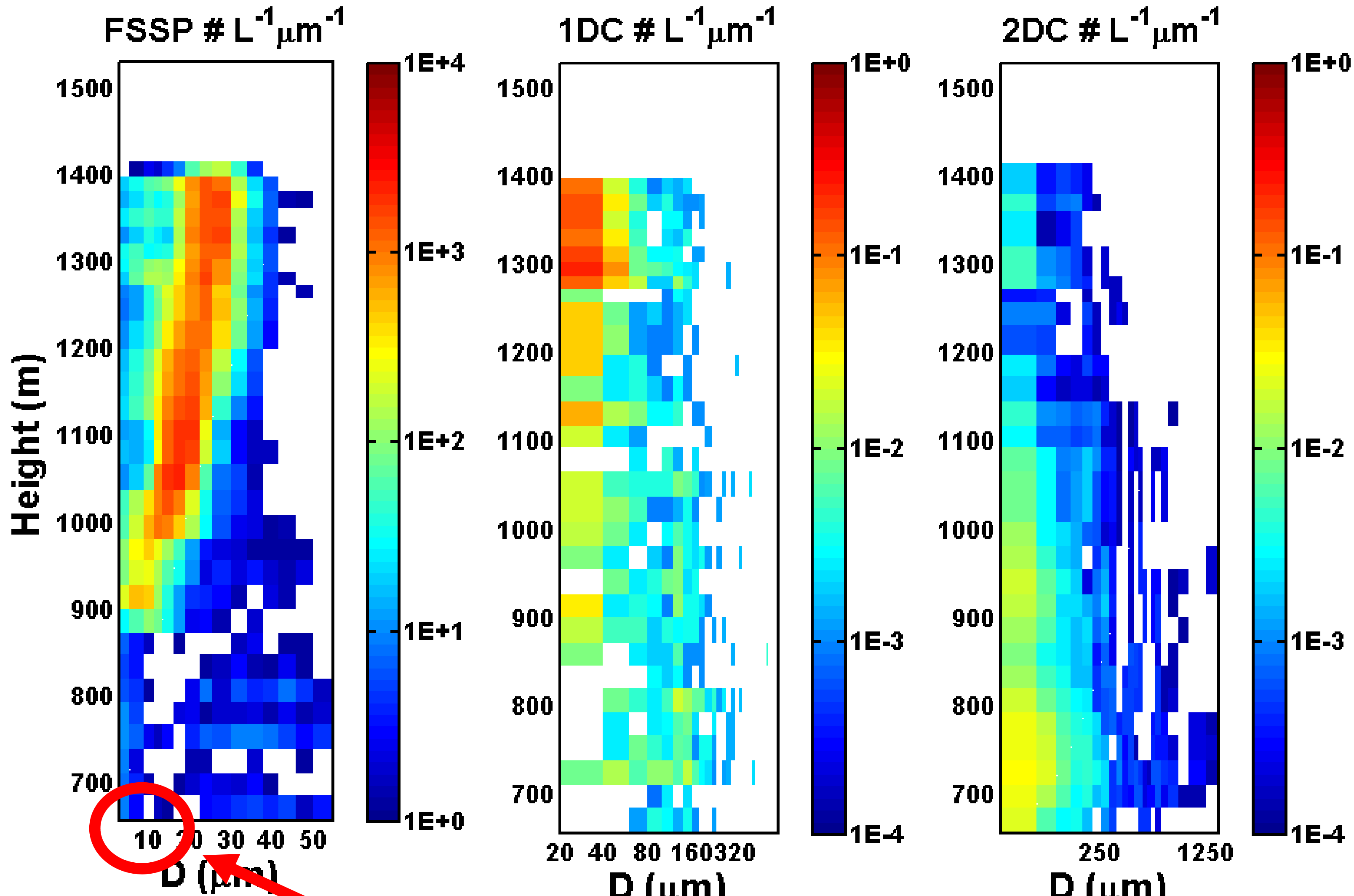


Where is cloud base?



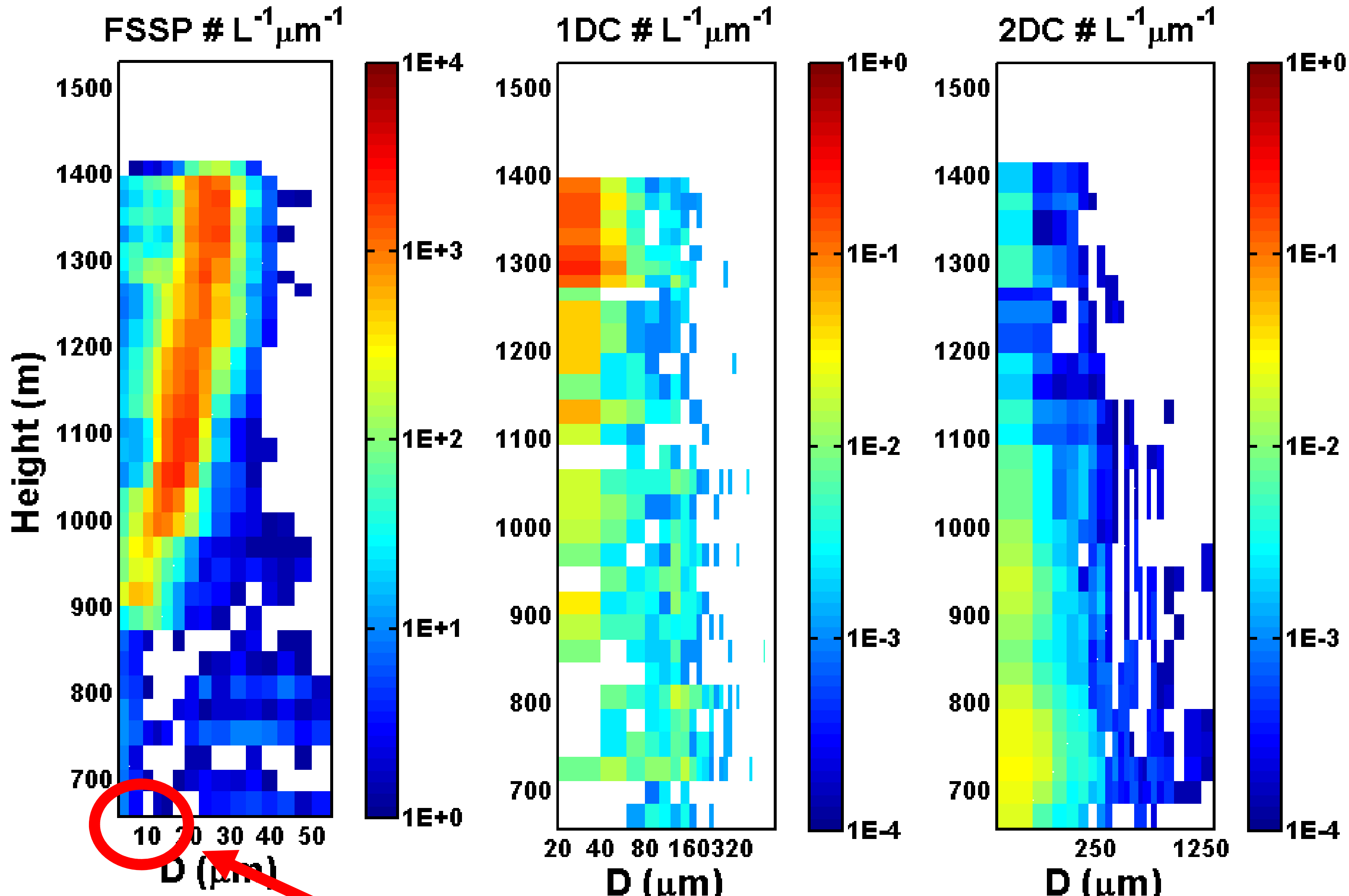
Where is cloud base?

Here?



Where is cloud base?

Or here?



Where is cloud base?

Or here?

Lidar shows cloud base at 900 m consistent with liquid cloud base

Definition of zb and zn

Define zb as:

base of lowest liquid layer from lidar

OR base of lowest liquid layer from aircraft profiles

Define normalized altitude for single layer clouds, zn, as

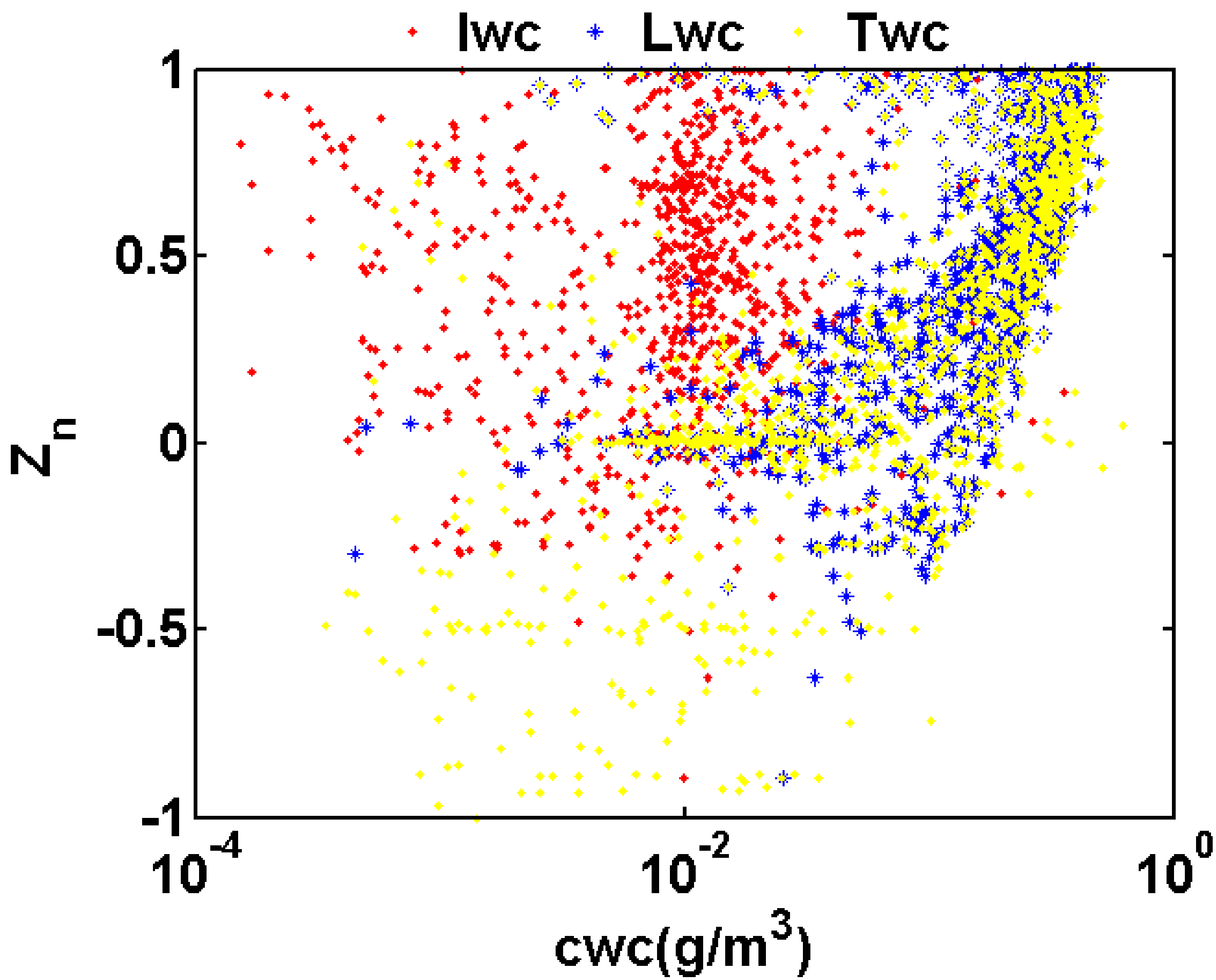
$$z_n = \frac{(z - zb)}{(zt - zb)}$$

Note: zn can be < 0

Precipitating ice regions beneath liquid base

Problems/Uncertainties in M-PACE Data

1. **Estimate cloud base & cloud top**
2. **Estimating IWC in mixed-phase clouds**



In mixed-phase clouds for z > zb, liquid dominates total mass

→ difficult to estimate IWC from bulk measures of TWC & IWC

Estimate IWC from SDs

- **If m=aD^b is mass of single crystal, then**

$$IWC = \int_0^\infty a D^b N(D)\, dD$$

with (a,b) chosen to reduce χ^2 difference between IWC measured by CVI & that from SDs

Can only do this for ice clouds as these are only clouds for which we have bulk IWC

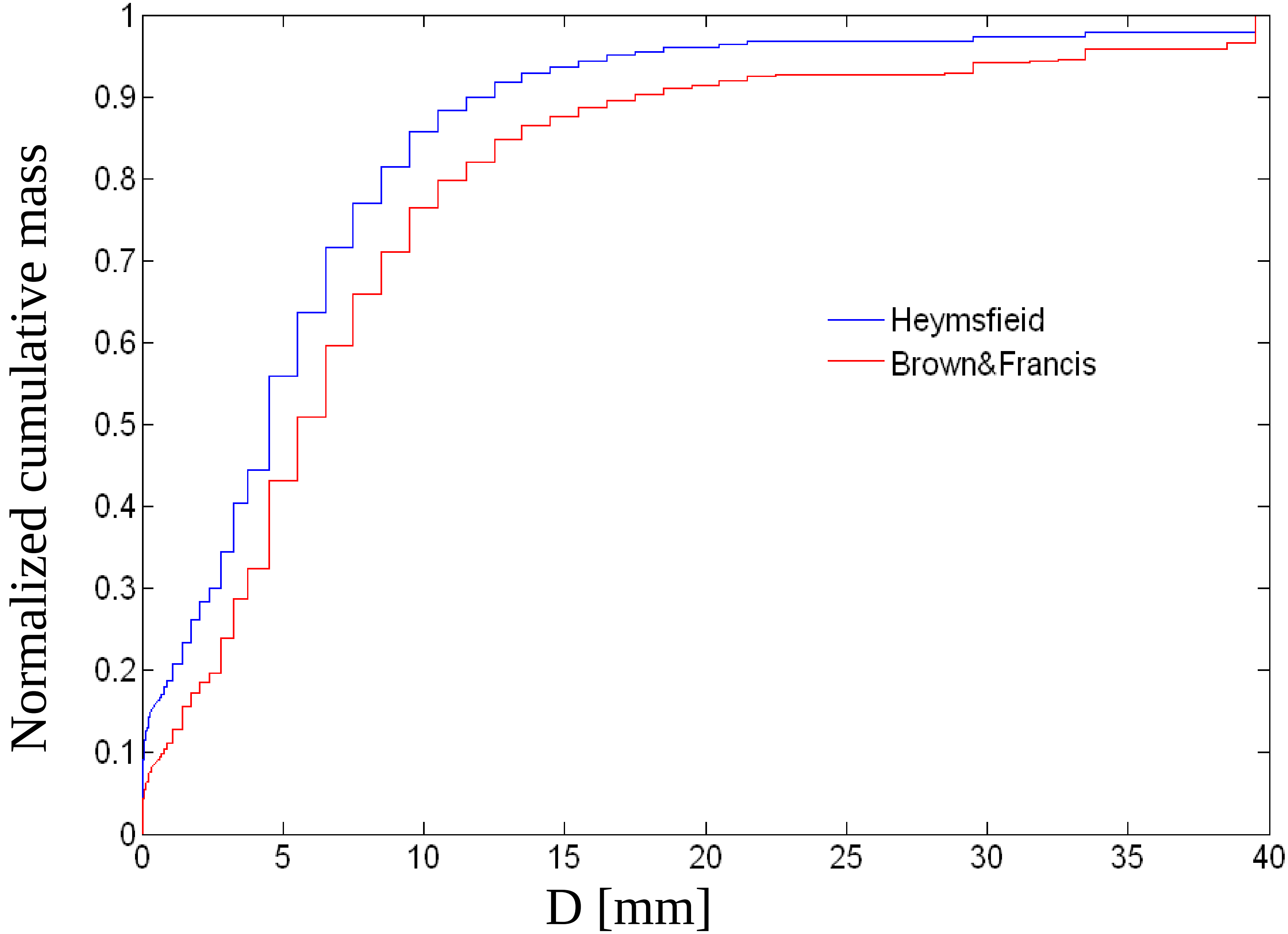
This approach gives reasonable agreement with bulk probe measurements

Problems/Uncertainties in M-PACE Data

1. **Estimate cloud base & cloud top**
2. **Estimating IWC in mixed-phase clouds**
3. **Missing mass from large crystals (HVPS) on some flights**

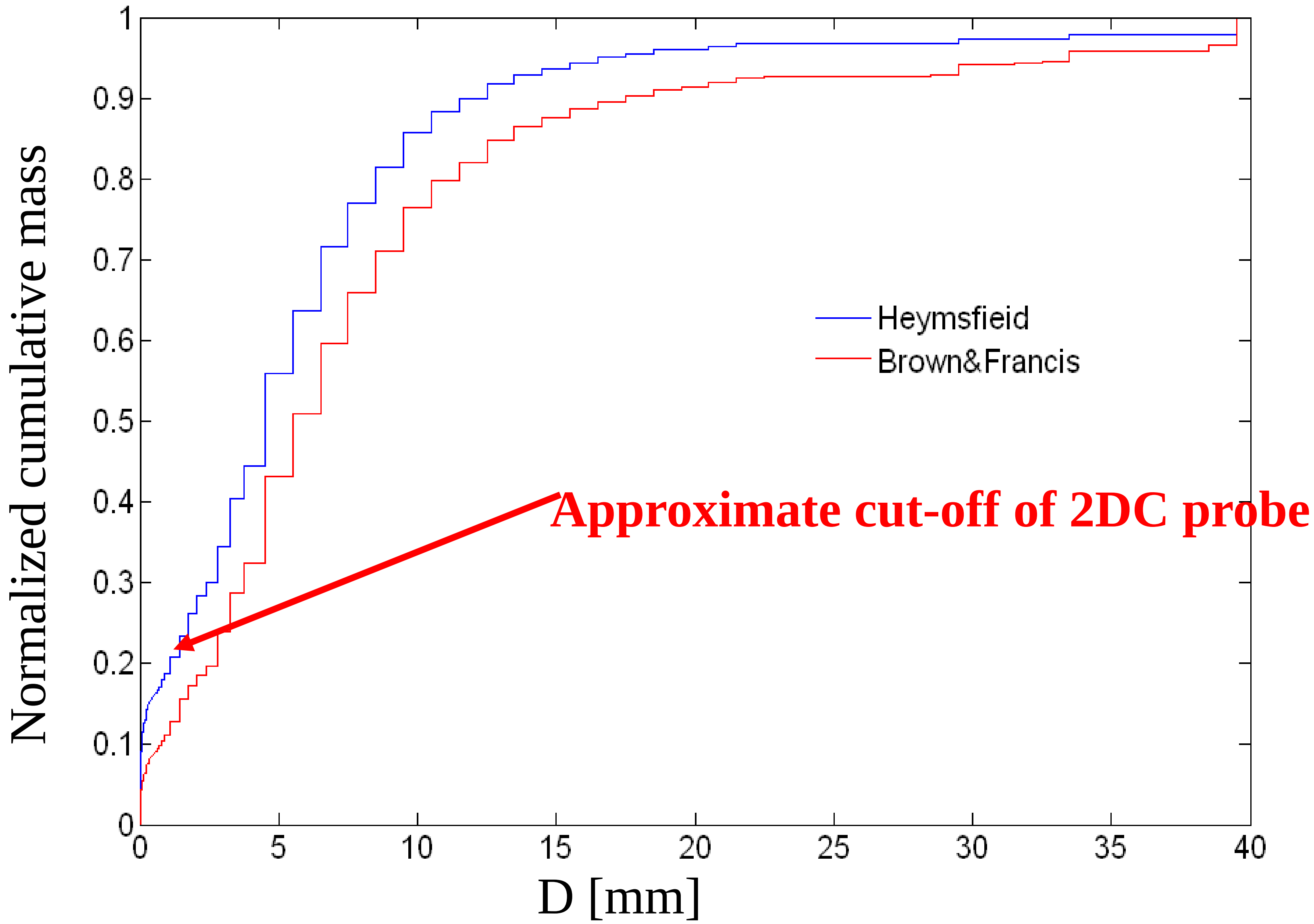
HVPS did not record data on some flights

Is mass from this probe important?



