Characteristics of ice supersaturated regions near the tropopause in START08 and HIPPO

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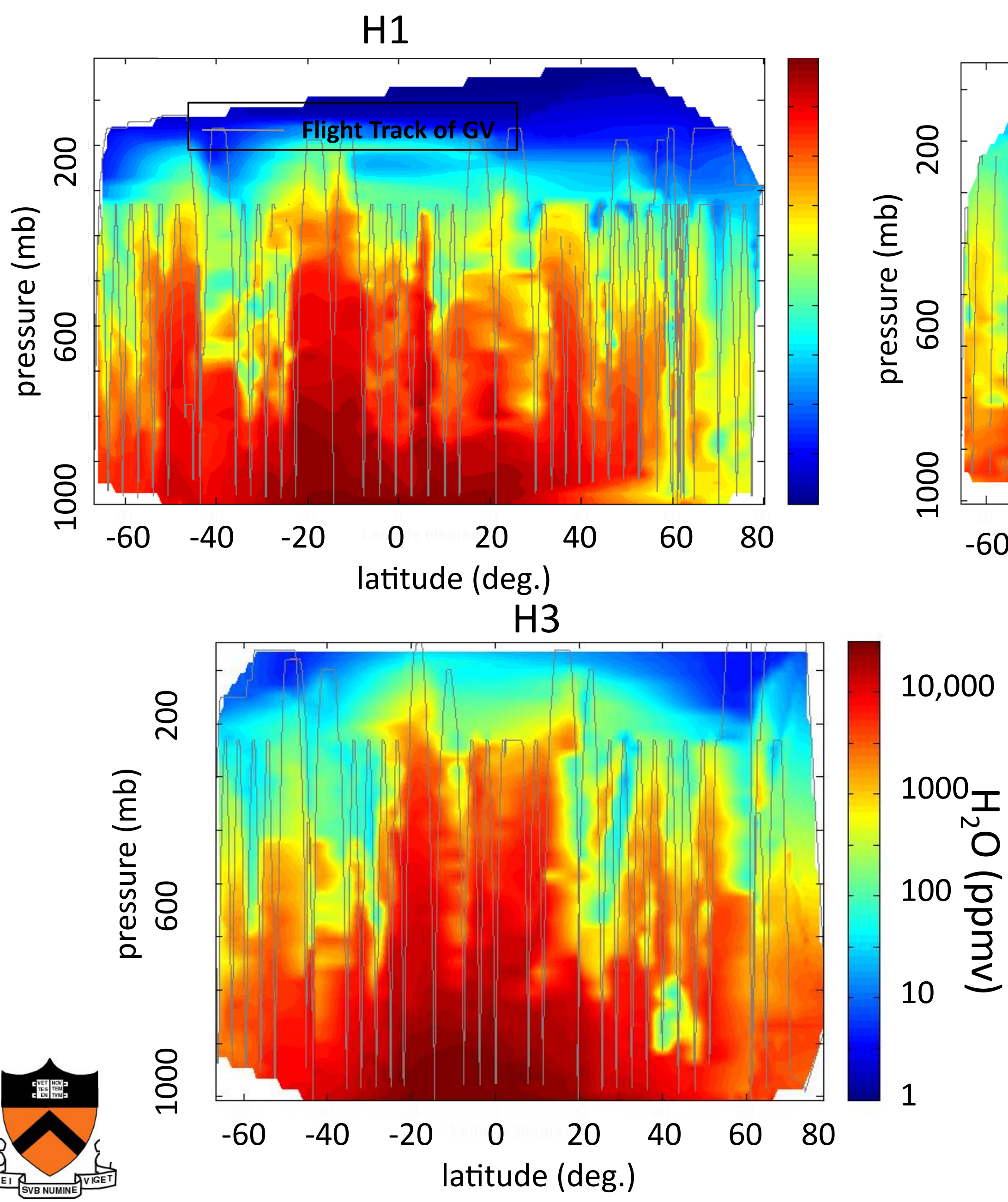
HIPPO Global: Distribution of water vapor



Large plumes of water vapor extending vertically

South Pacific Convergence Zone (~15°S)

How representative is this zonally as well as in time? (Minghui's talk)

Key questions to address:

1. What are the characteristics (magnitudes, length scales) of ice supersaturated regions based upon *in-situ* measurements?