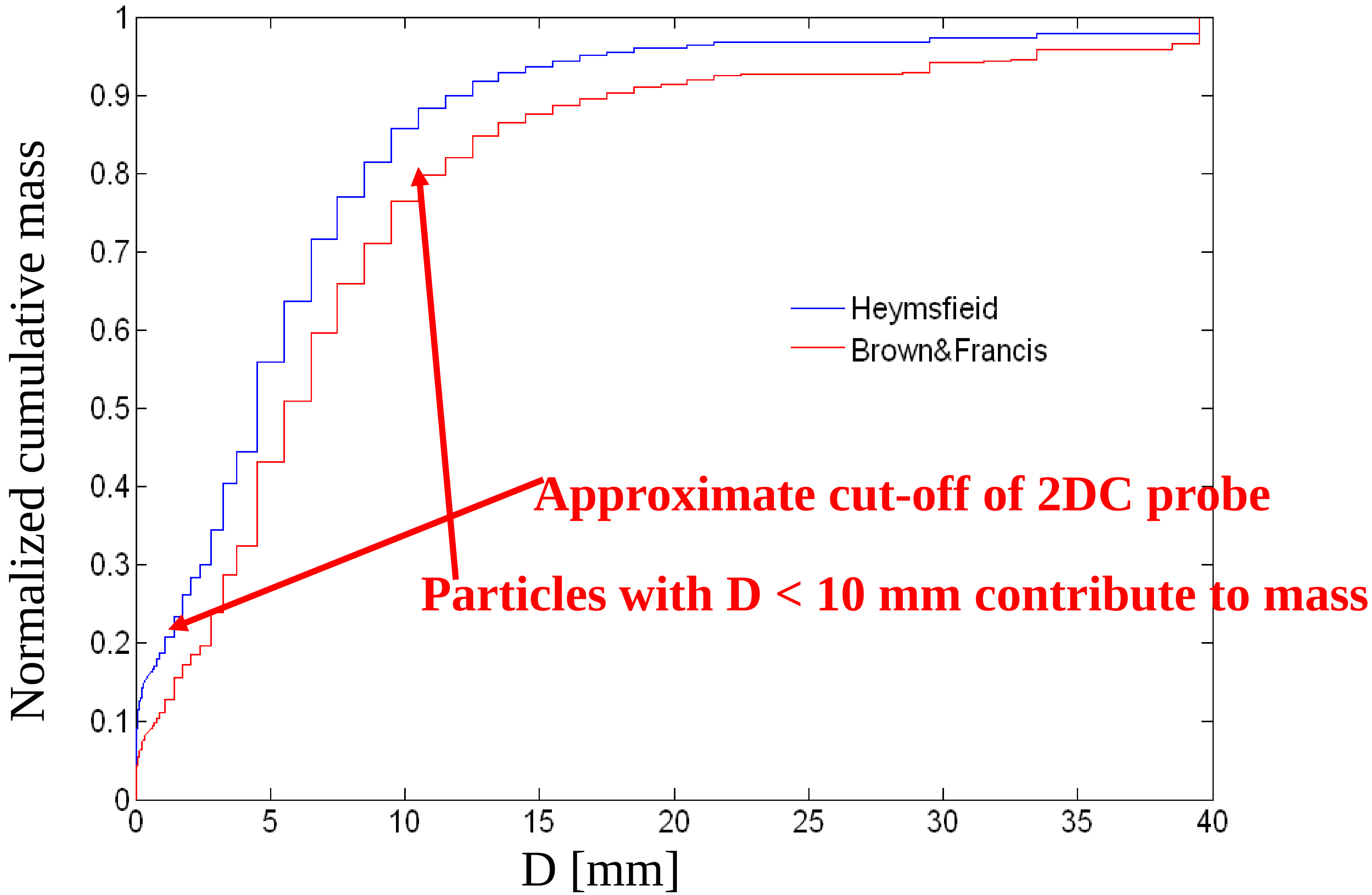
HVPS did not record data on some flights

Is mass from this probe important?



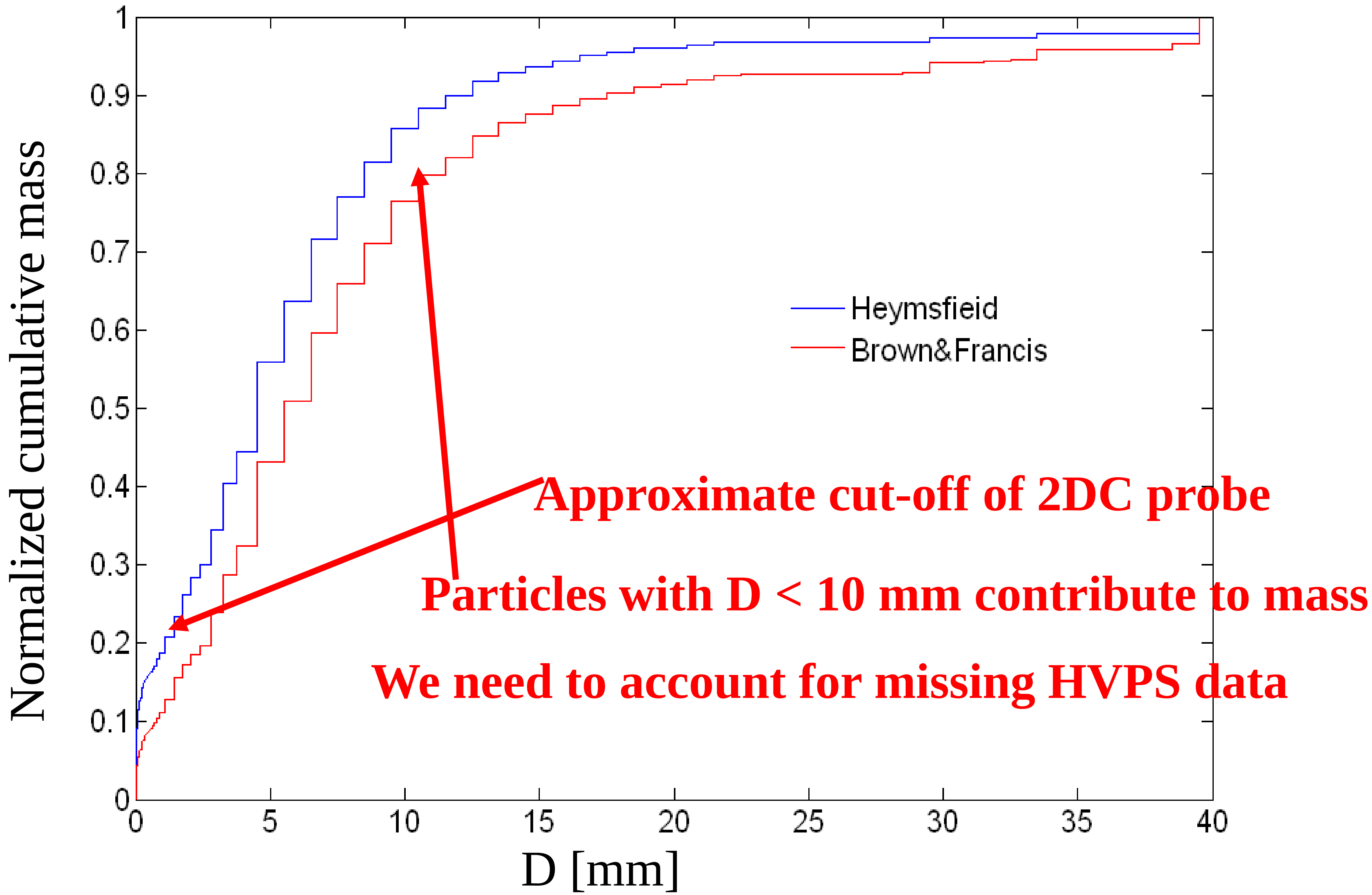
HVPS did not record data on some flights

Is mass from this probe important?



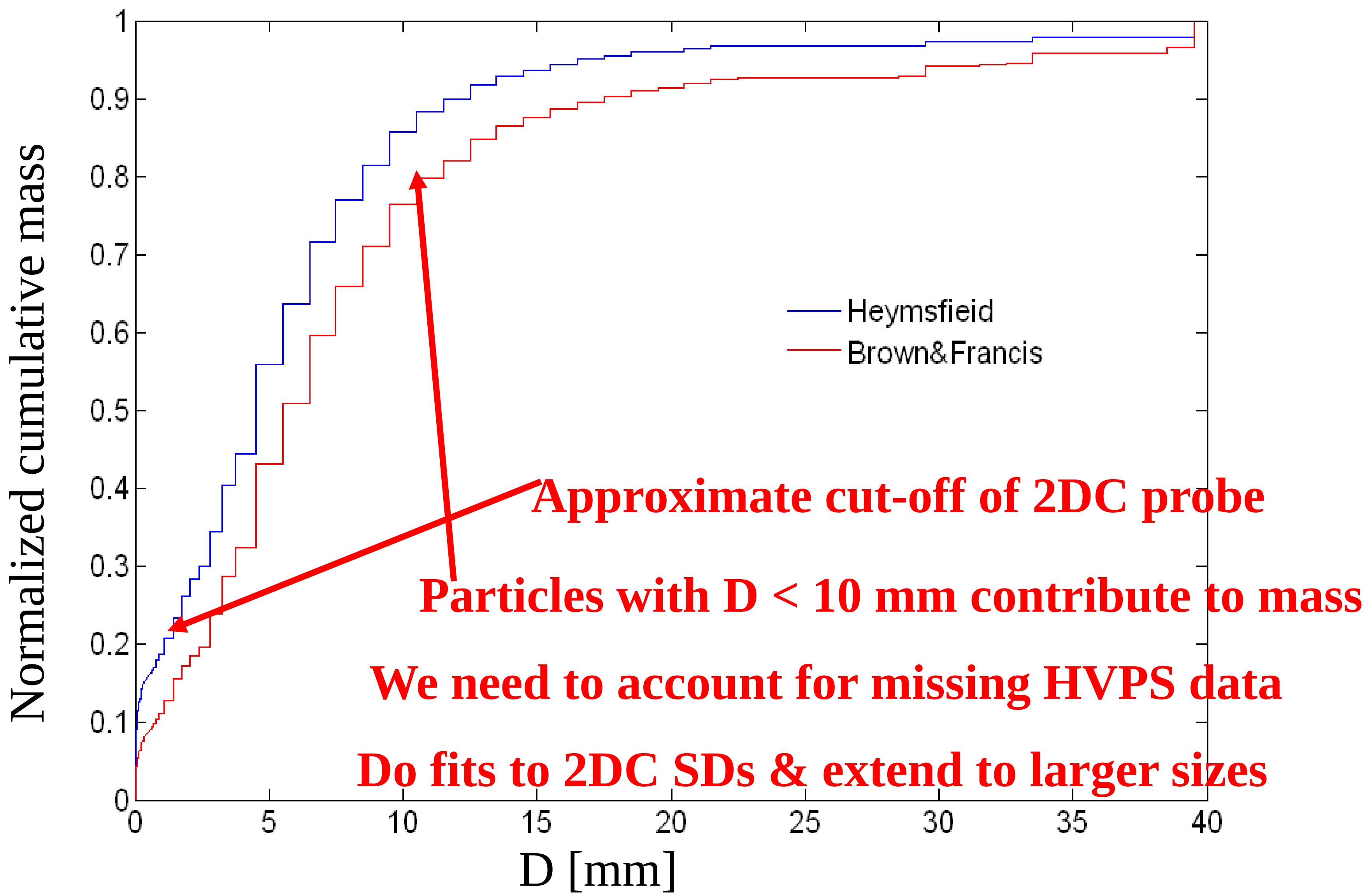
HVPS did not record data on some flights

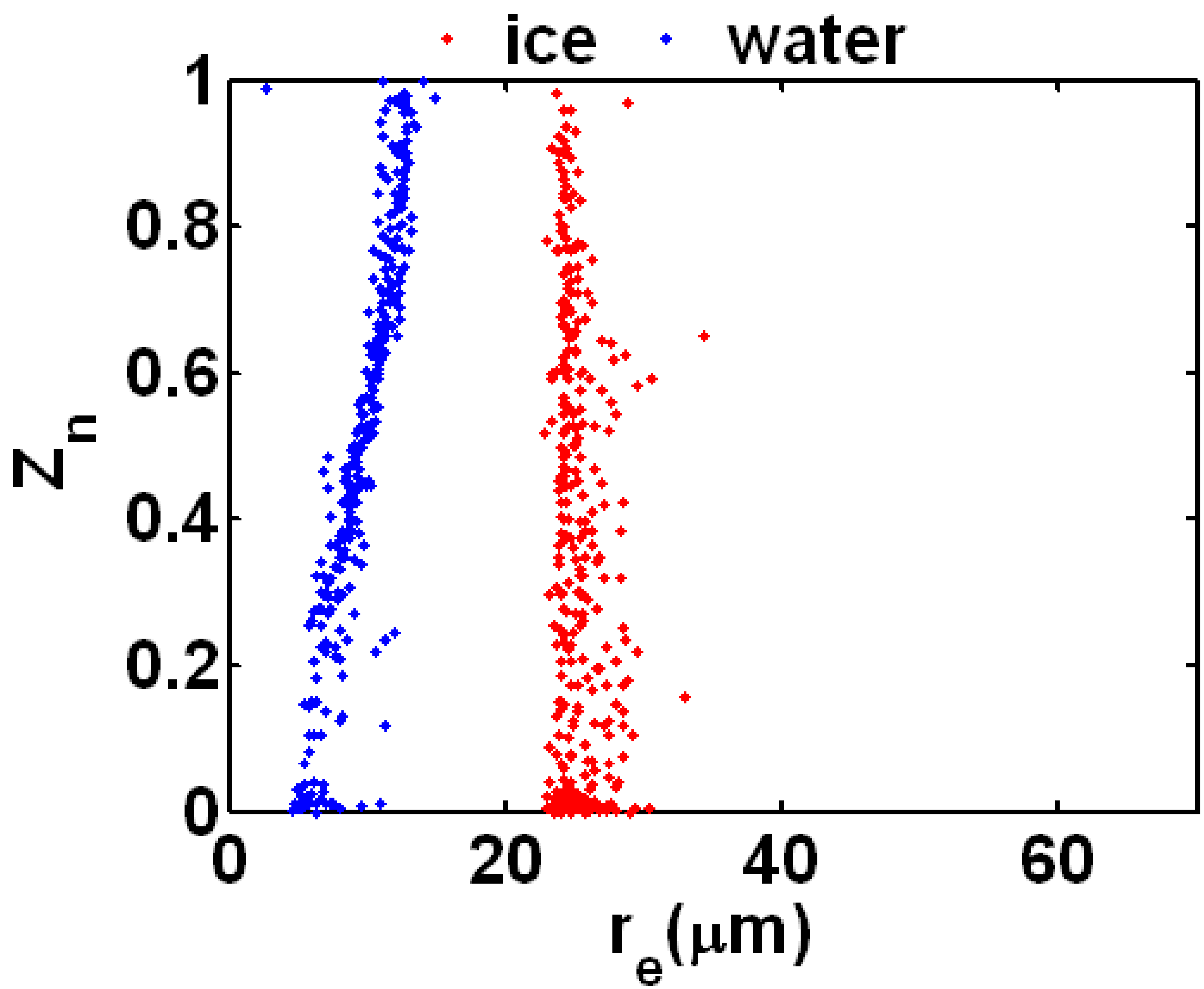
Is mass from this probe important?



HVPS did not record data on some flights

Is mass from this probe important?

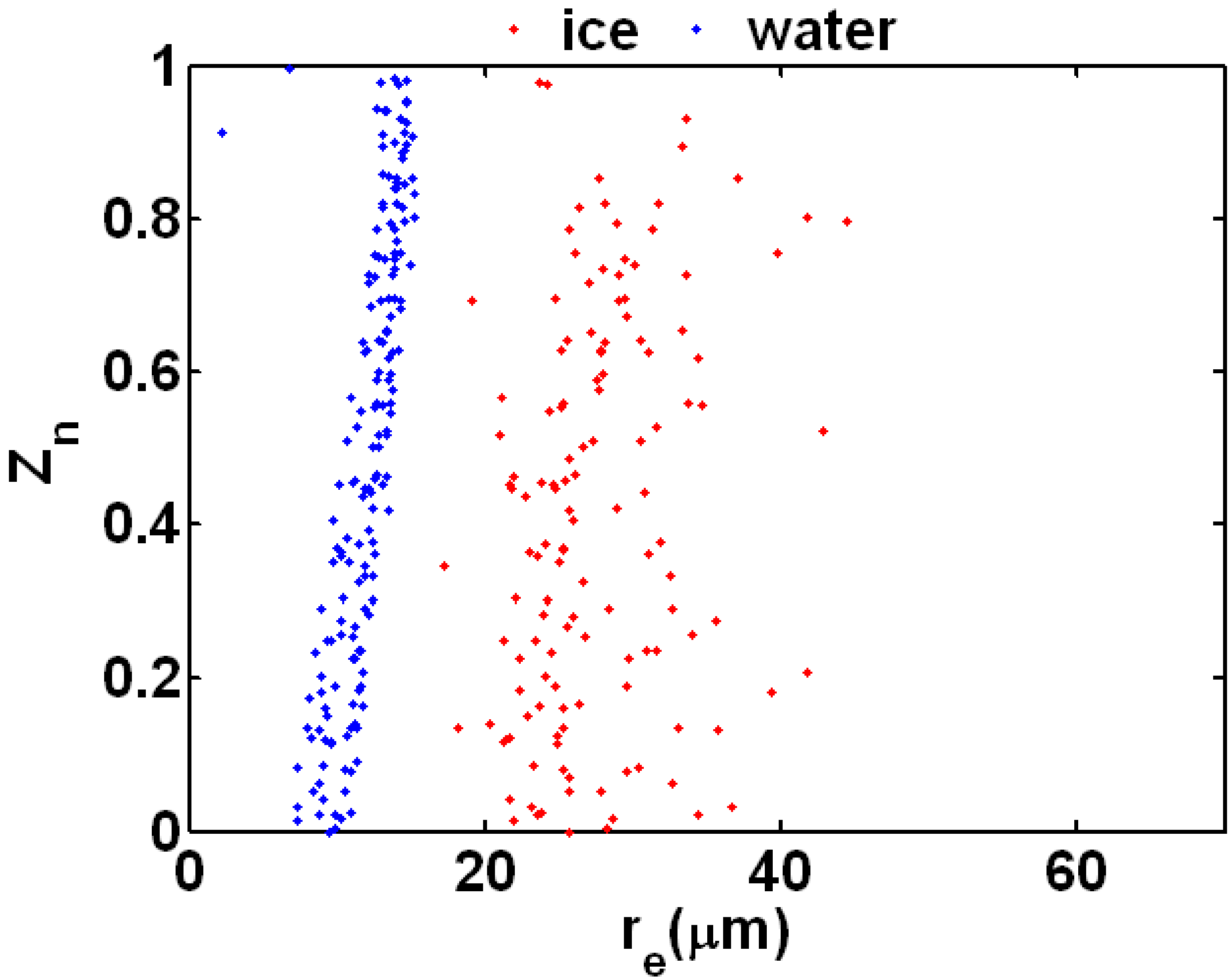




Oct. 9b

rei proportional to IWC/area of ice crystals

when HVPS SDs based on fits to 2DC, less variability in rei



Oct. 10

More scatter in rei when use actual HVPS data

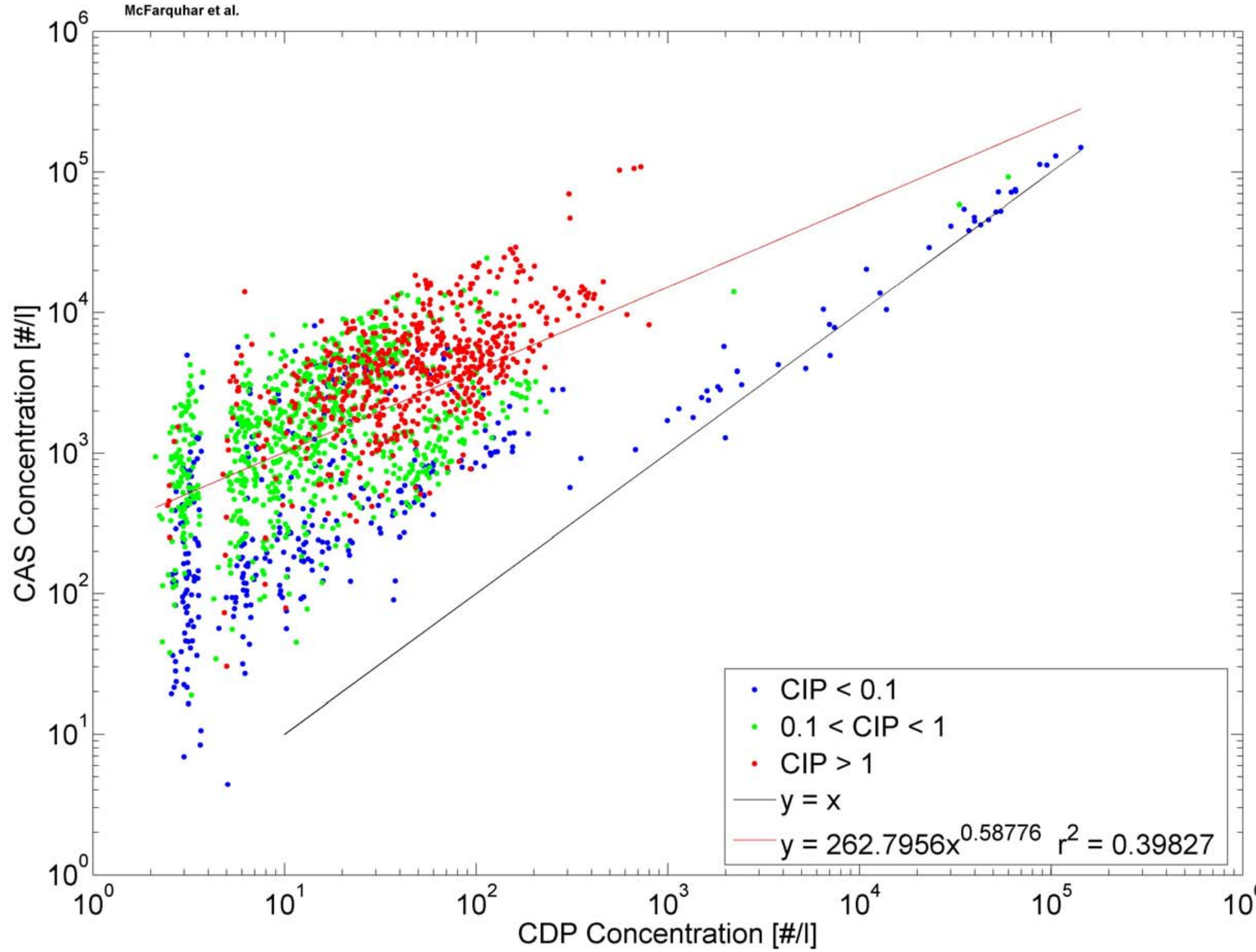
Problems/Uncertainties in M-PACE Data

1. **Estimate cloud base & cloud top**
2. **Estimating IWC in mixed-phase clouds**
3. **Missing mass from large crystals (HVPS) on some flights**
4. **Estimating small crystal number**

Estimating small crystal number

- **Does FSSP measure small ice crystals in ice clouds?**
  - **Large crystals might shatter on probe arms artificially enhancing small crystal concentrations**

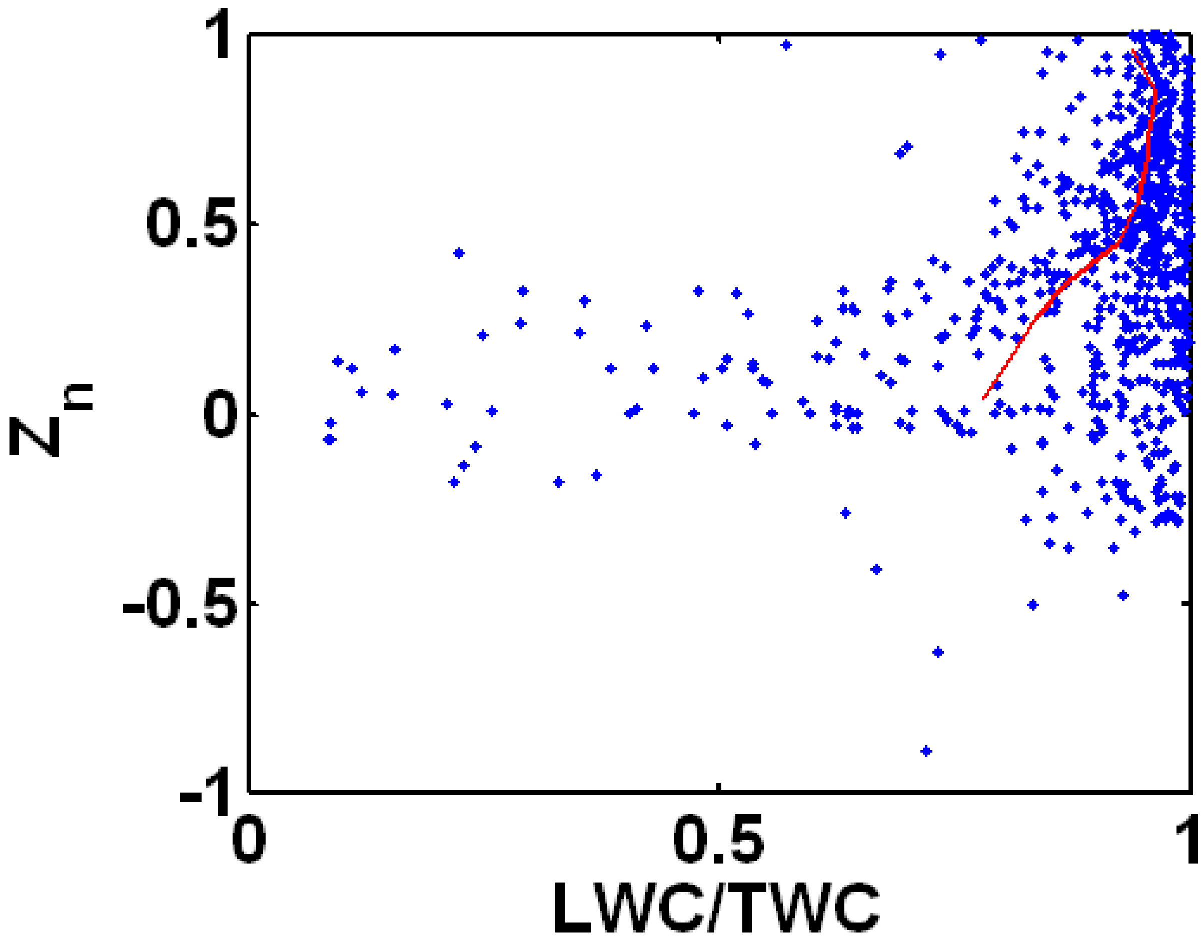
Answer to question is non-trivial and under investigation



From TWP-ICE, we found probe with protruding shroud (CAS) had higher concentrations than open-path probe (CDP)

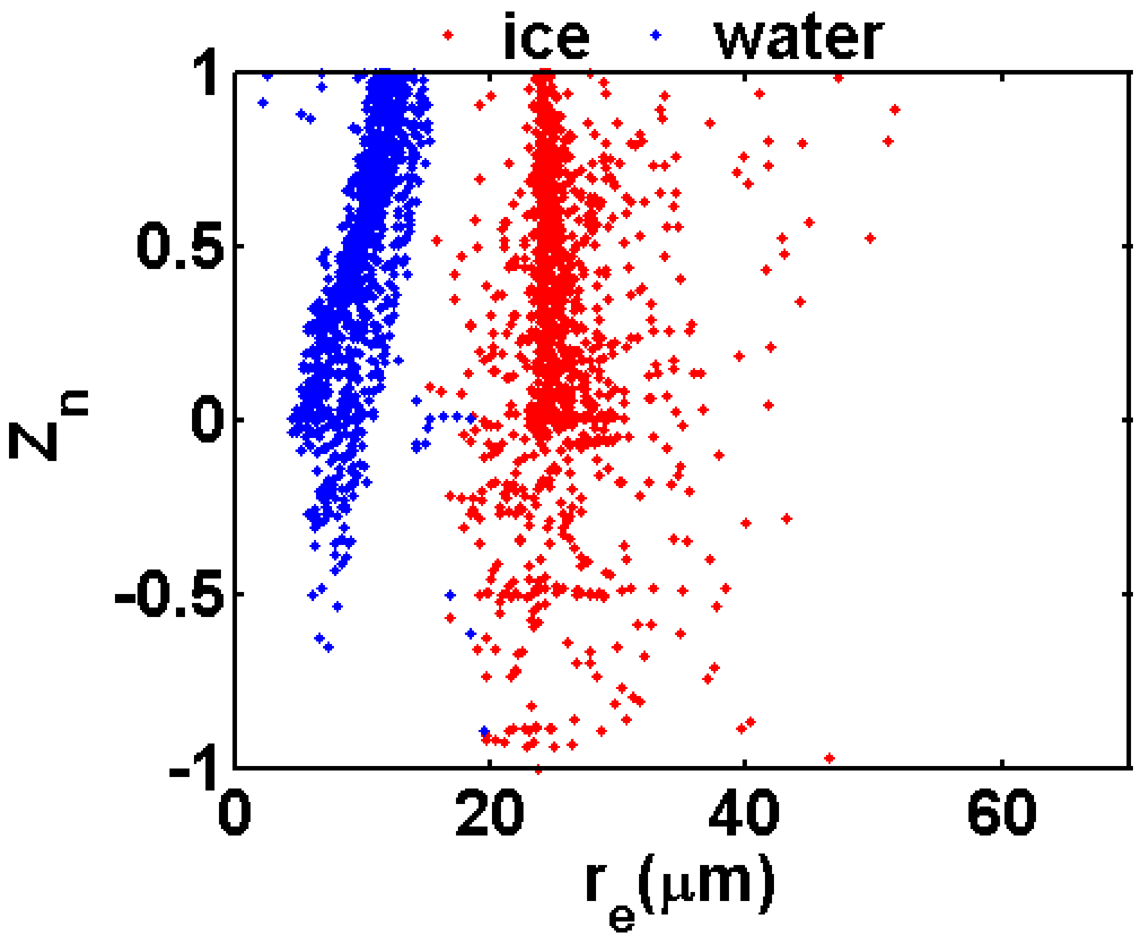
Results for single-layer clouds

- **Despite these uncertainties, can still look at how bulk parameters vary with zn**
- **But, be aware of uncertainties**



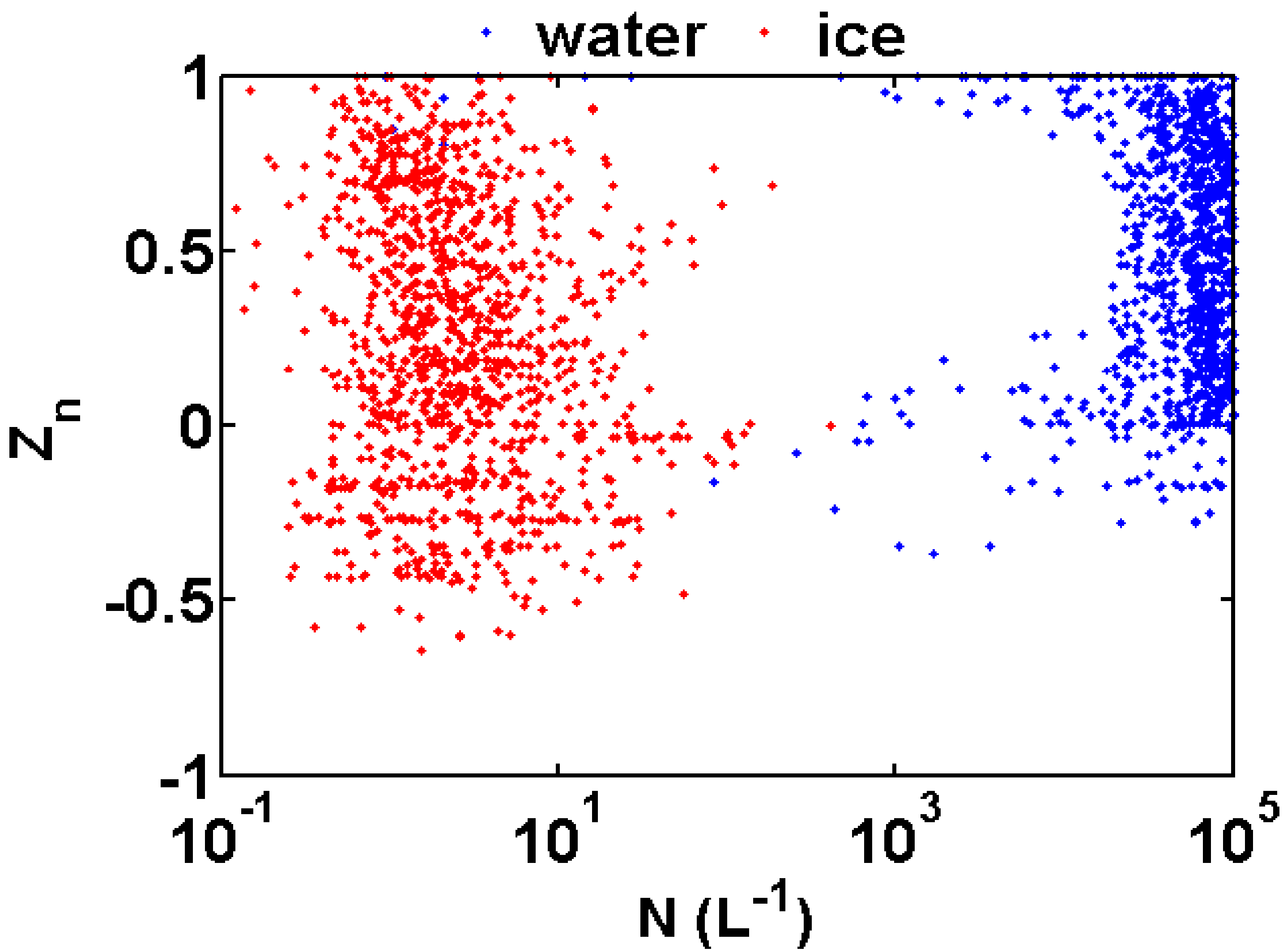
Greater fraction of ice near base

Liquid dominated top, precipitating ice below



rew increases with zn due to vapor diffusion growth

rei not strongly dependent on zn



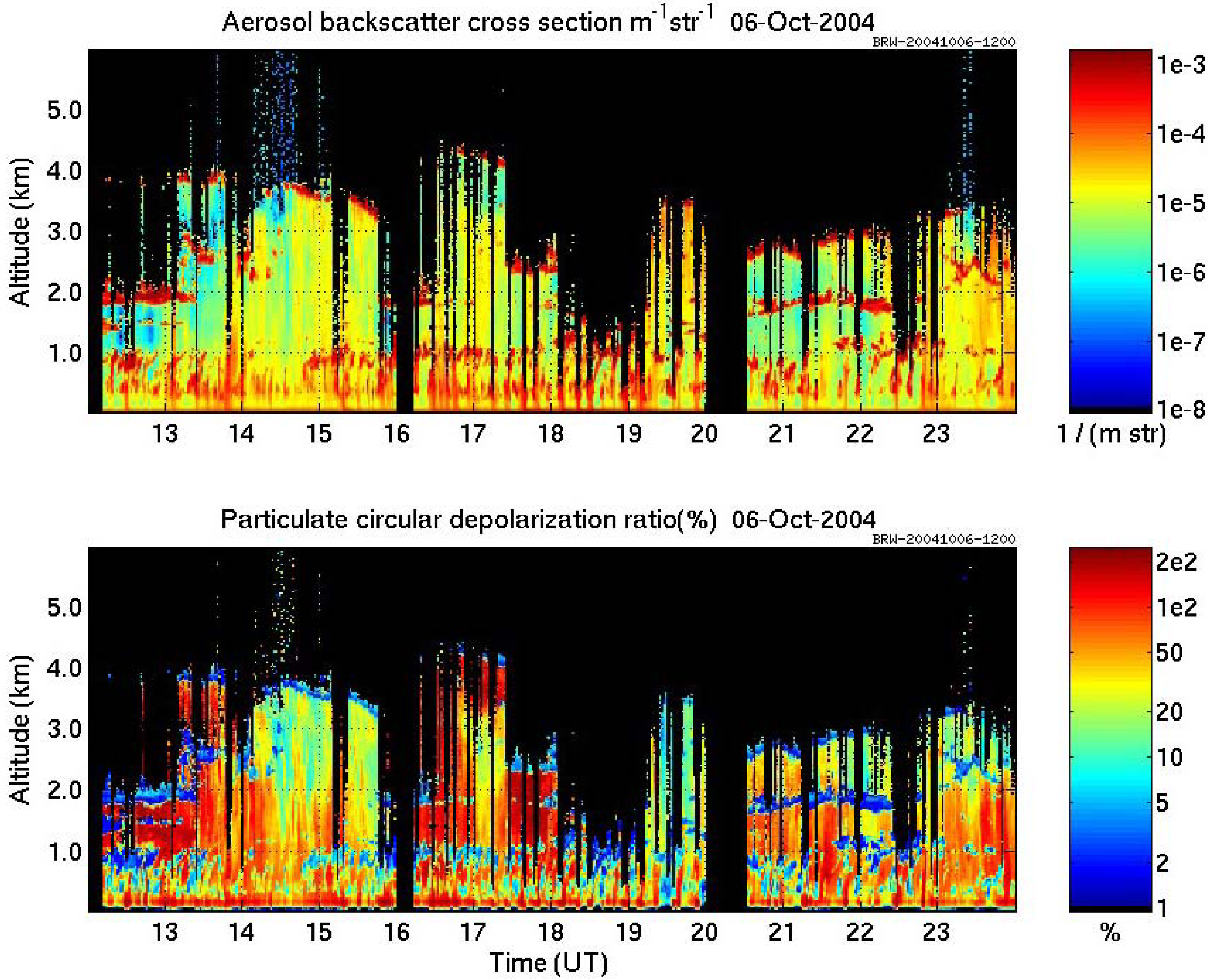
N not strong function of zn for either water or ice

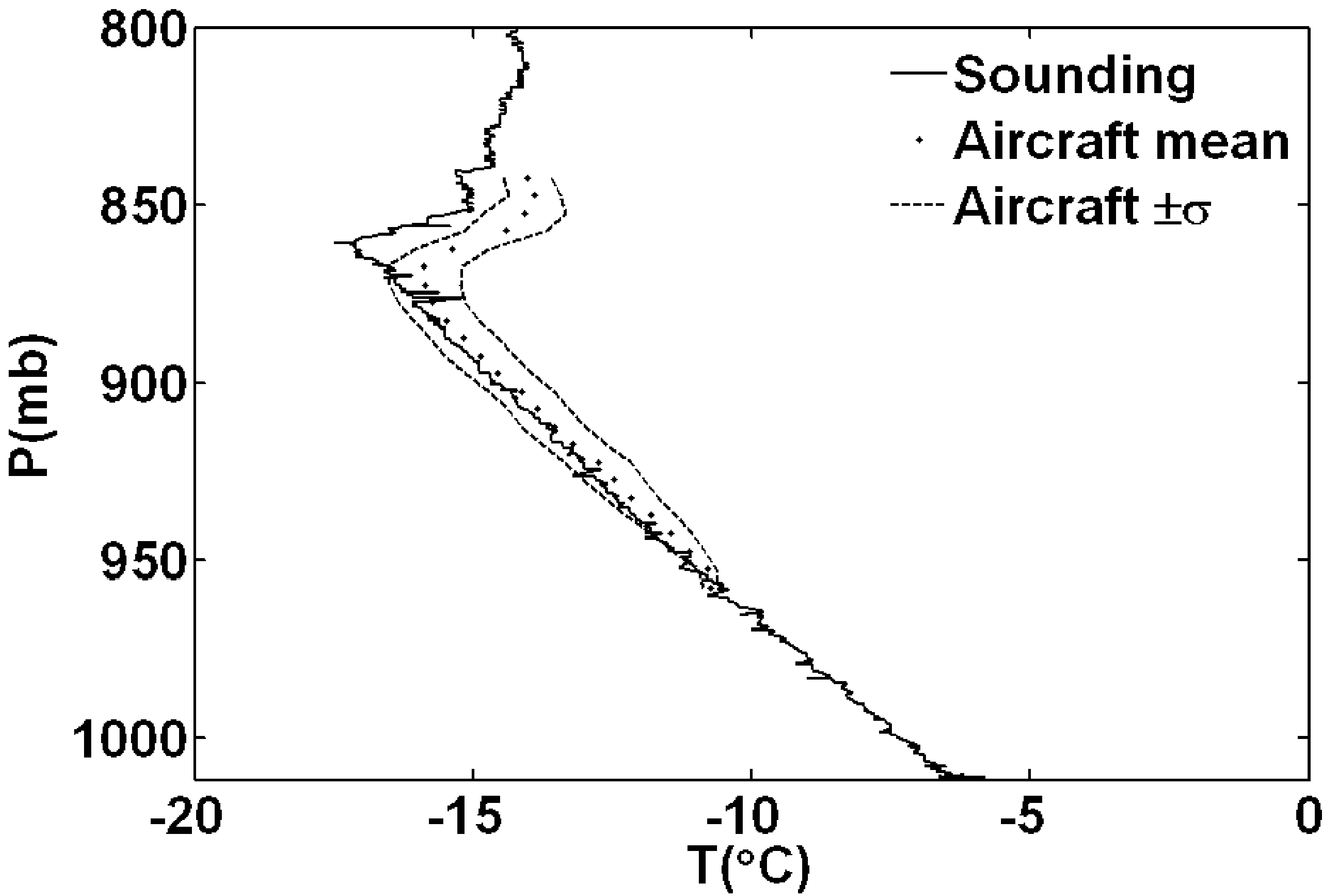
Crystals with D < 50 μm not included in Ni

Summary

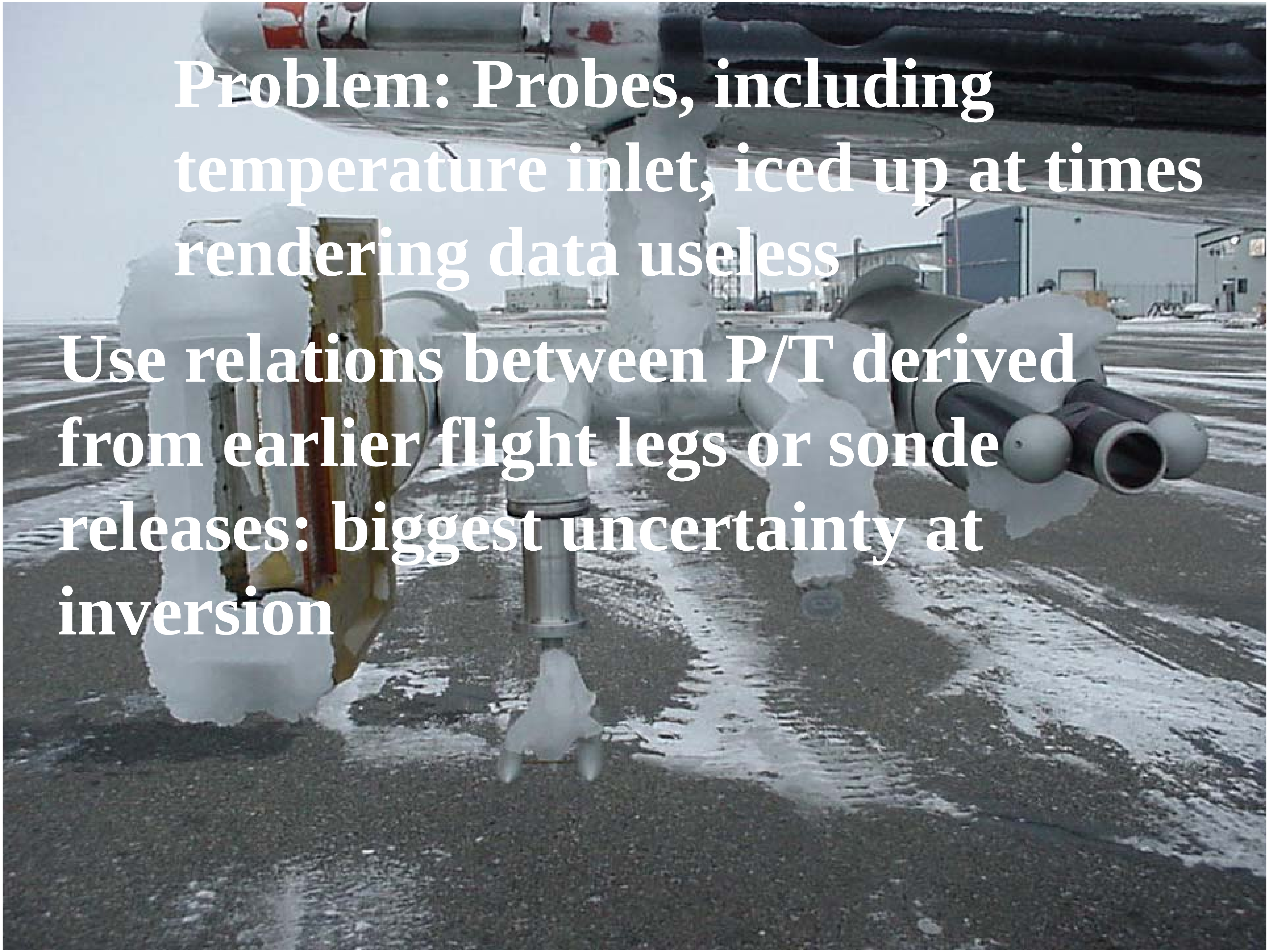
- **Unique set of in-situ data acquired during MPACE**
  - **Useful for model and remote sensing evaluation, and for parameterization development**
- **Single-layer clouds have consistent structure**
  - **Ice more important near cloud base, but occurs in patches throughout cloud**
  - **Growth of liquid through the cloud**
  - **Liquid topped clouds precipitating ice**
- **But, be aware of uncertainties when numerically comparing these data against model findings!**