2. What are the environmental conditions in/near ice supersaturated regions?

3. How representative are remote sensing observations at large scales compared to cloud scales?

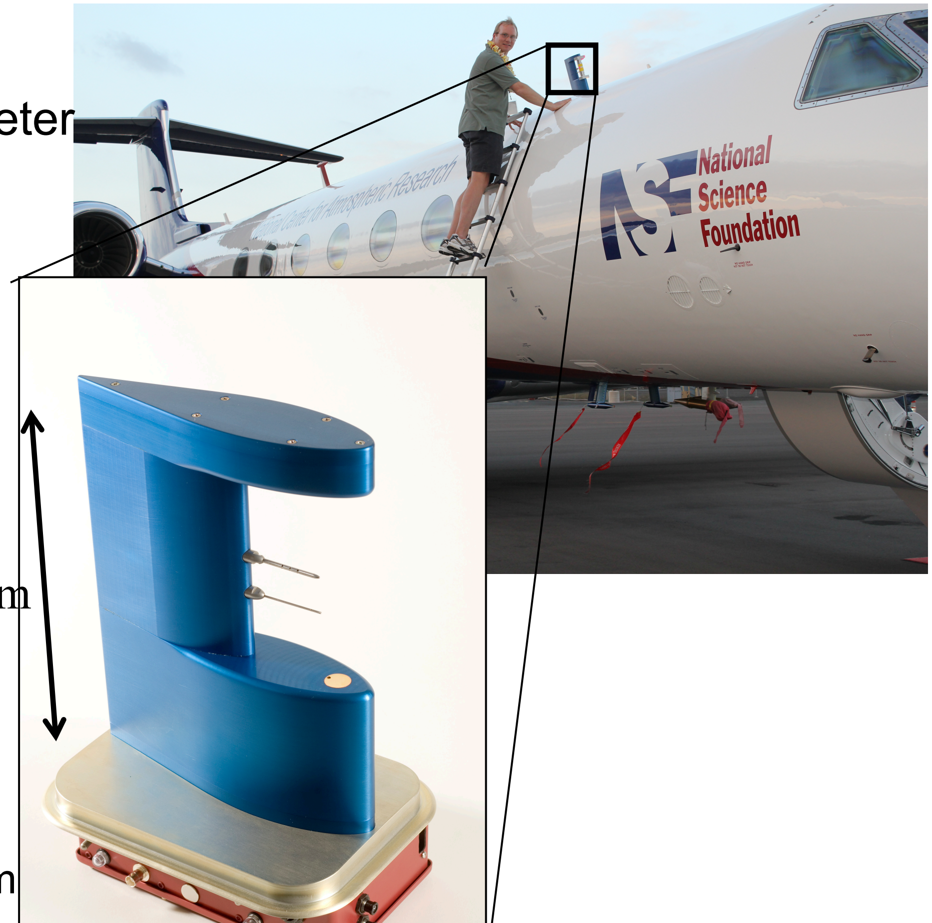
4. Can we link between cloud scales and satellite data to improve model ice parameterizations and cirrus cloud nucleation models?

Experimental: NSF Gulfstream-V VCSEL sensor

1854 nm fiberized Vertical Cavity Surface Emitting Laser (VCSEL) hygrometer

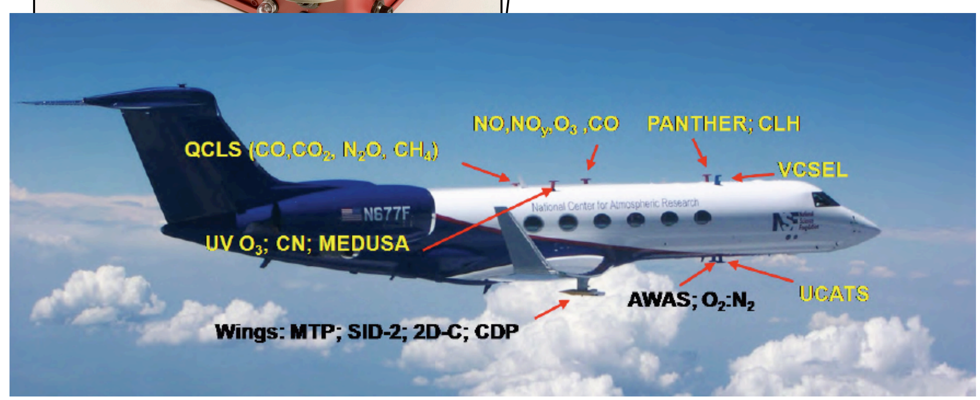
(Zondlo et al., JGR, 2010)