Example of multi-layer mixed-phase cloud from 10/06



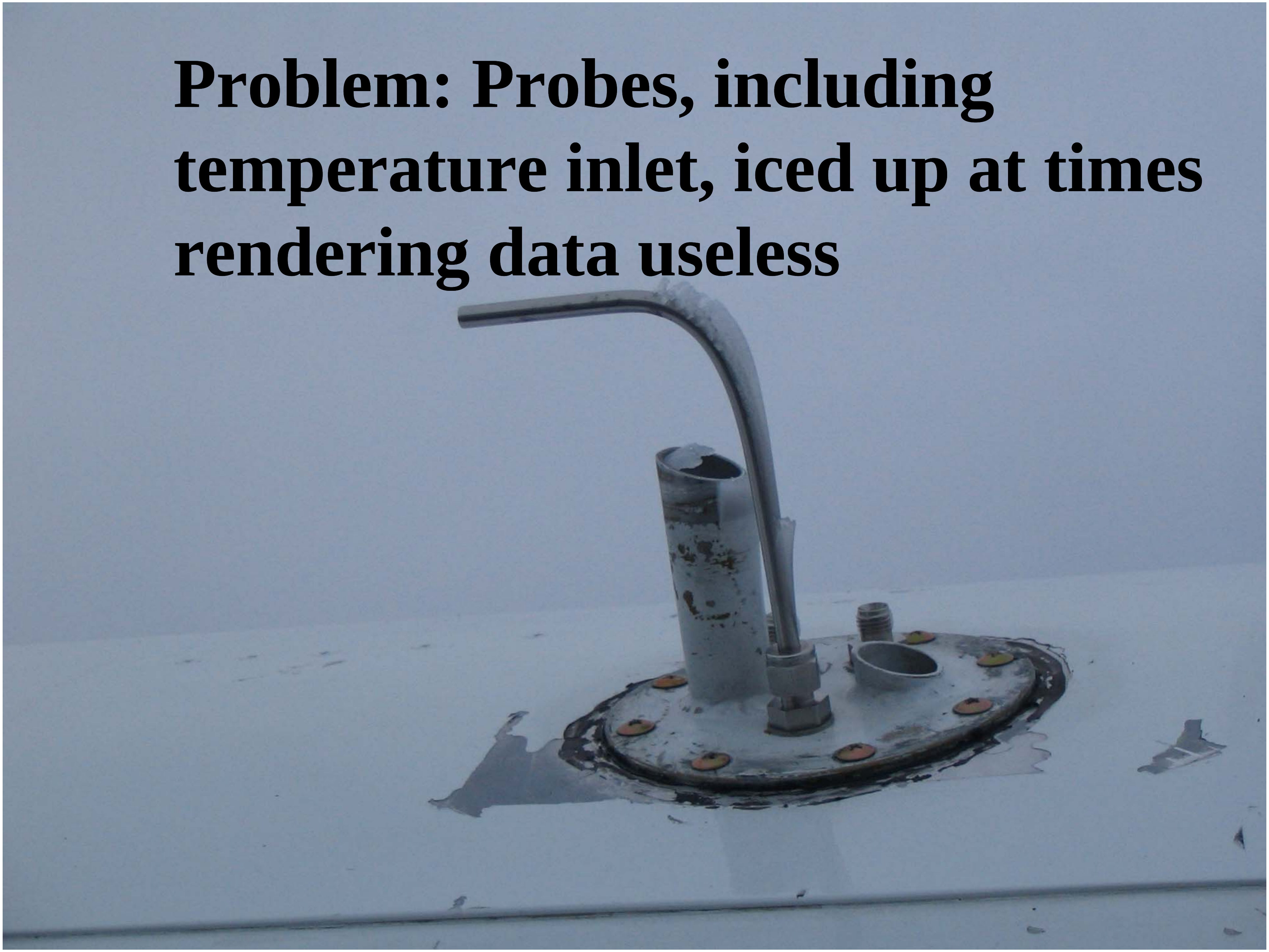


When no temperature data, use data from earlier aircraft spirals or ground-site soundings. Biggest inaccuracy around inversion



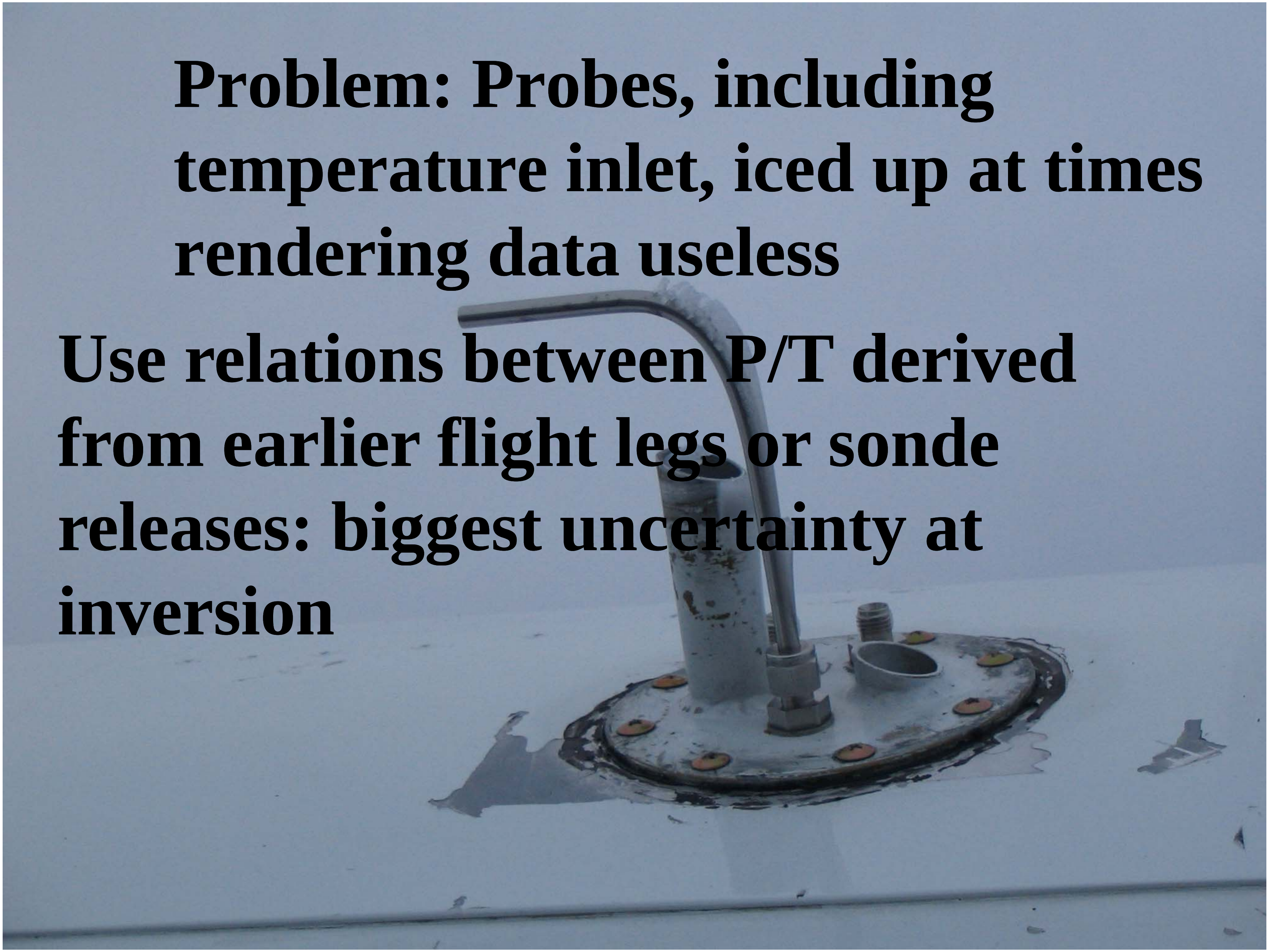
Problem: Probes, including temperature inlet, iced up at times rendering data useless

Use relations between P/T derived from earlier flight legs or sonde releases: biggest uncertainty at inversion


Problem: Probes, including temperature inlet, iced up at times rendering data useless

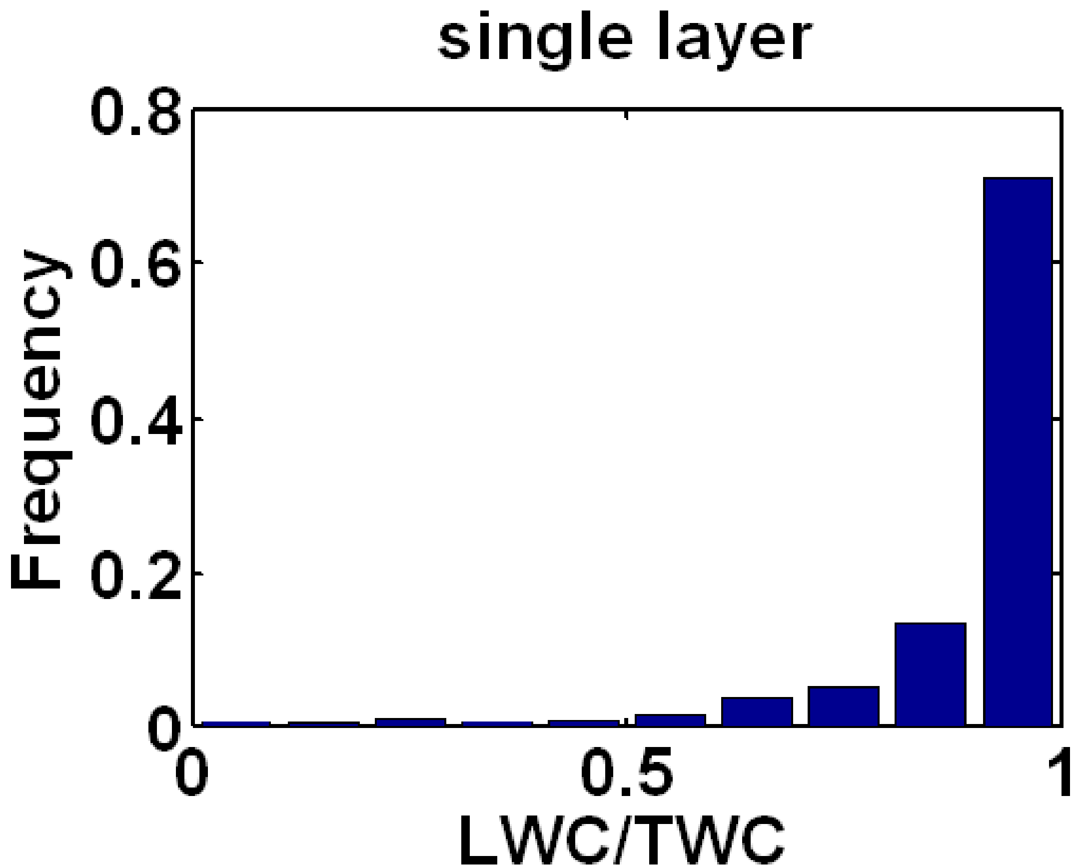
Problem: Probes, including temperature inlet, iced up at times rendering data useless

Use relations between P/T derived from earlier flight legs or sonde releases: biggest uncertainty at inversion

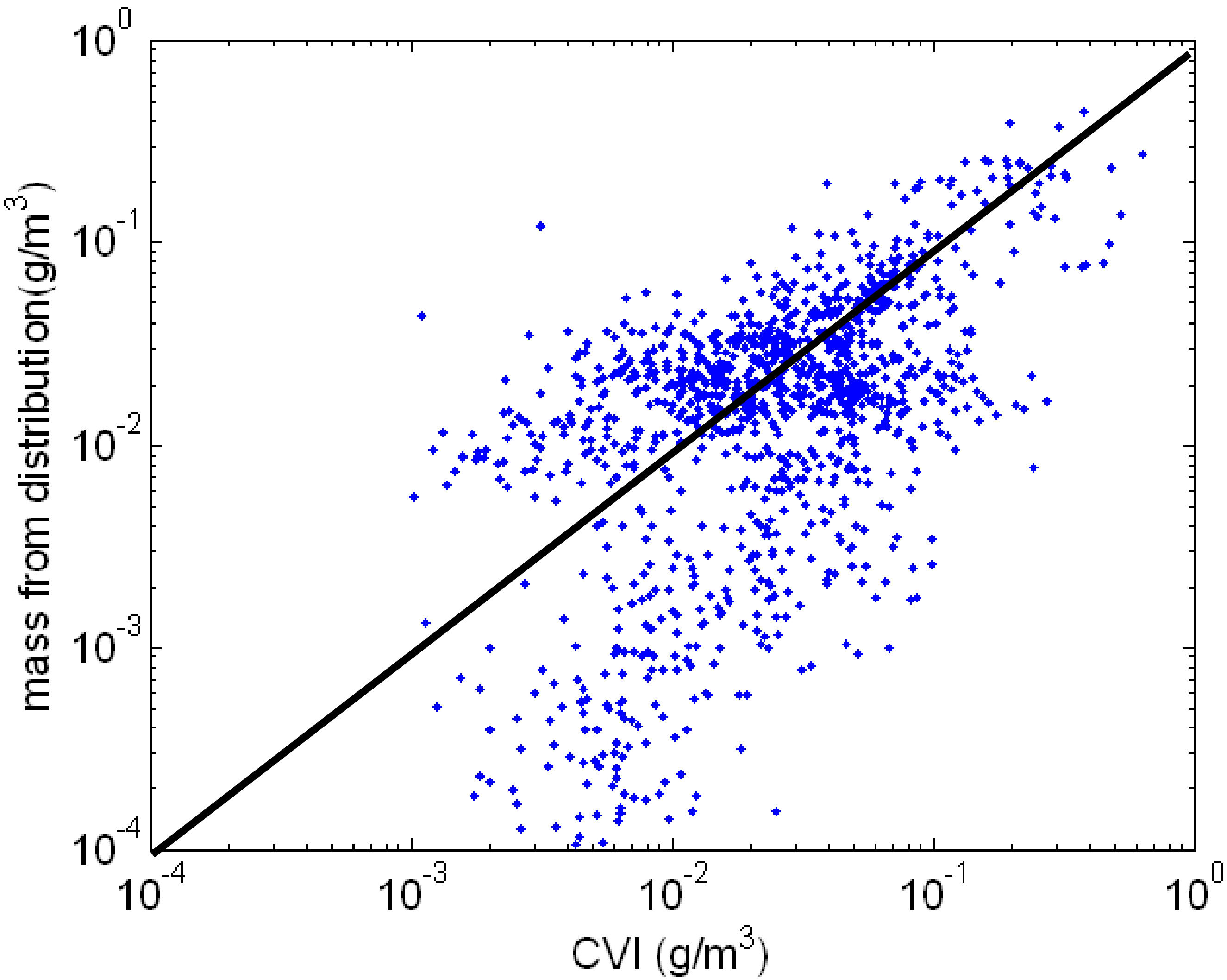


Problems/Uncertainties in M-PACE Data

1. **Estimate cloud base & cloud top**
2. **Temperature in cloud**



Consistent with previous studies, mixed-phase clouds are heavily dominated by water



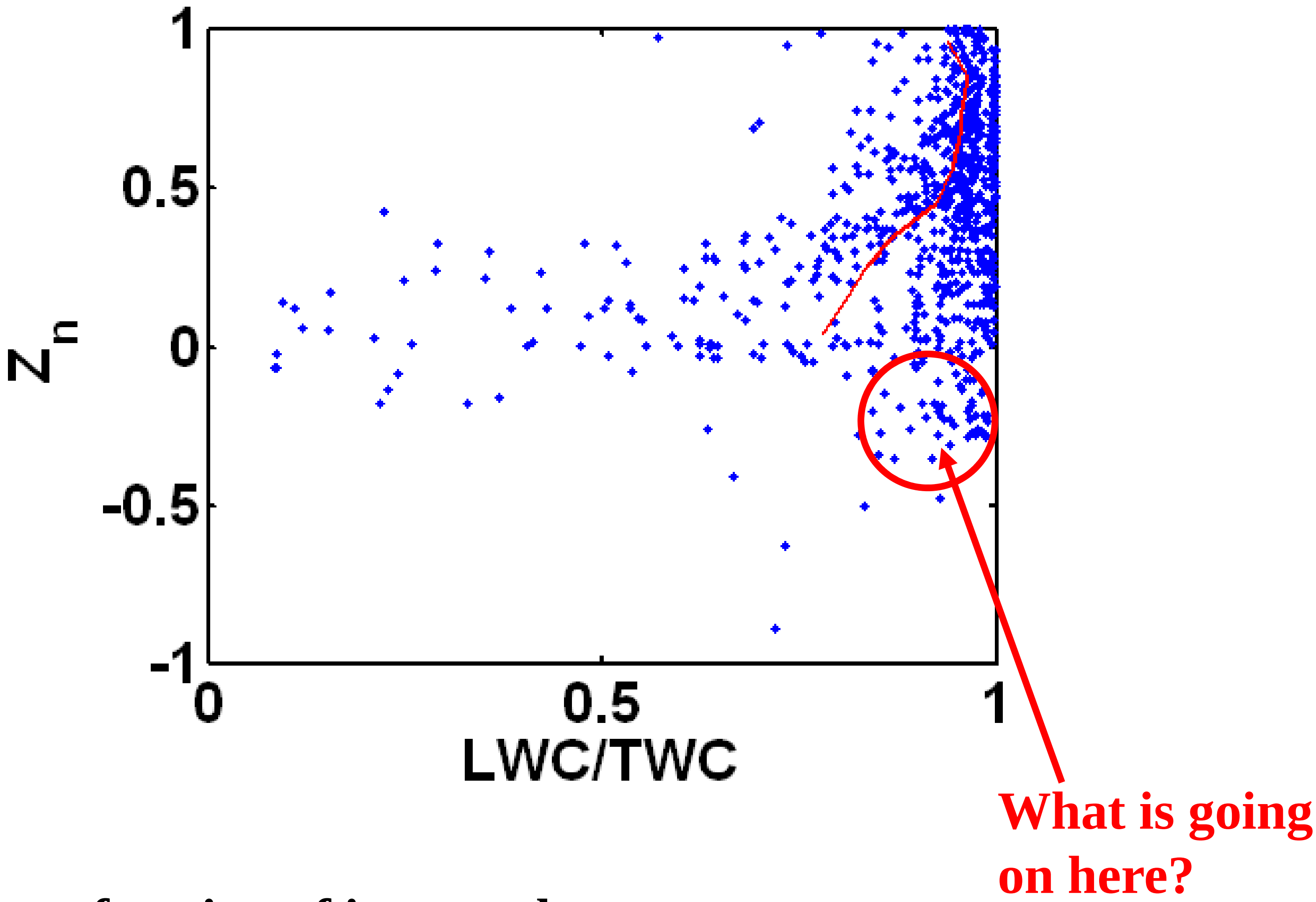
Get good agreement between CVI and SDs for ice-phase events

Note: SDs underestimate IWC from CVI by factor of ~ 2

Assume (a,b) for ice clouds applies to ice in mixed-phase clouds

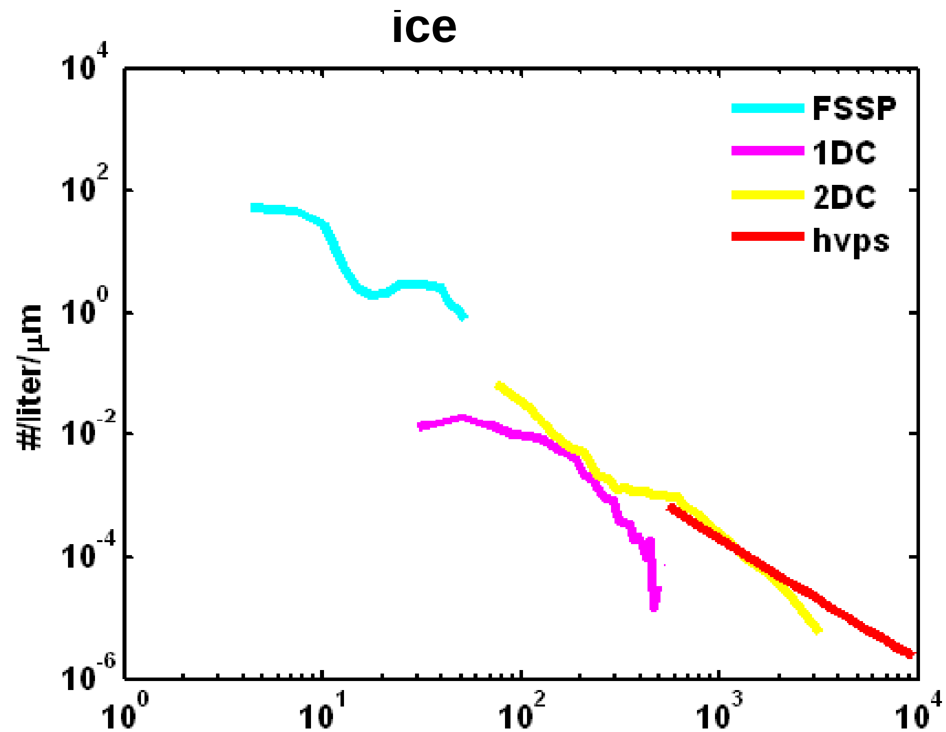
Multi-layer mixed-phase clouds

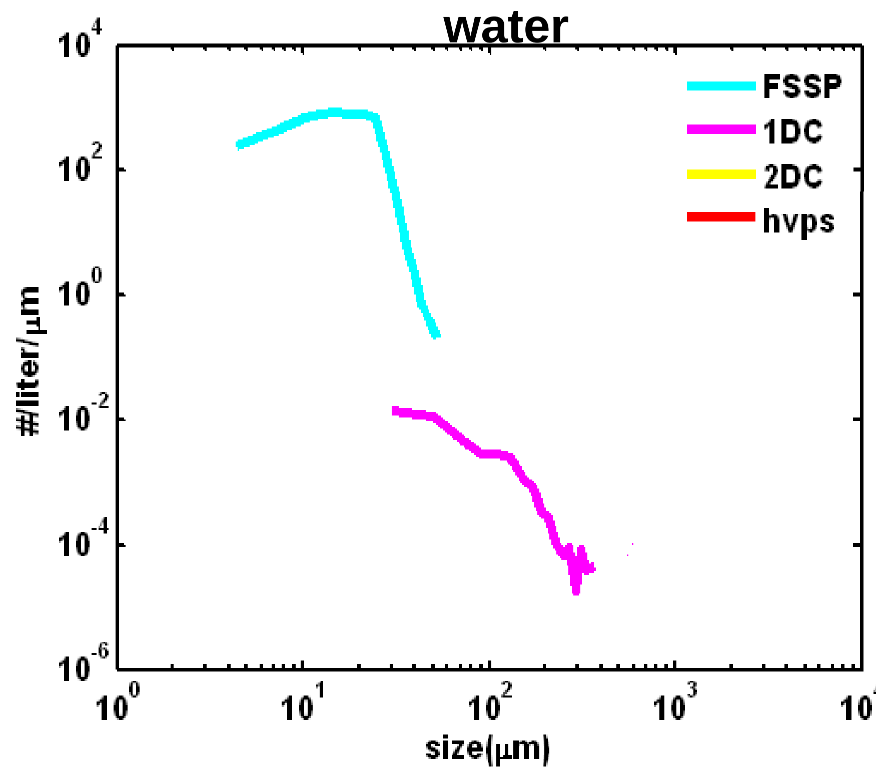
- Not easy to represent rew, rei, Nt, Ni as function of zn
- How do we represent properties of these clouds?
- Zhang et al. (2007) describe the properties in terms of fl=LWC/TWC
  - But, that will be a talk for another day

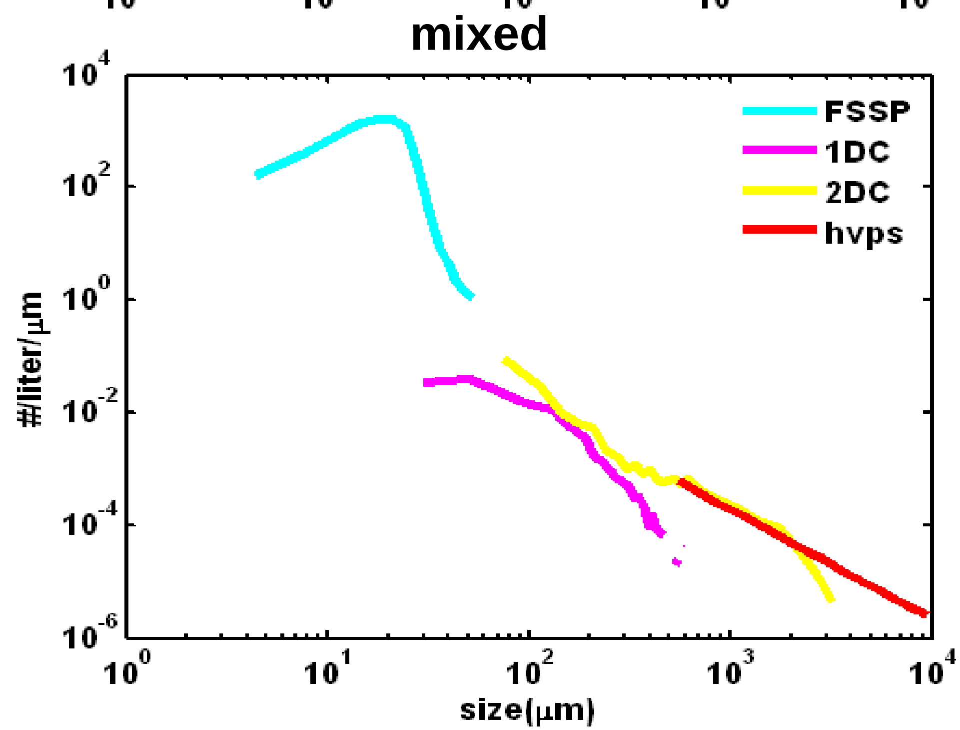


Greater fraction of ice near base

Liquid dominated top, precipitating ice below

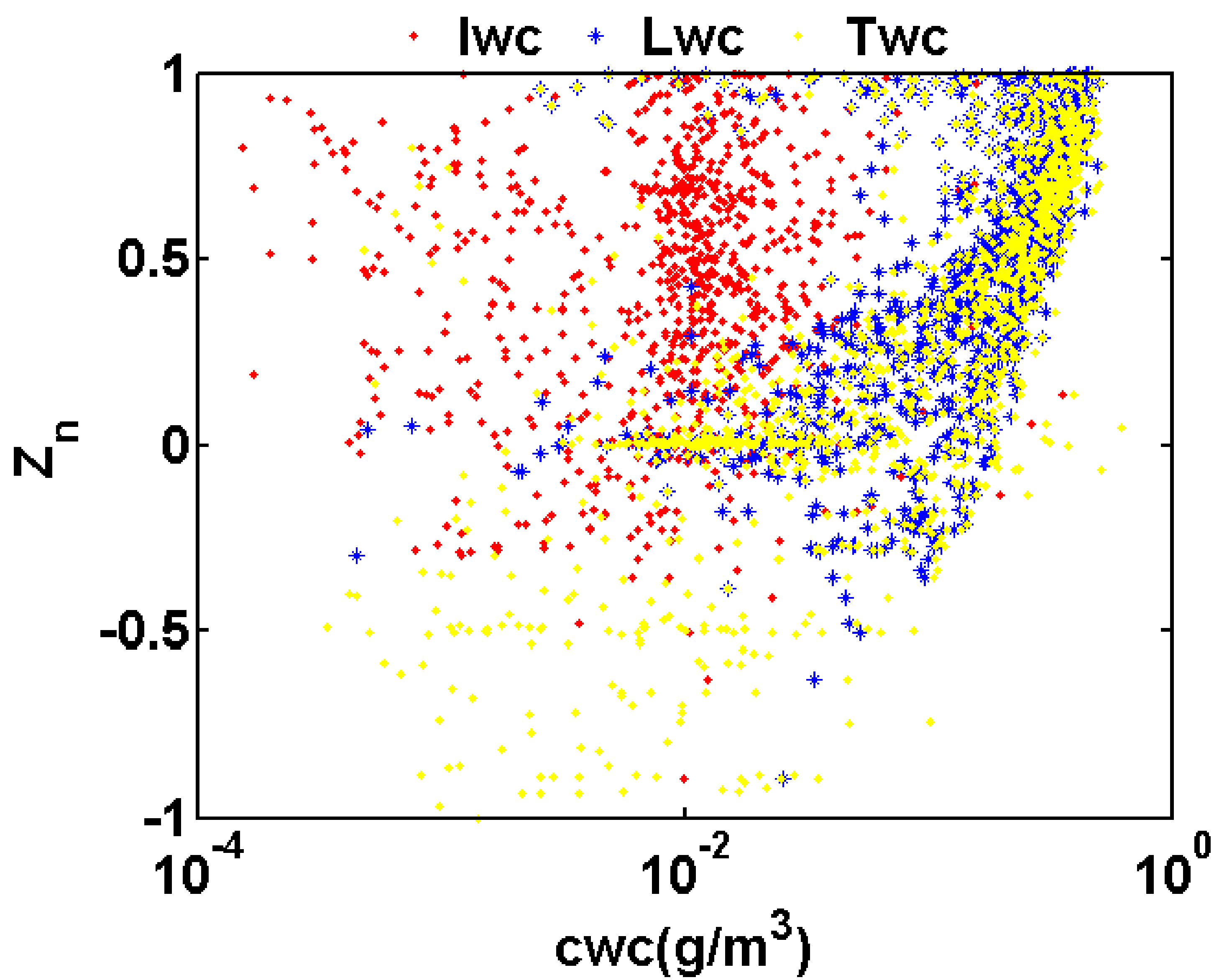






For cases with no HVPS data (e.g., Oct. 9b), we perform fits to 2DC data and extrapolate to larger sizes