Flies routinely on NSF G-V (since 2008)



Parameter	Specifications
Dew point range	-110°C to +30°C
Sensitivity (SNR=1, 1 Hz)	0.05 ppmv
Frequency	25 Hz
Accuracy	≤ 5%
Precision	≤ 3%
Power	5 W
Weight	5 kg
Size	25 cm × 16 cm × 5 cm
Operation	unattended
Design	open-path

VCSEL hygrometer is open-path, fast sensor and avoids common water vapor sampling artifacts

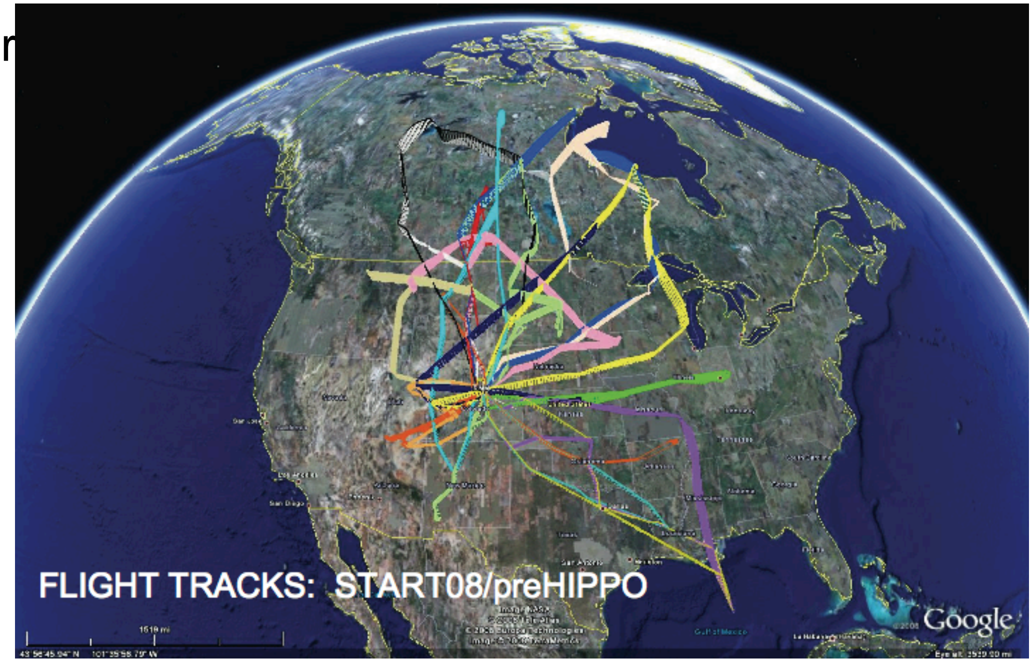


Datasets

NSF PreHIPPO/Stratosphere Troposphere Analyses of Regional Transport (START08)

North America, May-June 2008

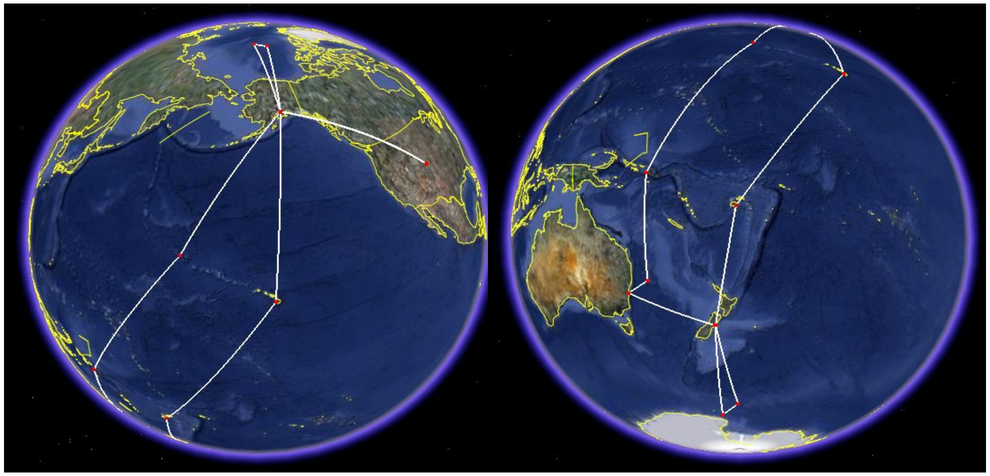
Transcontinental flight corridor



NSF HIAPER Pole-to-Pole Observation (HIPPO)