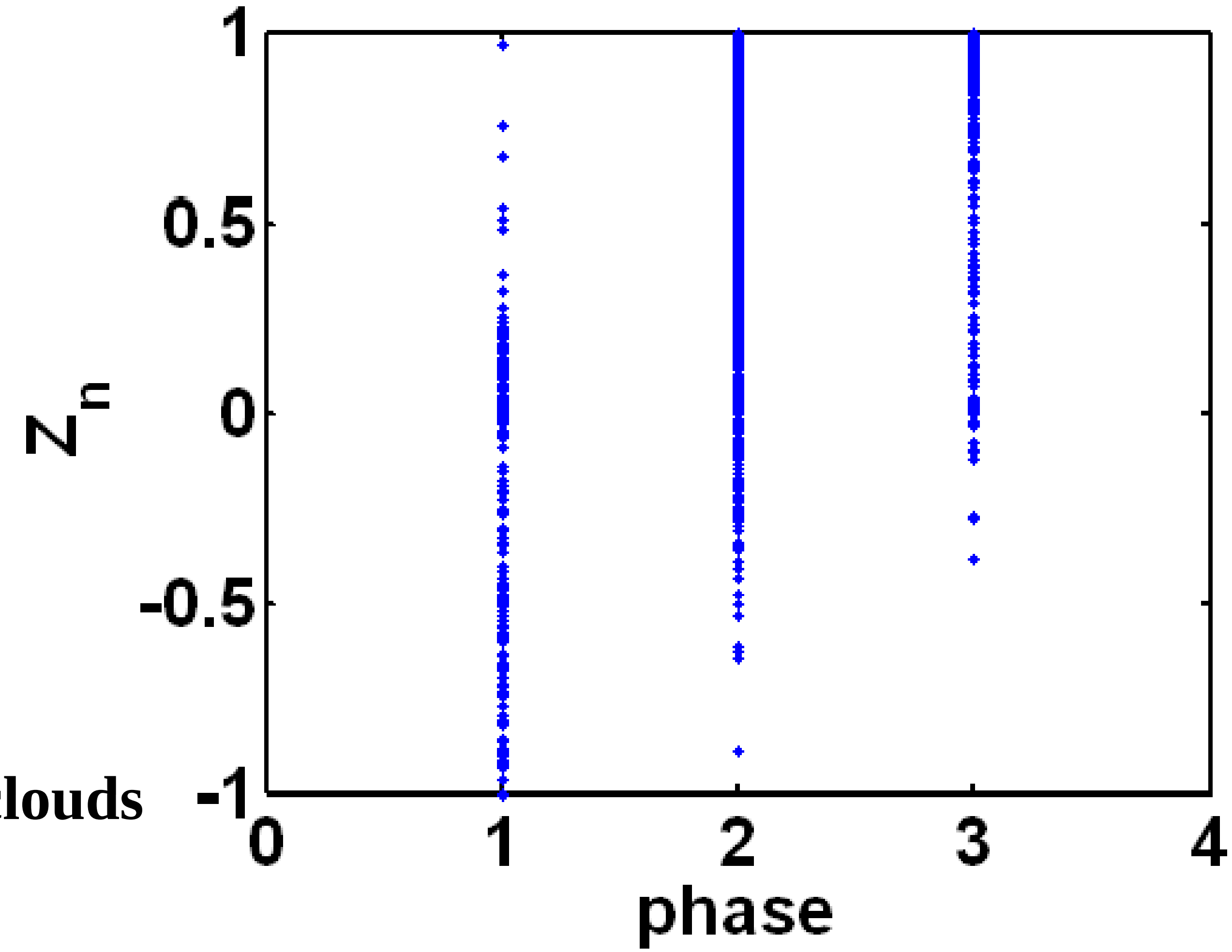
→ May reduce variability



Large fl fraction for zn < -1 does not indicate lots of water

IWC is relatively invariant with zn; LWC depends on zn

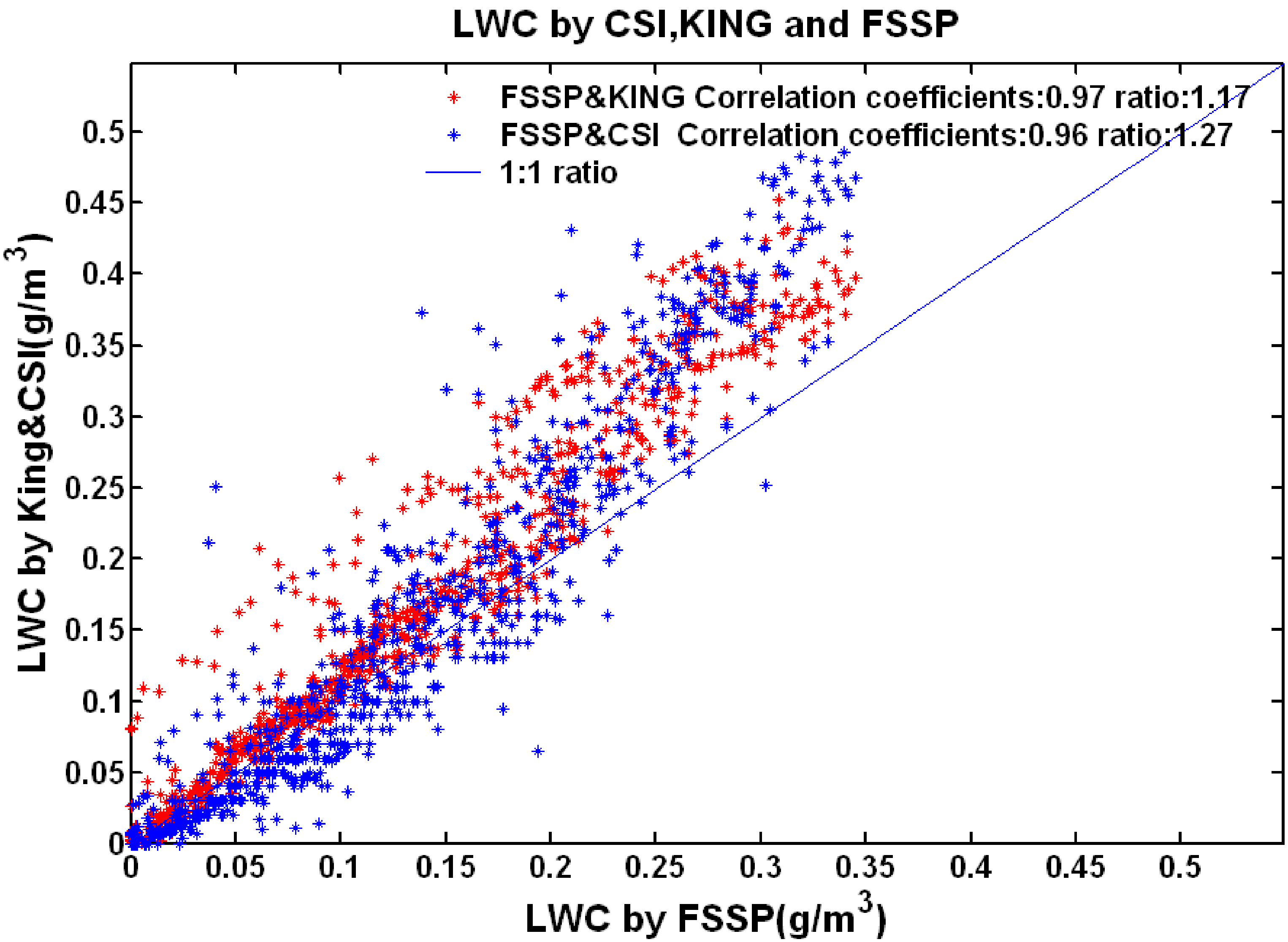
Vertical Profile of Phase



1: ice clouds

2: mixed-phase clouds

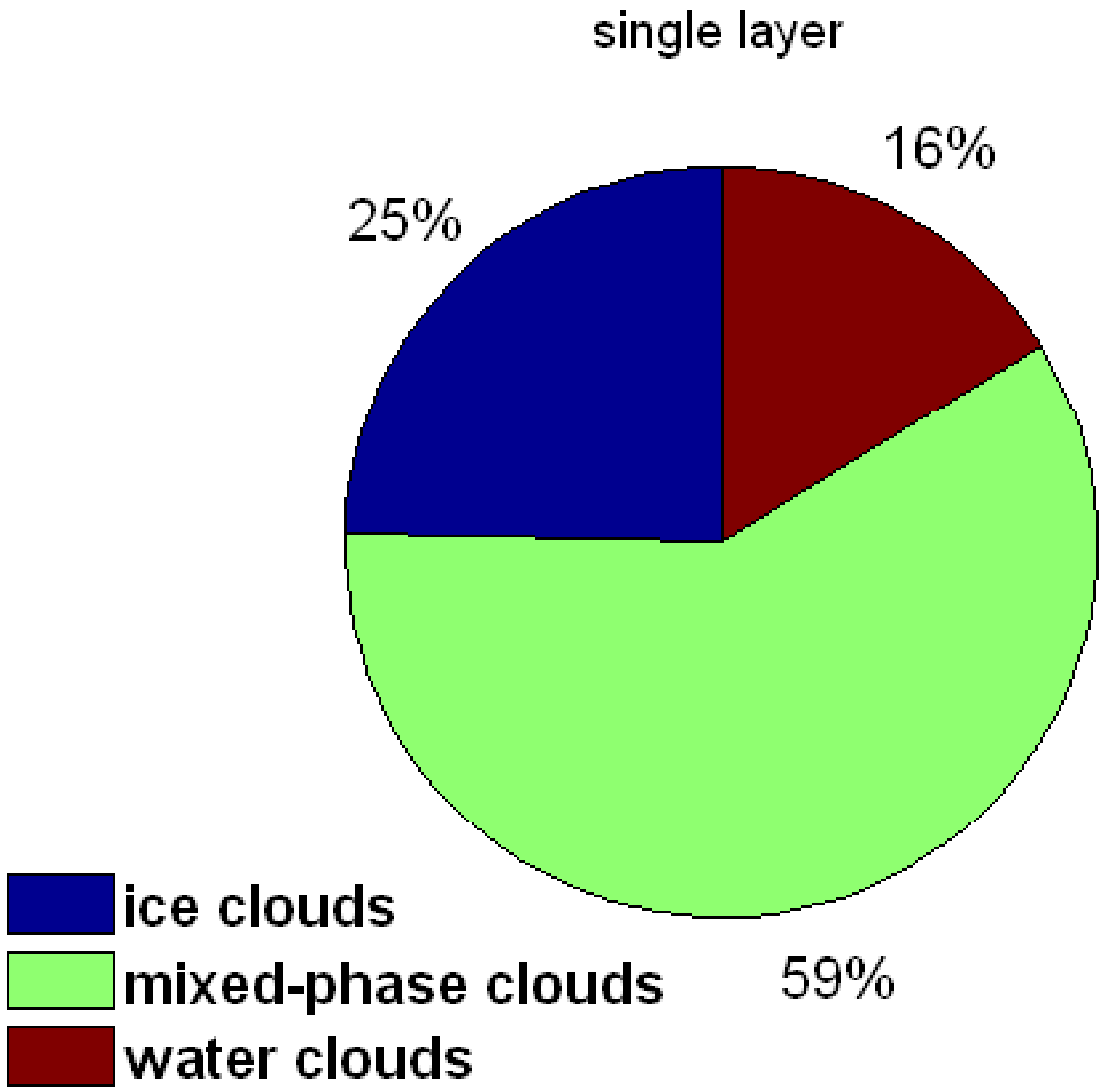
3: water clouds



Comparison of bulk water in liquid clouds

Agreement within 15% for LWC < 0.2 g m^{-3}

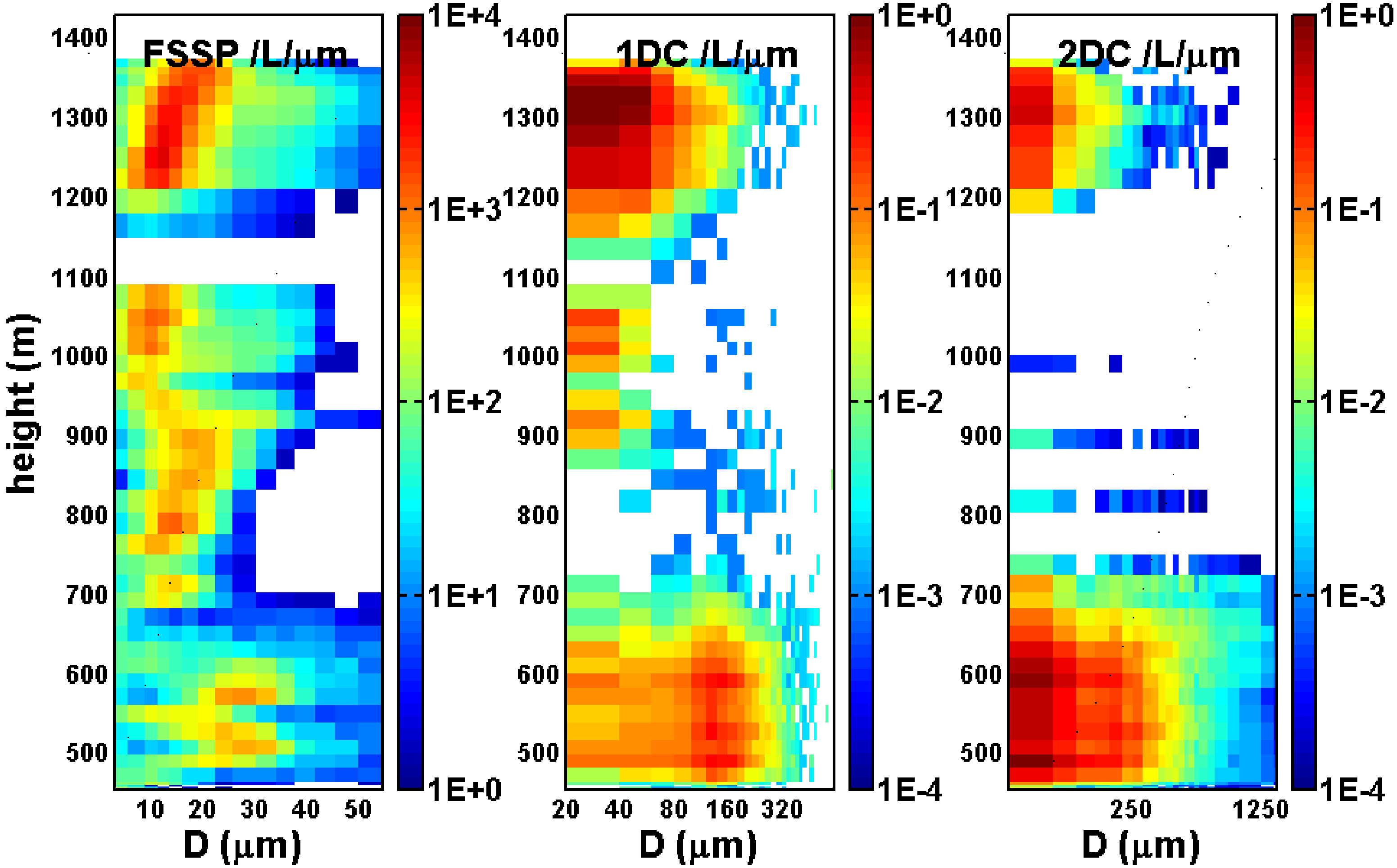
FSSP underestimates King/CSI LWC by ~25% for LWC > .2 g m^{-3}



Total frequency of occurrence of different cloud types

Citation Instrumentation

Instrument	Derived Parameters	Nominal Range	Comments
FSSP	PSDs, N_t, LWC	1 – 55 μm	Uncertain in mixed-phase
1DC	PSDs, N_t, LWC	20 –620 μm	Use between 50-120 μm
CPI	Images (2.3 μm resolution); habits	15-2000 μm	Small sample volume
2DC	PSDs, N_t, LWC/ IWC, images	32-960 μm	125 < D > 960 μm
HVPS	PSDs, N_t, LWC/ IWC, images	400 – 40000 μm	D > 960 μm
DMT CSI	TWC	Bulk measure	
King	LWC	Bulk measure	
RICE	Supercooled H_2O	Presence	

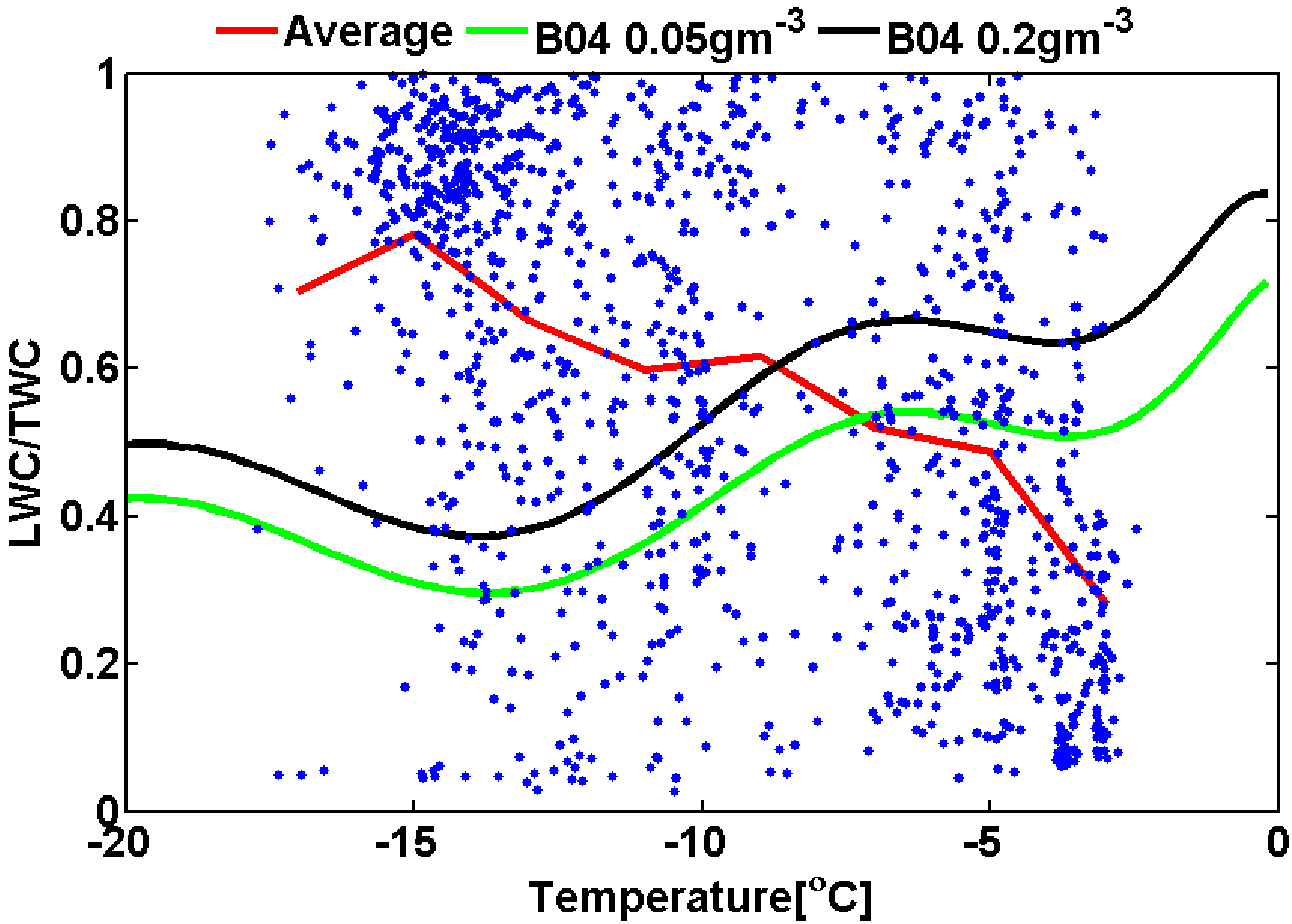


Multi-layer cases observed on Oct. 5th are more complex and don't yield simple patterns

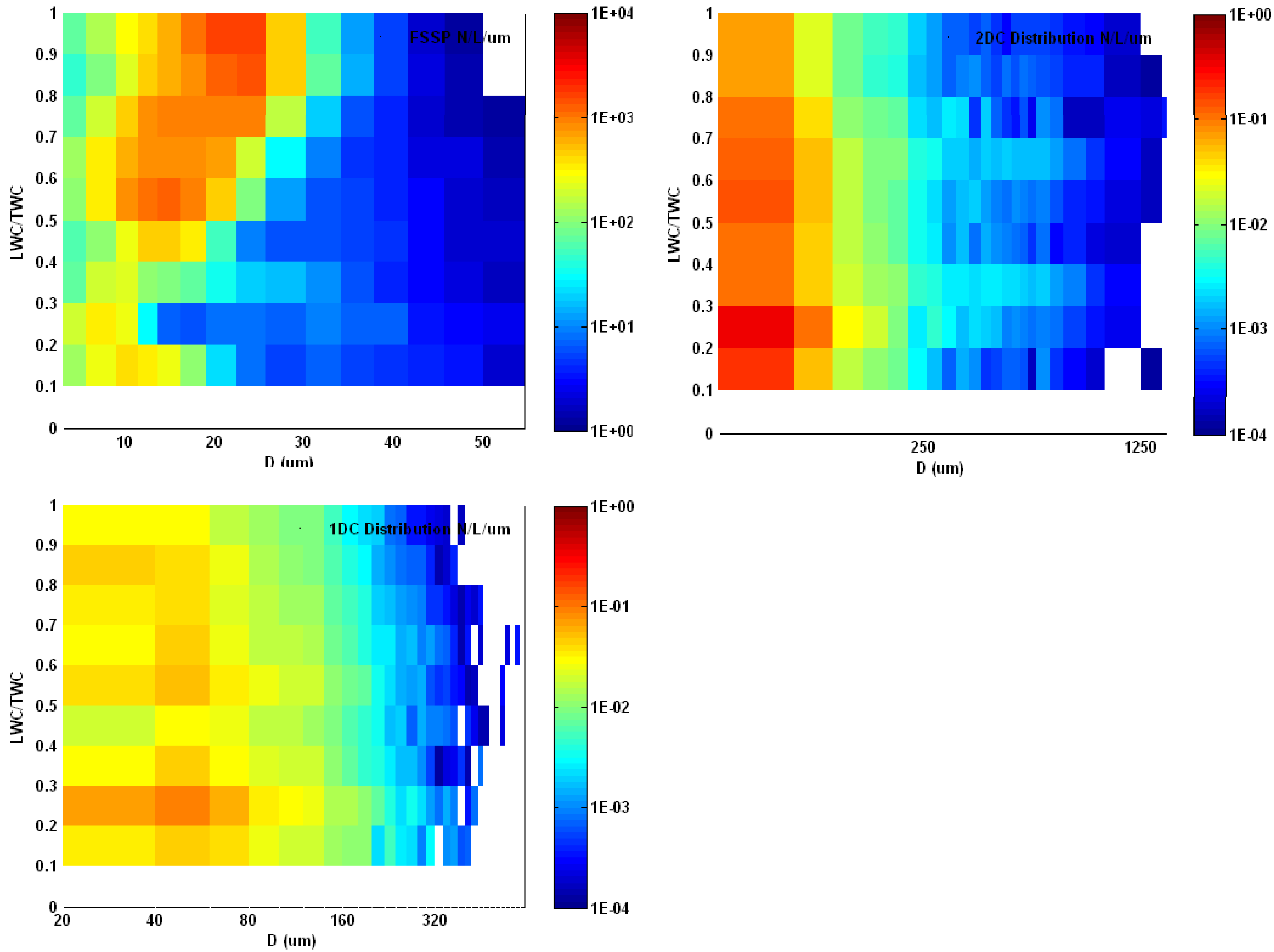
How do we represent these properties for comparison with models? Statistics and how properties depend on LWC/TWC

Variability of concentration between single-layer cases

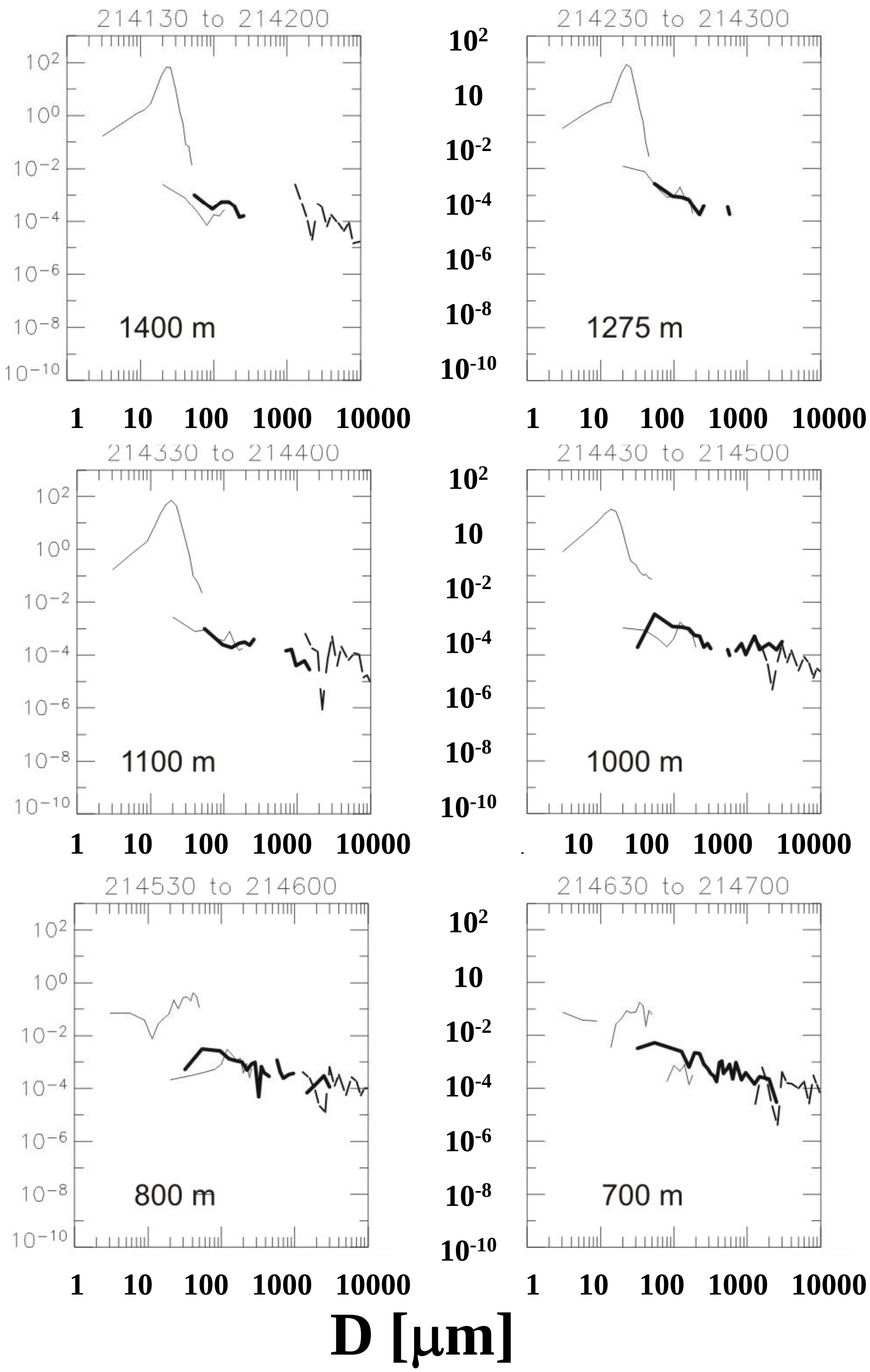
	N_w [cm^{-3}]	N_i [cm^{-3}]
10/09 a	20.46	0.0395
10/09 b	7.342	0.1014
10/10	6.240	0.1579
10/12	21.04	0.0156



Large-scale parameterization does not represent these Arctic clouds



FSSP N/L/um
LWC/TWC
D (um)
1E+04
1E+03
1E+02
1E+01
1E+00
2DC Distribution N/L/um
LWC/TWC
D (um)
250
1250
1E+00
1E-01
1E-02
1E-03
1E-04
1DC Distribution N/L/um
LWC/TWC
D (um)
20
40
80
160
320
1E+00
1E-01
1E-02
1E-03
1E-04

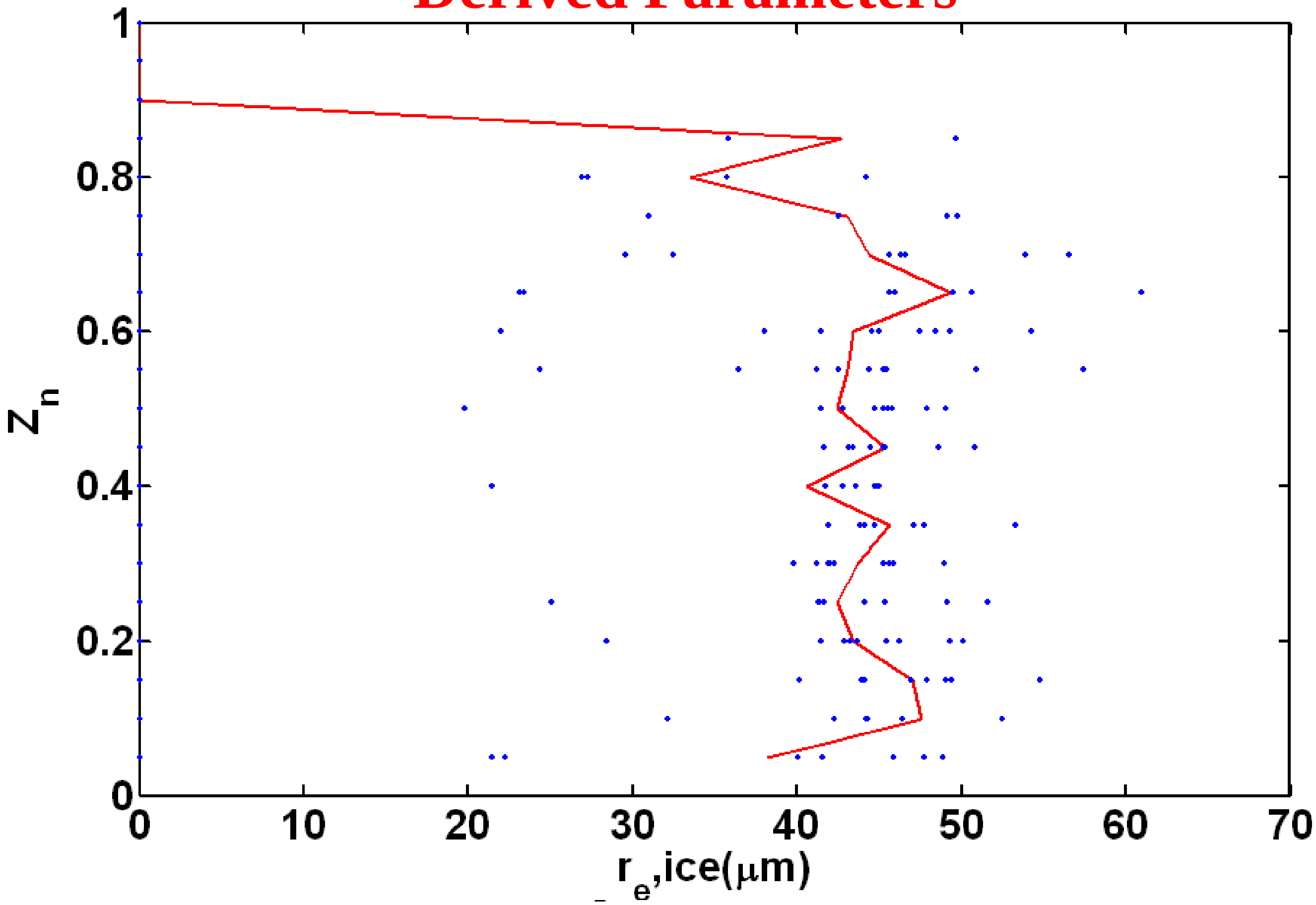


How do microphysics properties vary in the vertical?