Deployment #1: Jan. 2009

Extratropical and tropical data



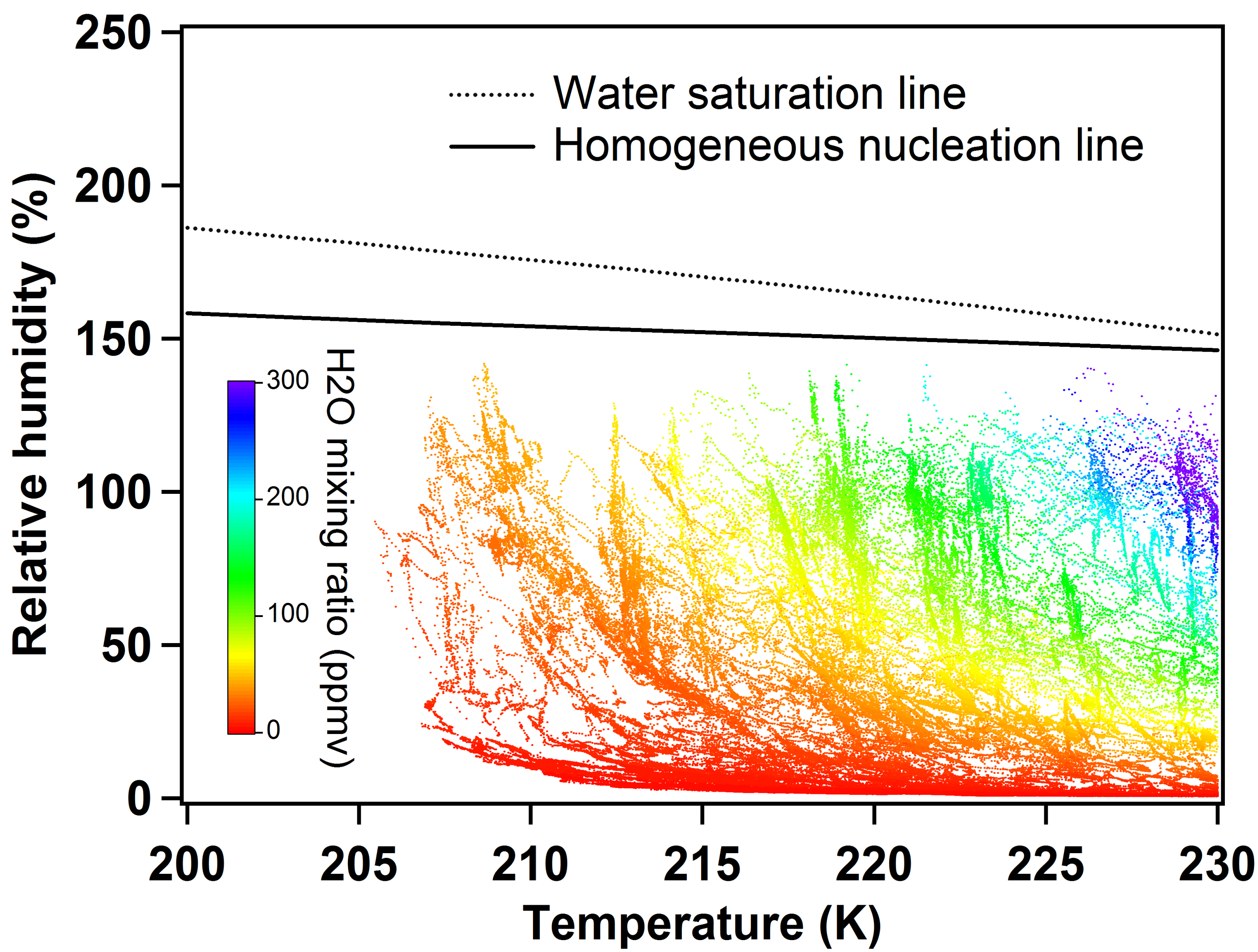
Overall:

735 ice supersaturated regions

530 in START08 (62 hrs at T<-40°C)

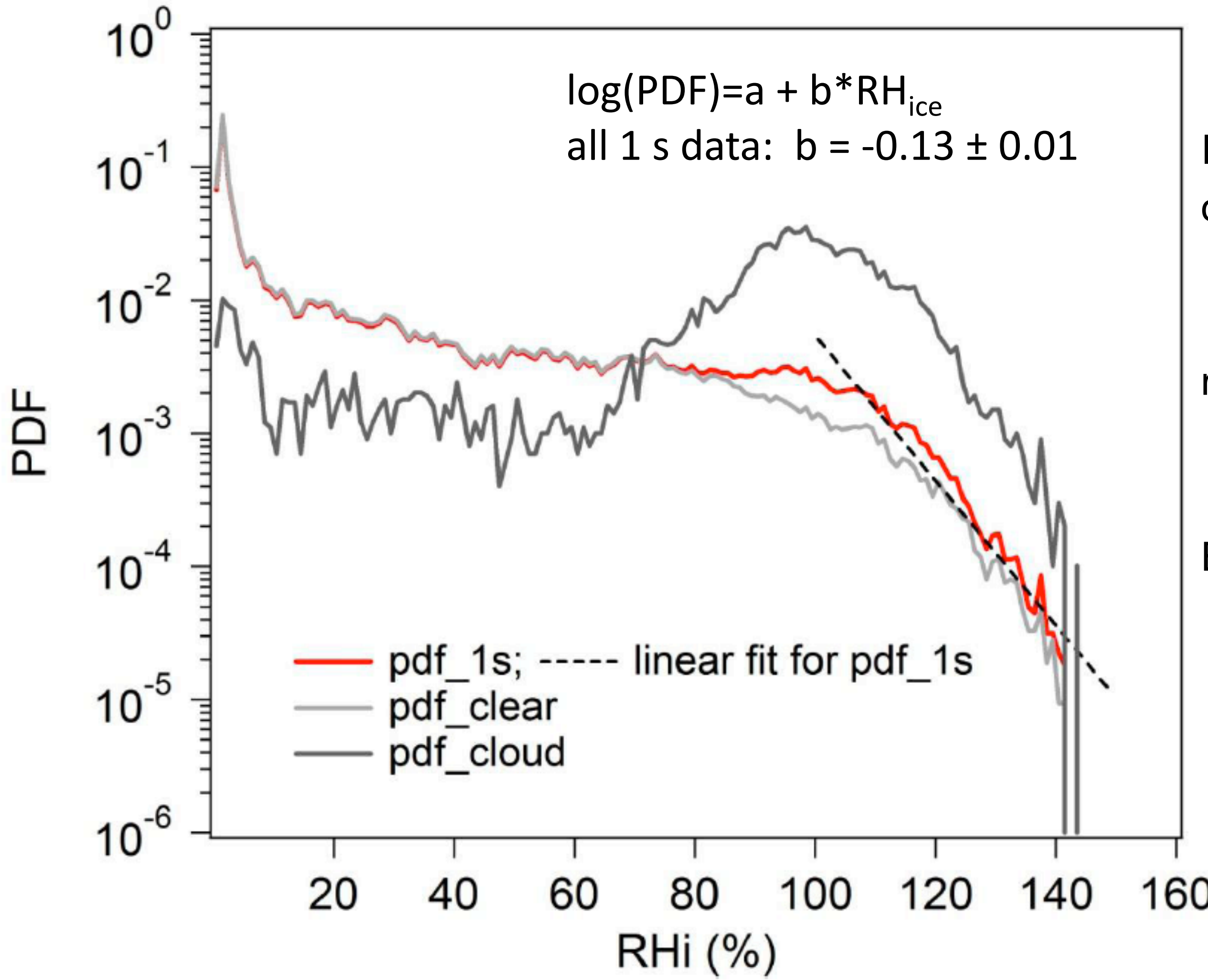
215 in HIPPO-1 (24 hrs at T <-40°C)

RH$_{ice}$ vs. temperature in START08 (62 hours with T < -40°C)



2% clear air ice supersaturation; 39% in-cloud ice supersaturation

PDF of RH_{ice}



In-cloud peak at 93%
out-of-cloud at <10%;

AIRS: 85% and 13%,
respectively *(Kahn et al., 2009)*

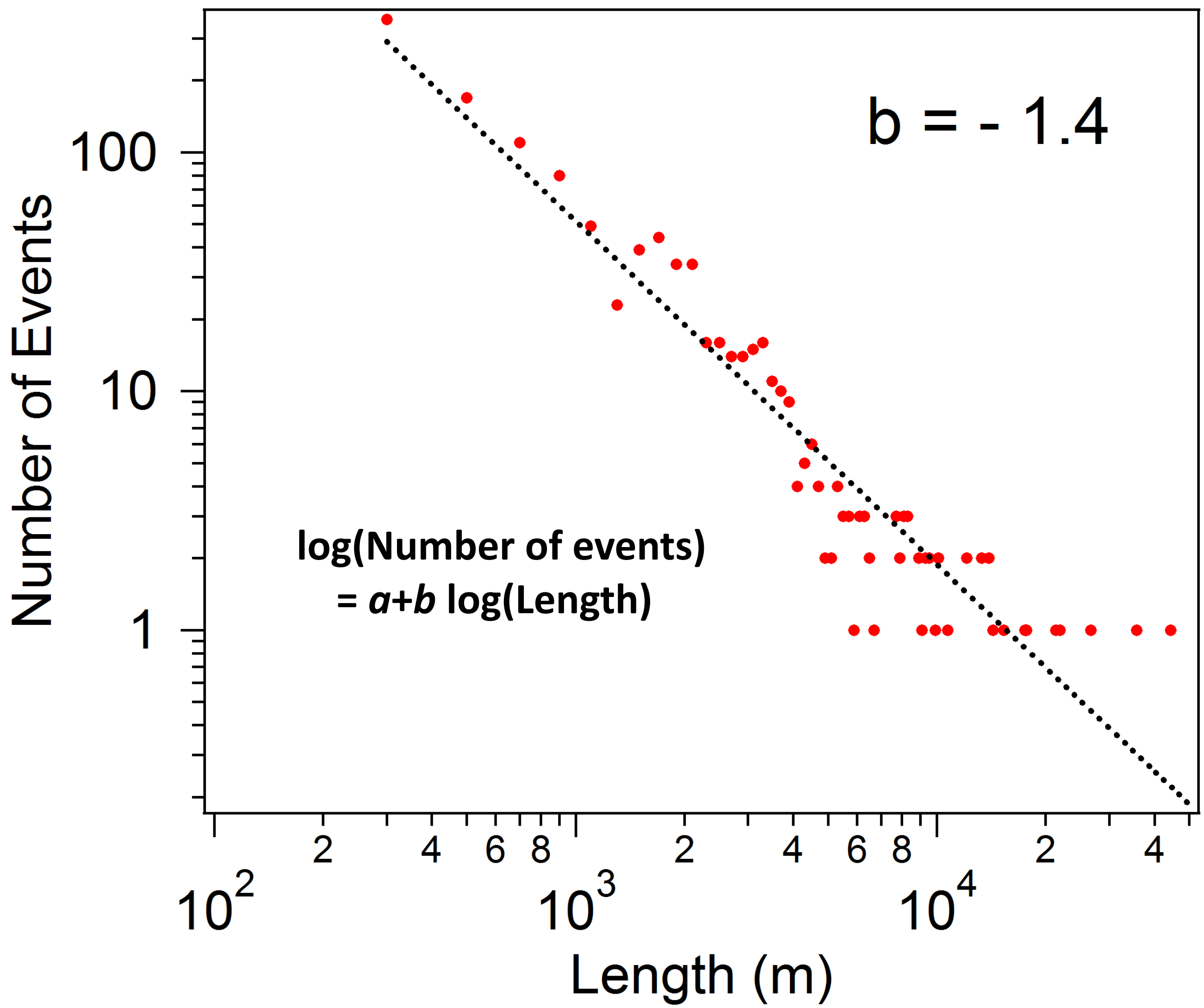
Exponent for RH_{ice} > 100%:
VCSEL 1 s = 0.13 ± 0.01
1 min = 0.09 ± 0.01

AIRS = 0.06
MOZAIC = 0.07
(200-600 hPa,40-60 N)
(Gettelman et al., 2006)

AIRS / MOZAIC see many more larger ISSRs than the G-V data
Faster removal of ice supersaturated regions in G-V data;
related to scale differences or sampling protocols?