In general, more liquid near the tops and more ice near the bottom but lots of variation between the cases

Example from Oct. 10

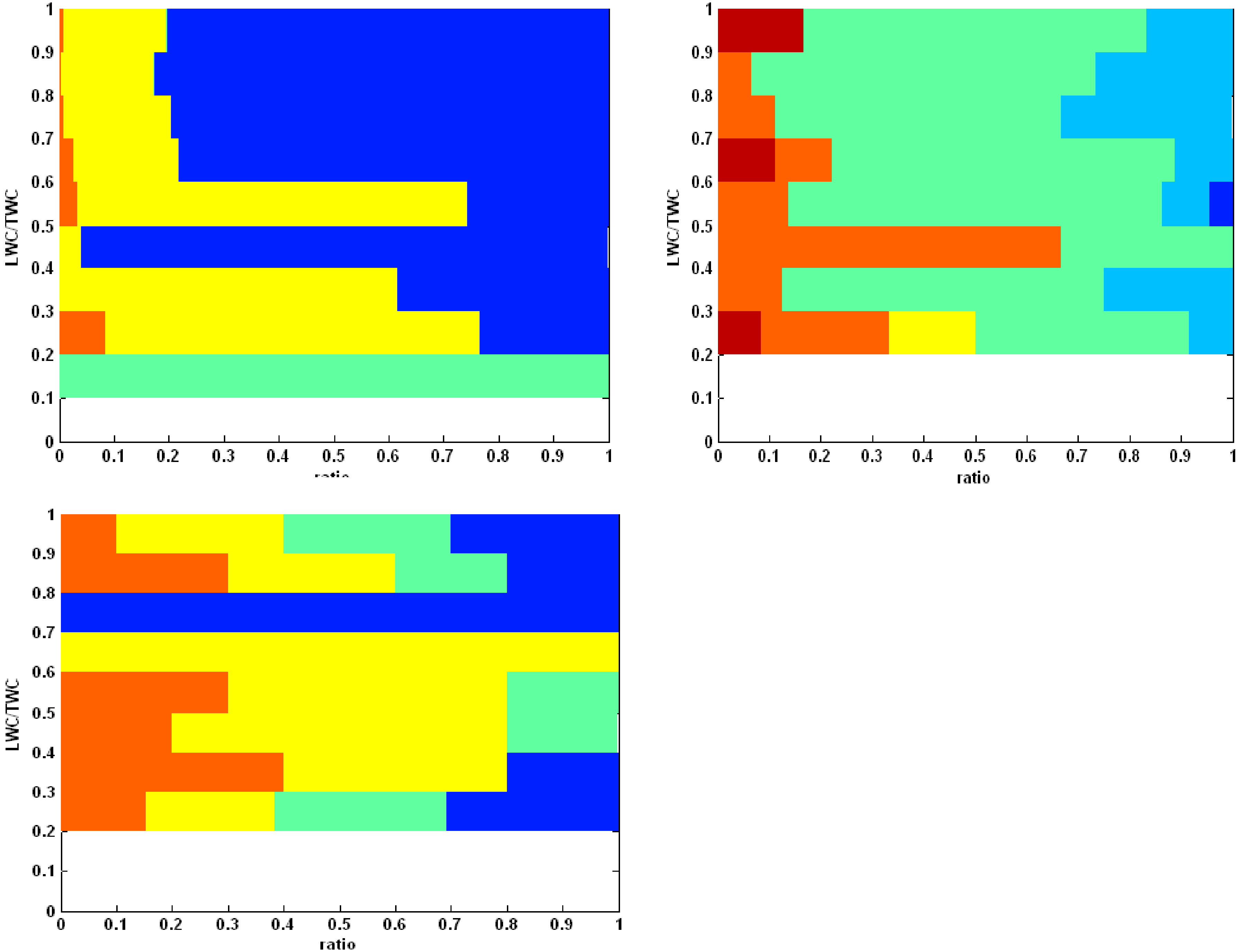
Derived Parameters

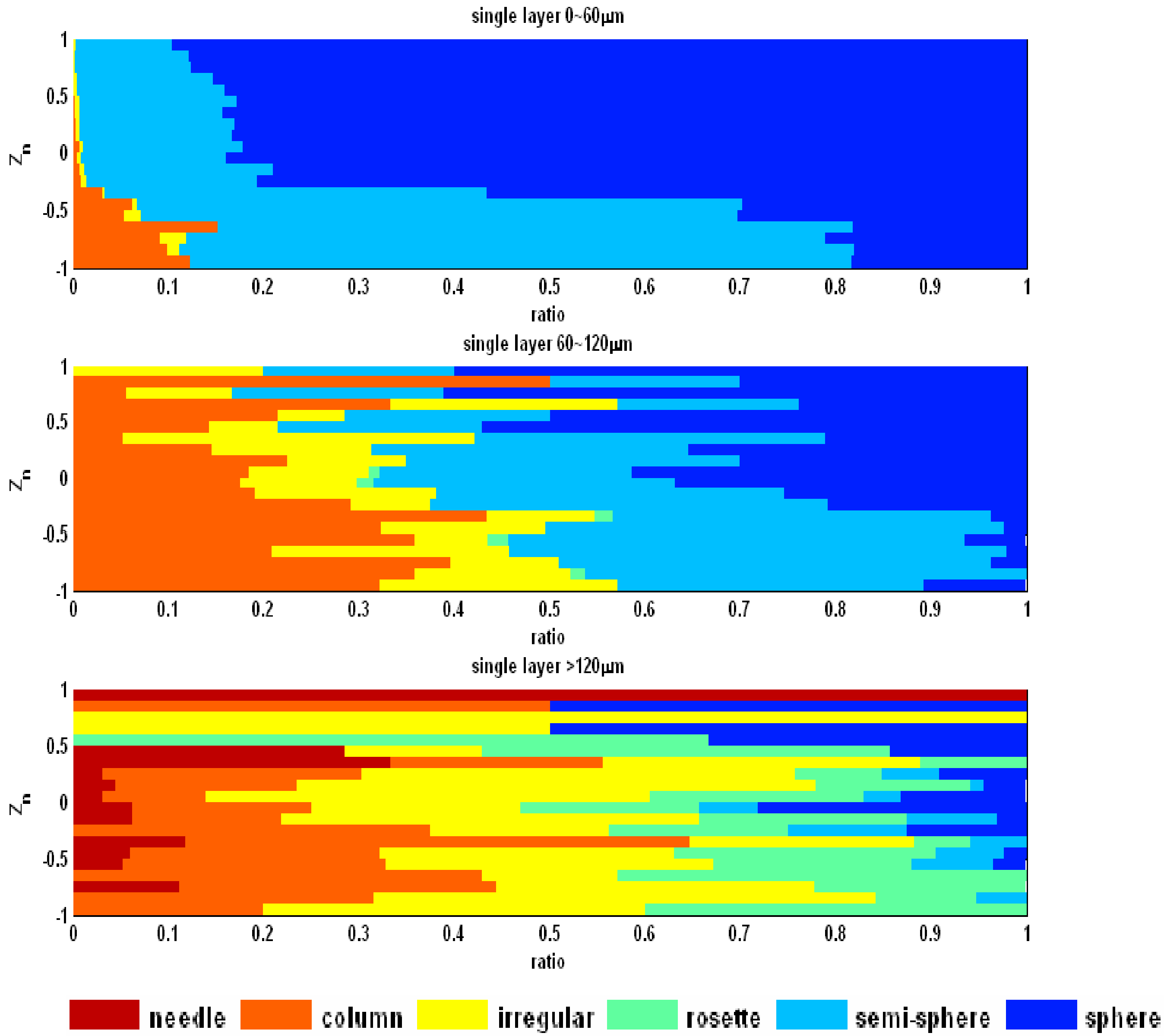


TWC measured by bulk CSI probe

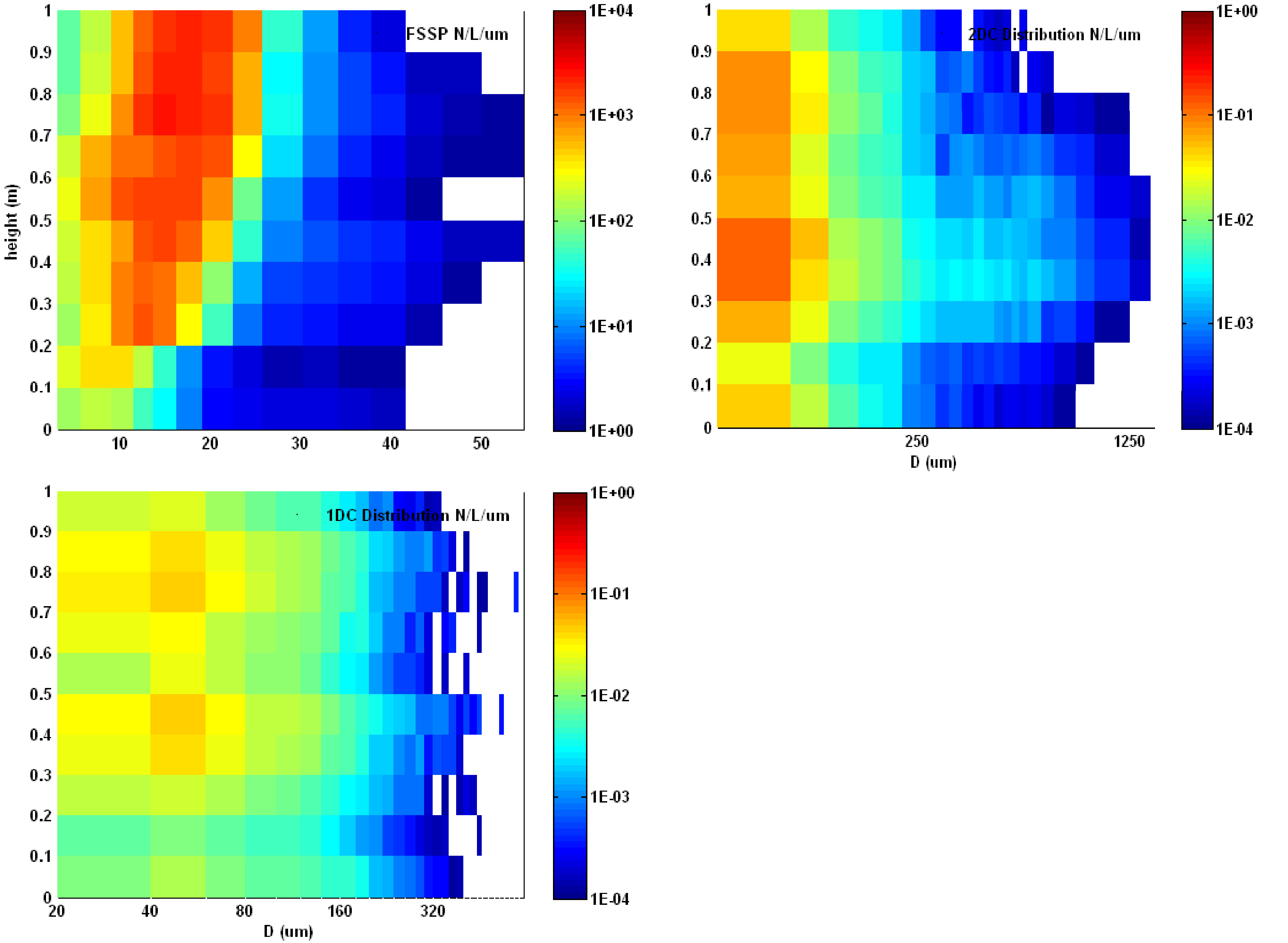
Single Layer Clouds: Vertical profiles of IWC/TWC, $r_{e,water}$ and $r_{e,ice}$ in terms of normalized altitude (Z_n) show some consistency

Greater fraction of ice near base; bigger water drops near top; ice size relatively invariant throughout cloud depth


LWC/TWC
ratio
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Also get information on dependence of particle shape with zn for different particle sizes

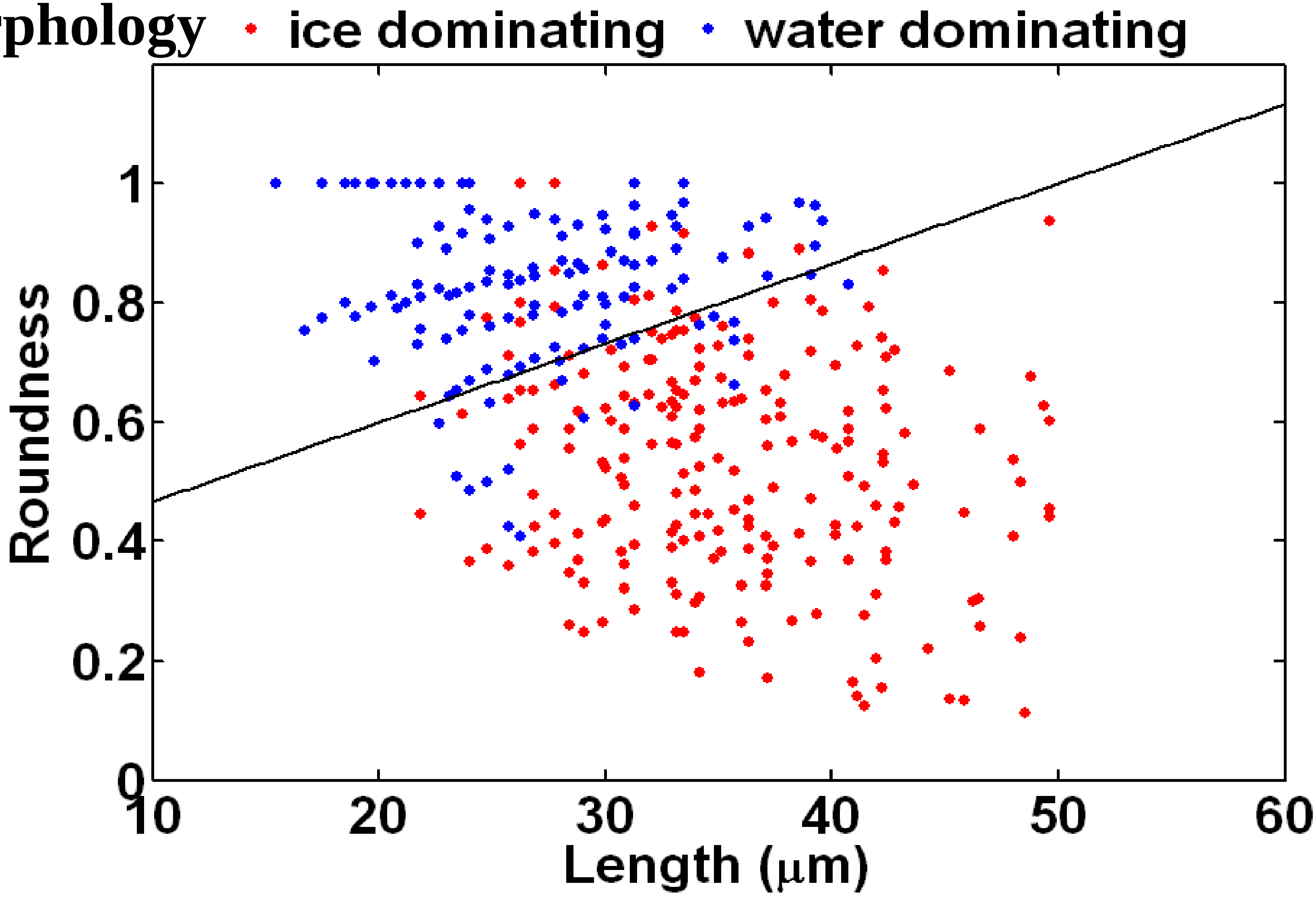


FSSP N/L/um
height (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
1E+04
1E+03
1E+02
1E+01
1E+00
2DC Distribution N/L/um
250
1250
D (um)
1E+00
1E-01
1E-02
1E-03
1E-04
1DC Distribution N/L/um
20
40
80
160
320
D (um)
1E+00
1E-01
1E-02
1E-03
1E-04

Can the CPI distinguish water and ice for D < 50 μm?

1. **Use ice & water dominated scenes**

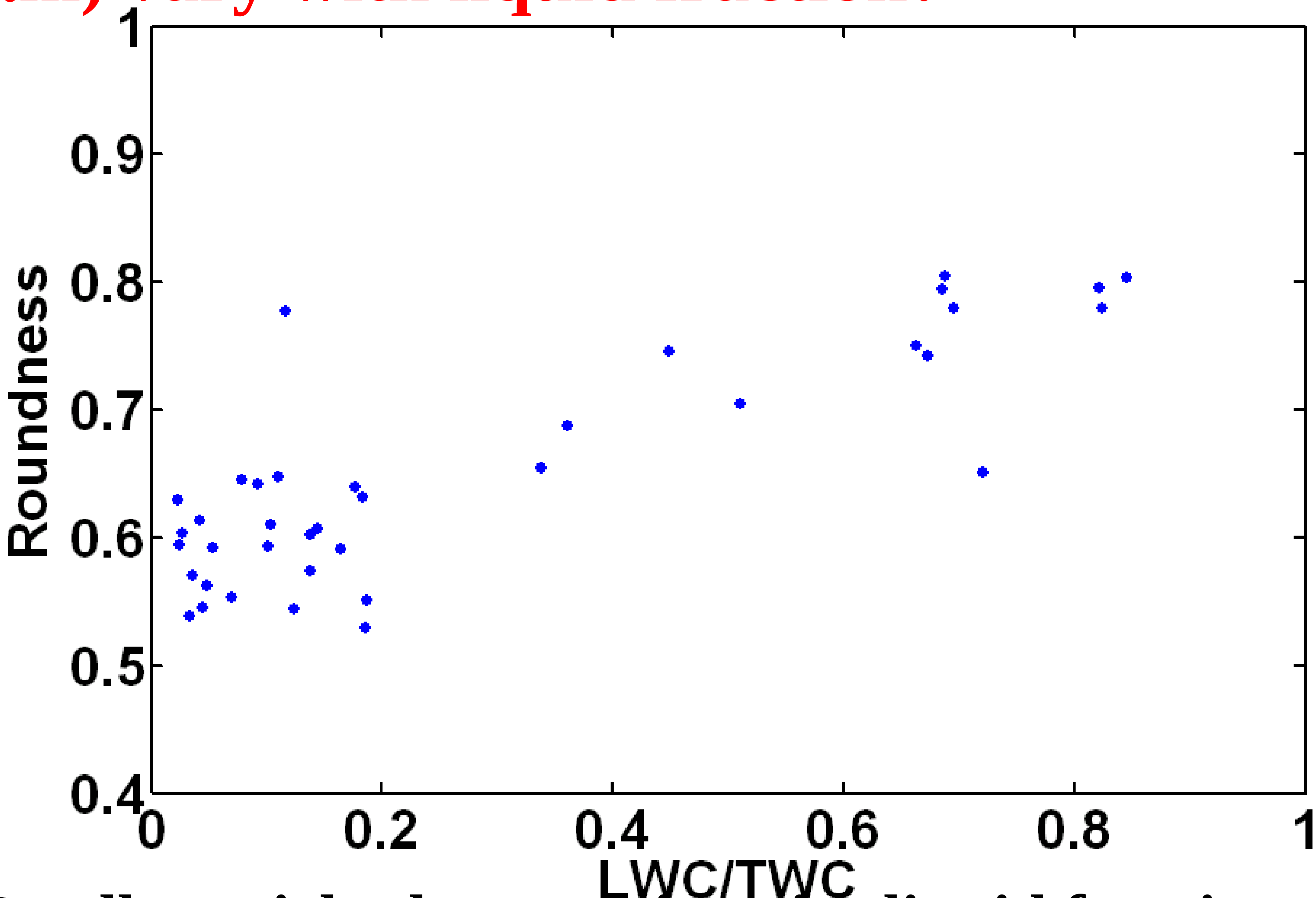
2. Determine roundness of each CPI image using particle morphology



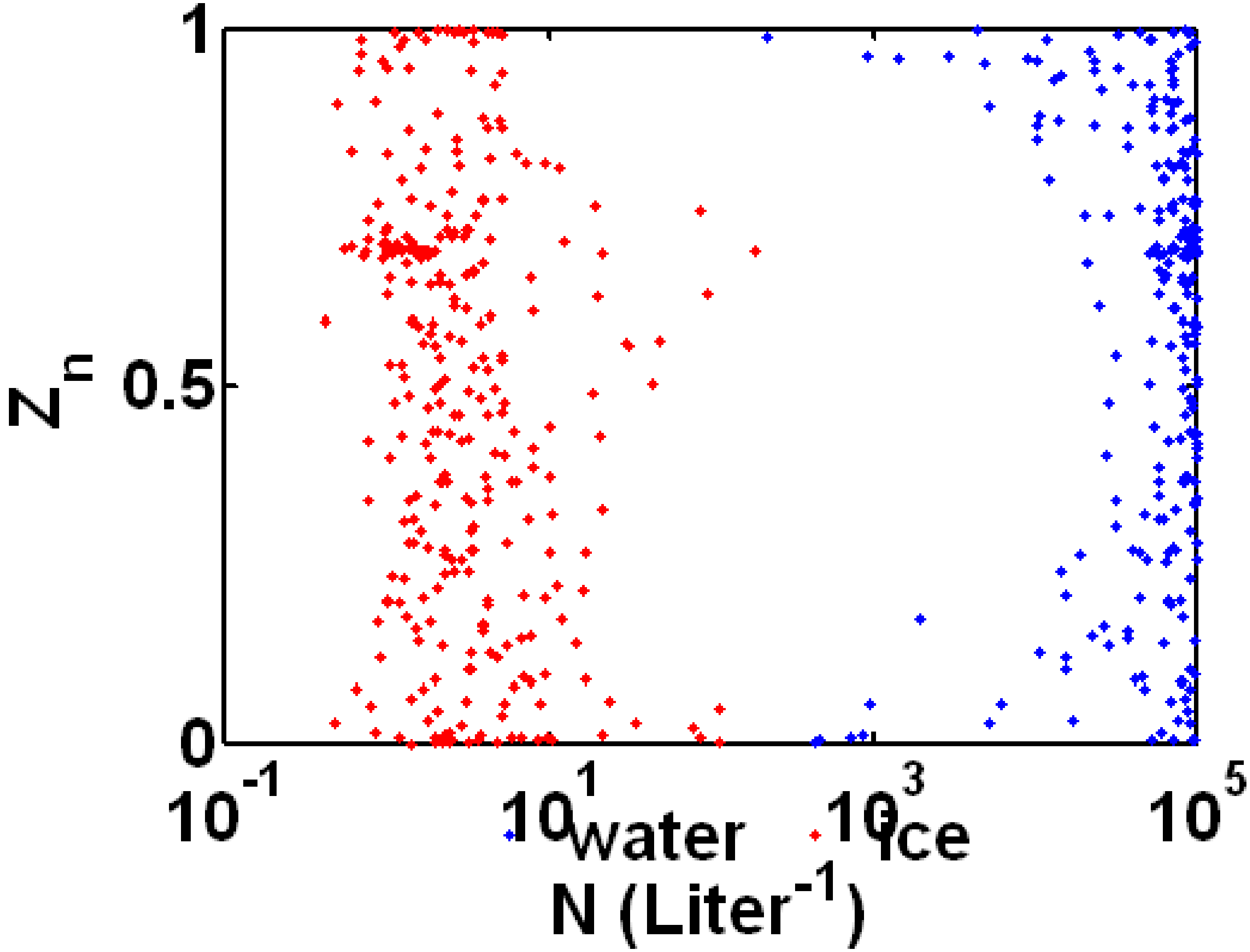
M-PACE - summary

1. Sept. 27 – Oct. 22, 2004
2. 13 Citation research flights:
   - 6 multi-layer,
   - 5 BL stratus,
   - 2 Cirrus
3. 5 Proteus flights
4. Ground-based remote sensing sites
   - Barrow NSA site
   - Oliktok Point (PARSL)

How does average shape of small particles (D < 50 μm) vary with liquid fraction?