What are the sizes of ice supersaturated regions?

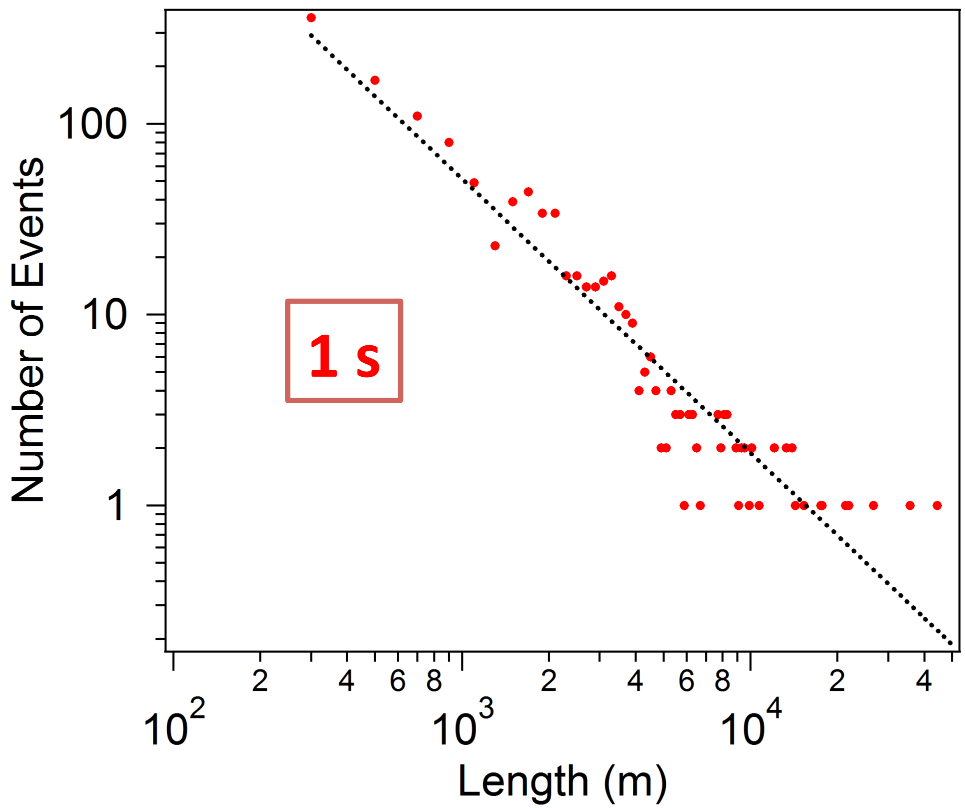
(START08 = extratropical spring/summer)



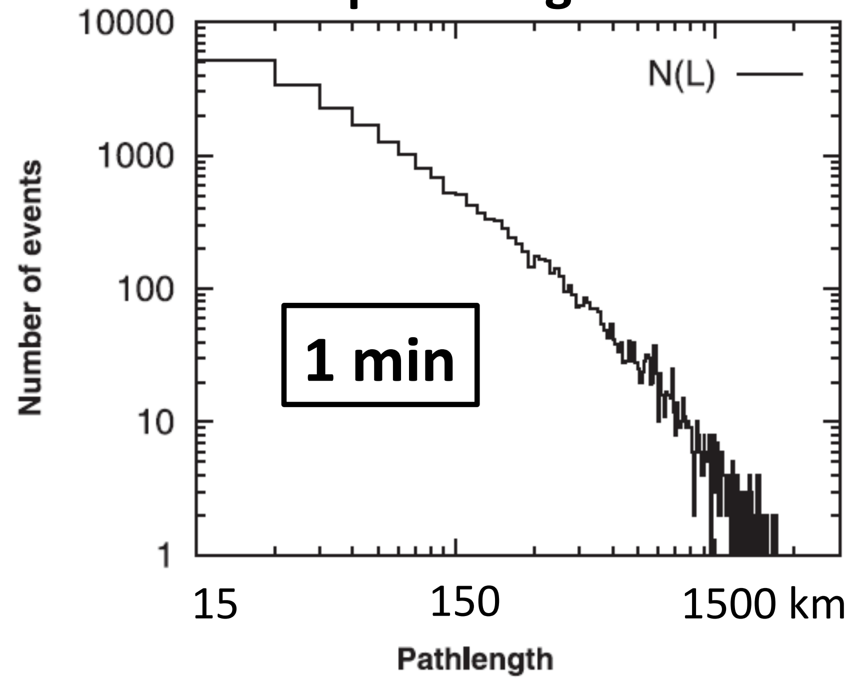
median length (0.9 km) << MOZAIC or AIRS footprints