Small particle shape varies with liquid fraction → FSSP not all water when LWC/TWC < 0.5

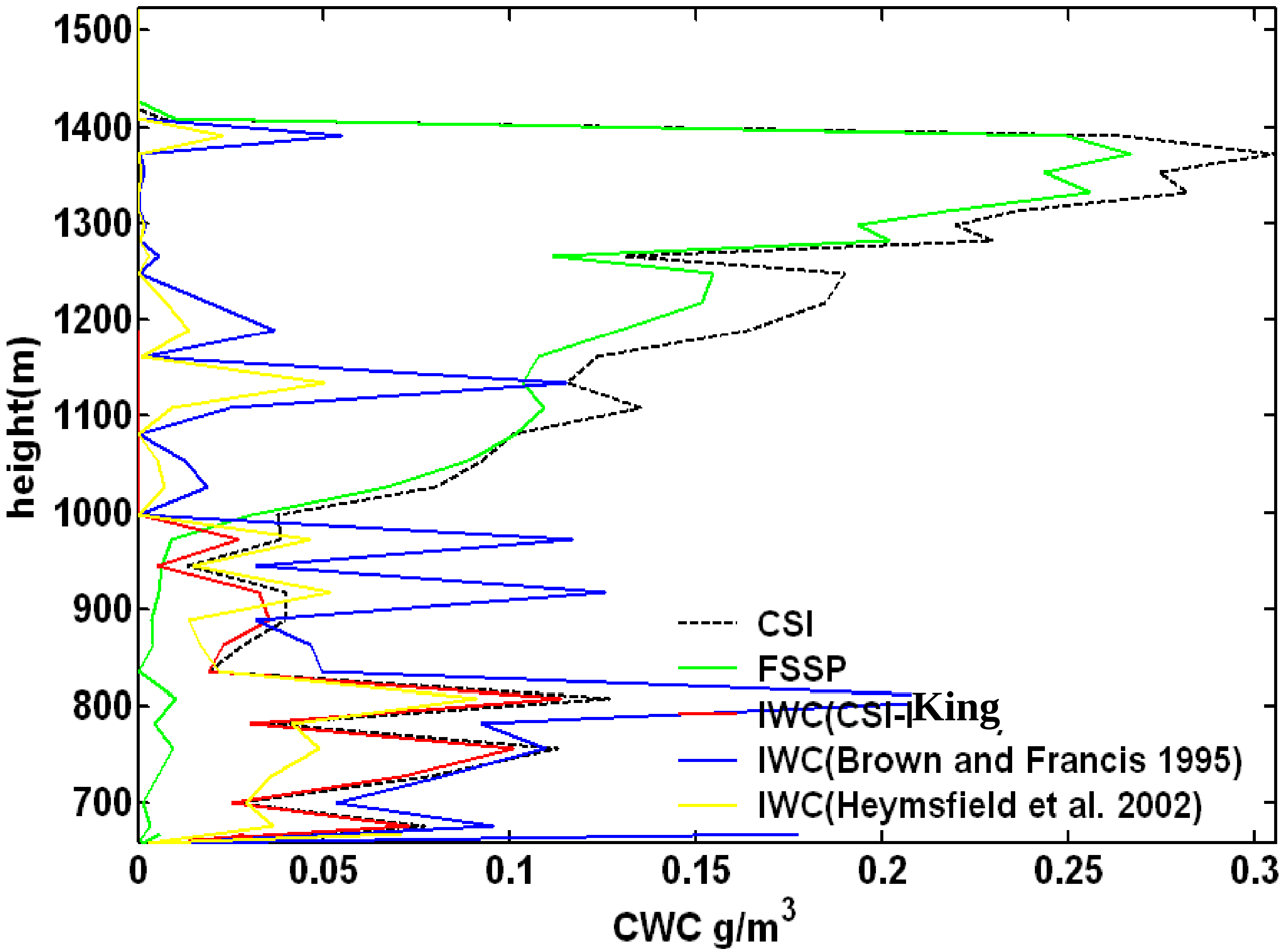


N not strong function of zn for either water or ice

There are some variations between different dates

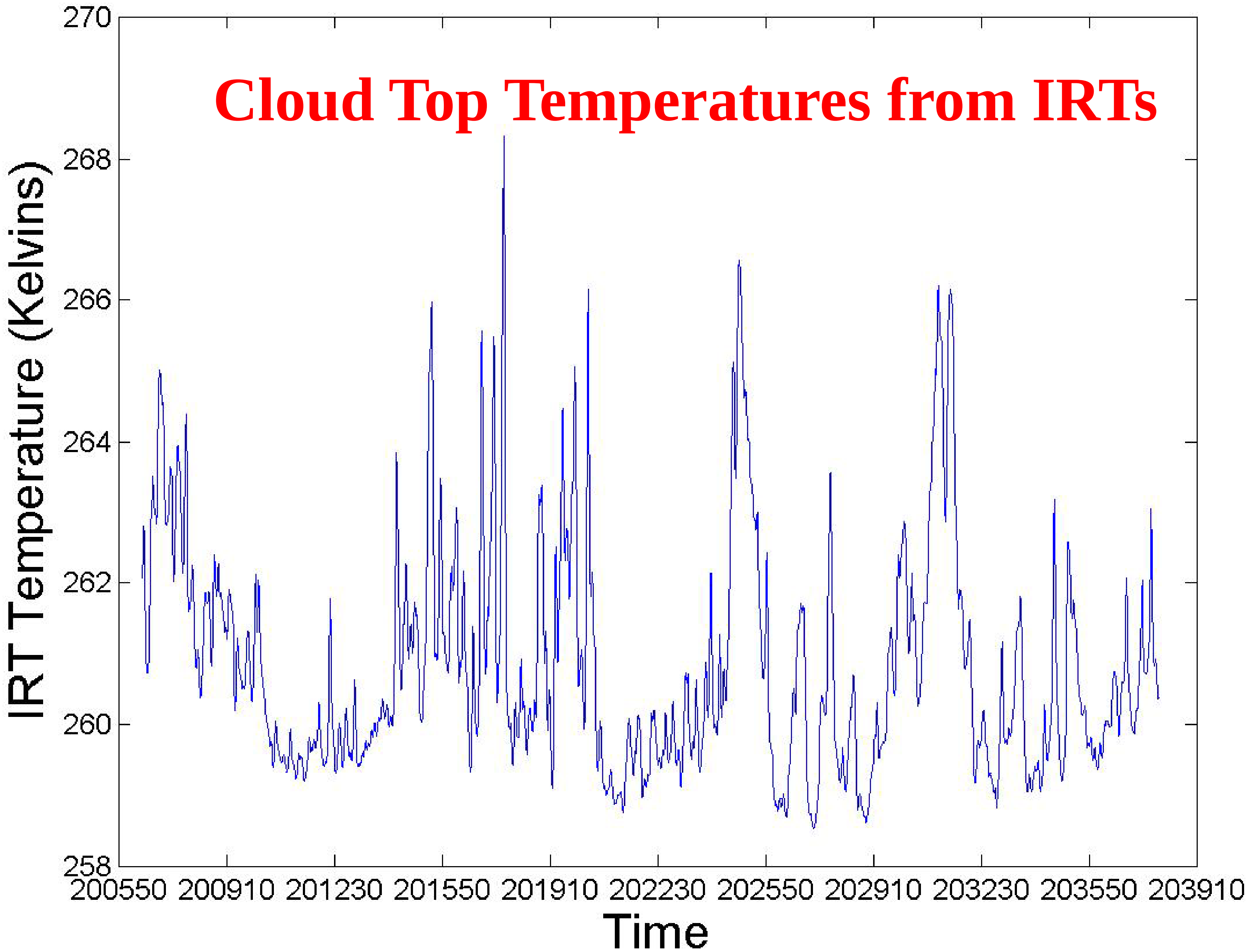
Proteus Instrumentation

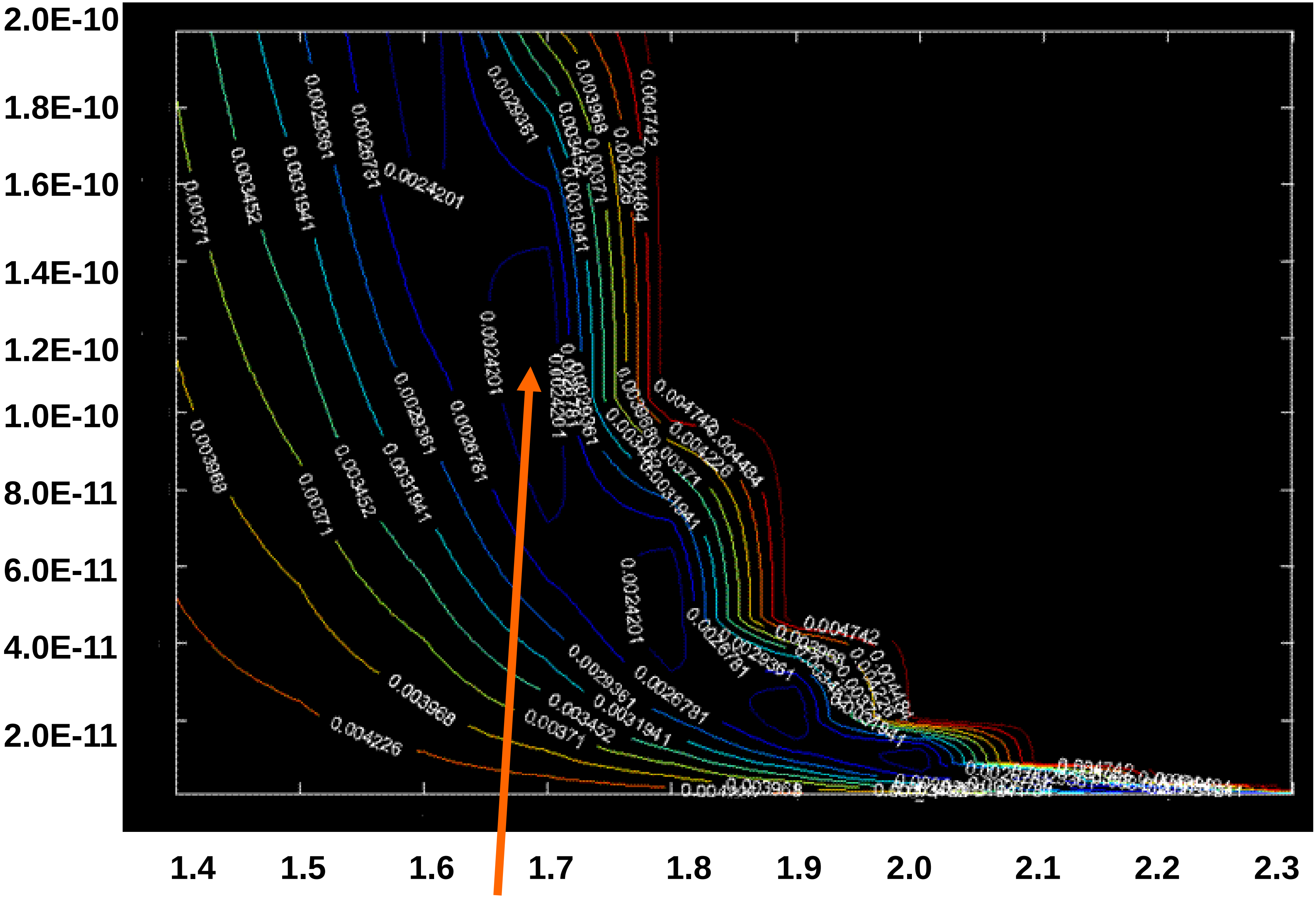
- **Active Remote Sensing**
  - **1.053 μm 5kHz lidar (48 μJ/pulse)**
- **Passive Remote Sensing**
  - **Broadband Radiometers (.3-4 and 4-40 μm)**
  - **Spectral Radiance Package (VIS, NIR, A-band)**
  - **Solar Spectral Flux Radiometer (300-1700 nm)**
  - **Diffuse Field Cameras (VIS & NIR)**
  - **Infrared Thermometers (8-10 μm; 9.6 to 11.5 μm)**
  - **Scanning High-Resolution Interferometer Sounder (3.3-18 μm)**
- **In-situ Microphysics & State Parameters**
  - **CAPS (CAS: .35-50 μm; CIP: 25-1550 μm; LWCD .1-3 g m^{-3})**
  - **Cloud Integrating Nephelometer (g, β_{ext})**
  - **Nevzorov Probe (LWC, TWC: .003 to 3 g m^{-3})**
  - **Video Ice Particle Sampler (10-200 μm)**
  - **MET package (laser & cryogenic hygrometers, state parameter**



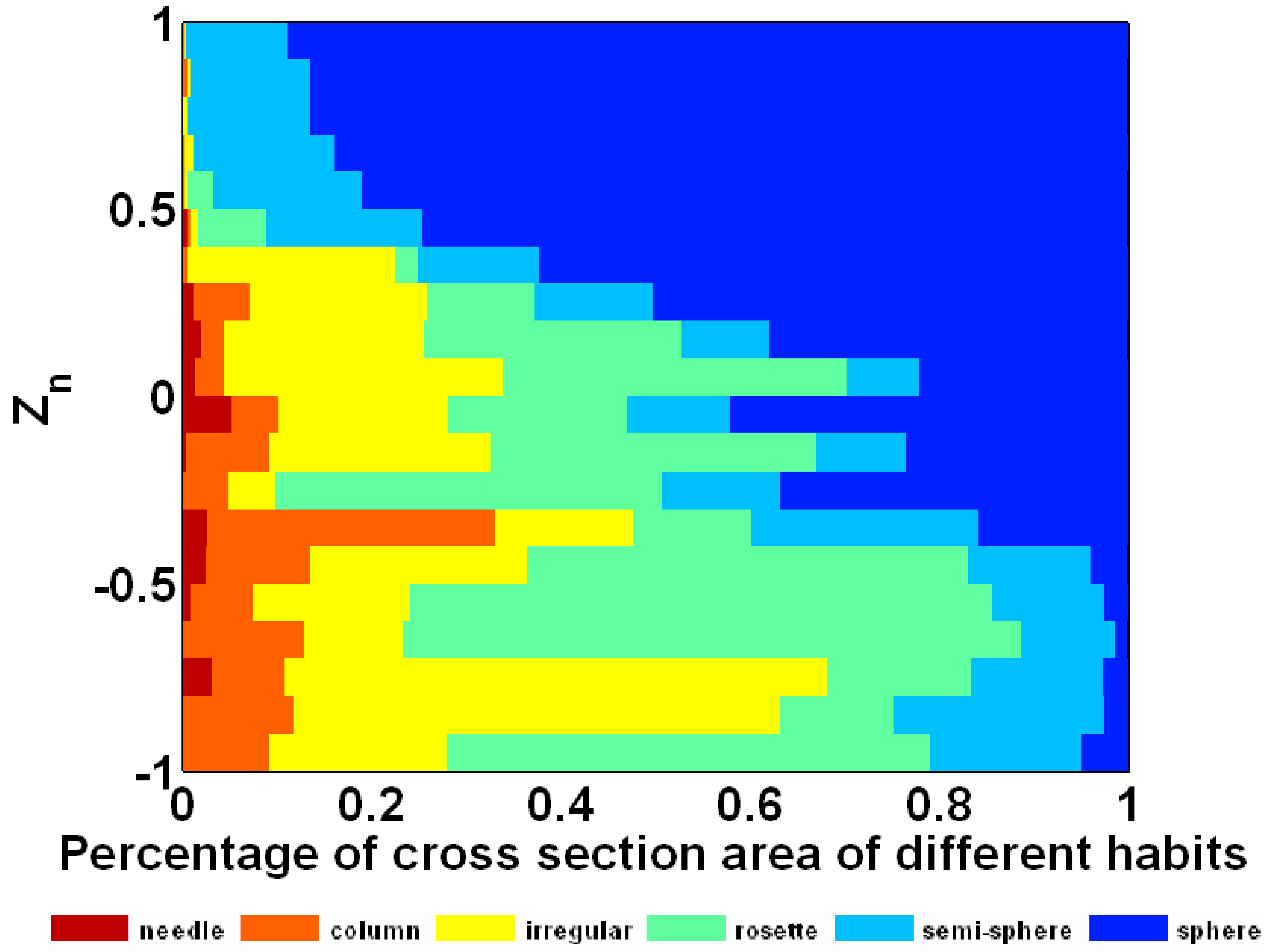
Bulk IWC estimated from CSI-King LWC

Compare with IWC calculated from 2DC/HVPS distributions shows good agreement

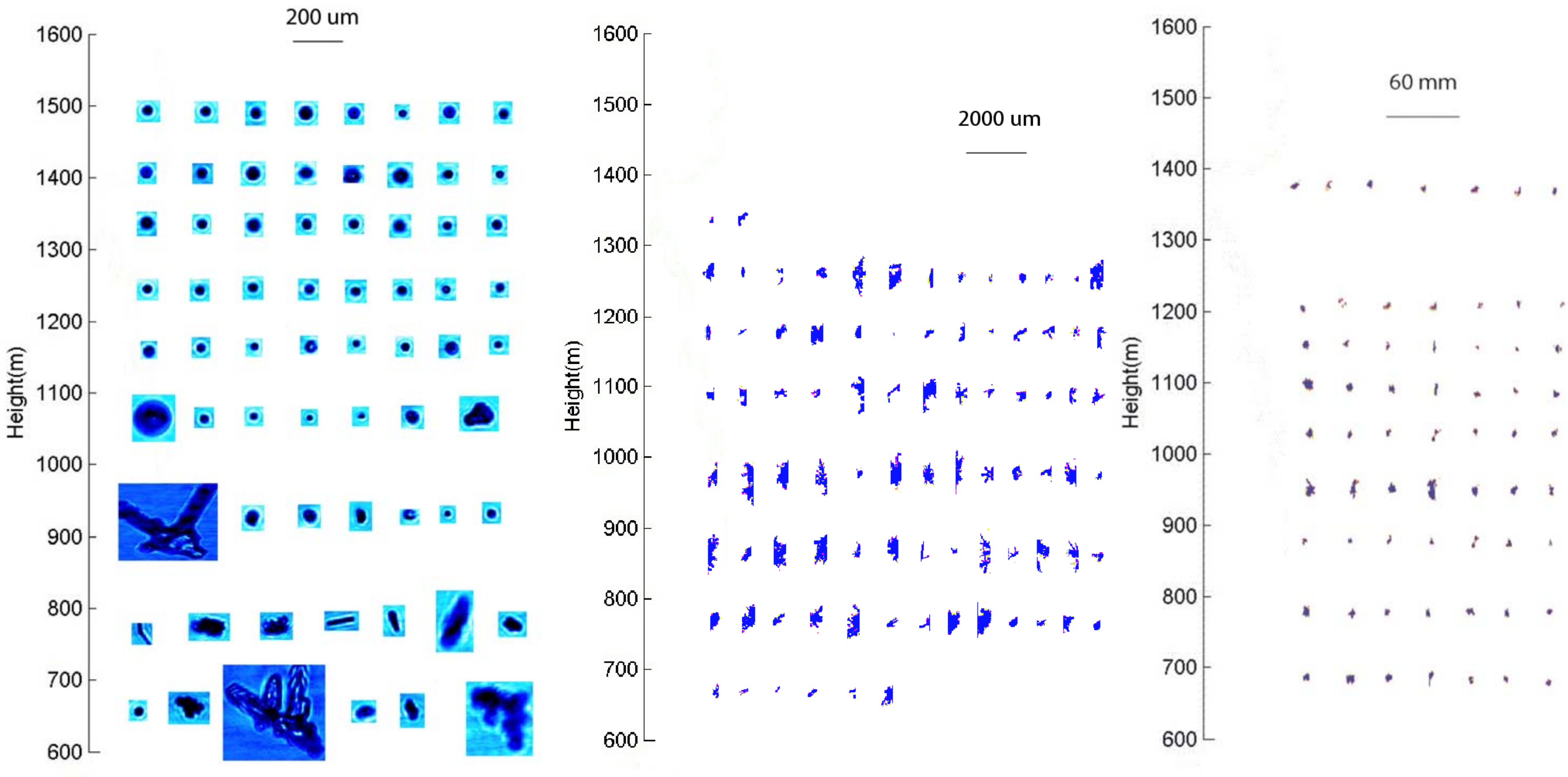

Cloud Top Temperatures from IRTs
IRT Temperature (Kelvins)
270
268
266
264
262
260
258
200550
200910
201230
201550
201910
202230
202550
202910
203230
203550
203910
Time


2.0E-10
1.8E-10
1.6E-10
1.4E-10
1.2E-10
1.0E-10
8.0E-11
6.0E-11
4.0E-11
2.0E-11
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3

A=1.07E-10 B=1.7



Habit distributions help determine single-scattering properties



CPI 2DC HVPS

Drizzle/supercooled drops near cloud top (1500 m);

Precipitating ice below cloud base (900 m), but ice occurs in packets throughout cloud

This structure observed for many single layer clouds