Comparison of size distribution of ISSRs

mean path length: 1.5 km



mean path length: 150 km

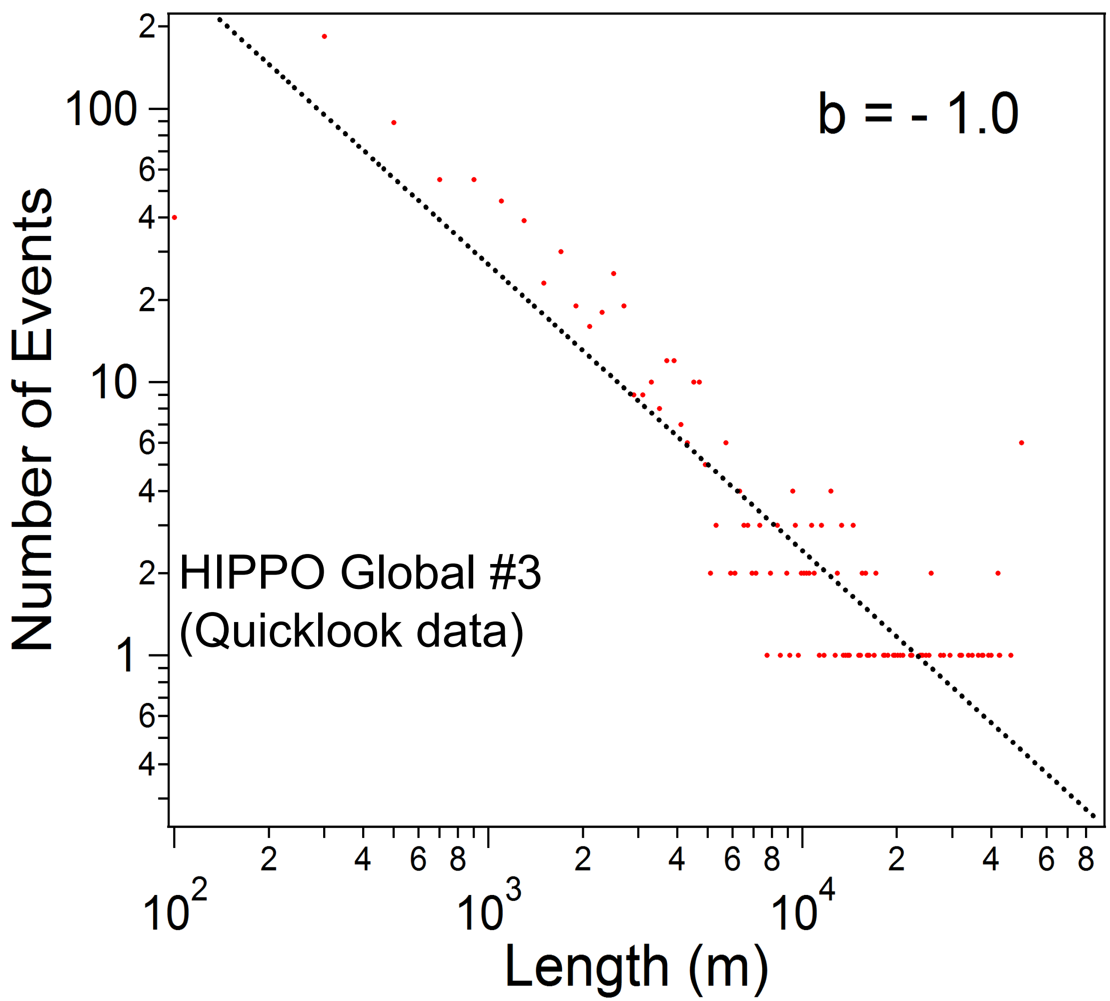


(Gierens and Spichtinger, 2000)

Predicted "**more very small ISSRs** than apparent from the (MOZAIC) data"

How does this compare to HIPPO data?

HIPPO #3

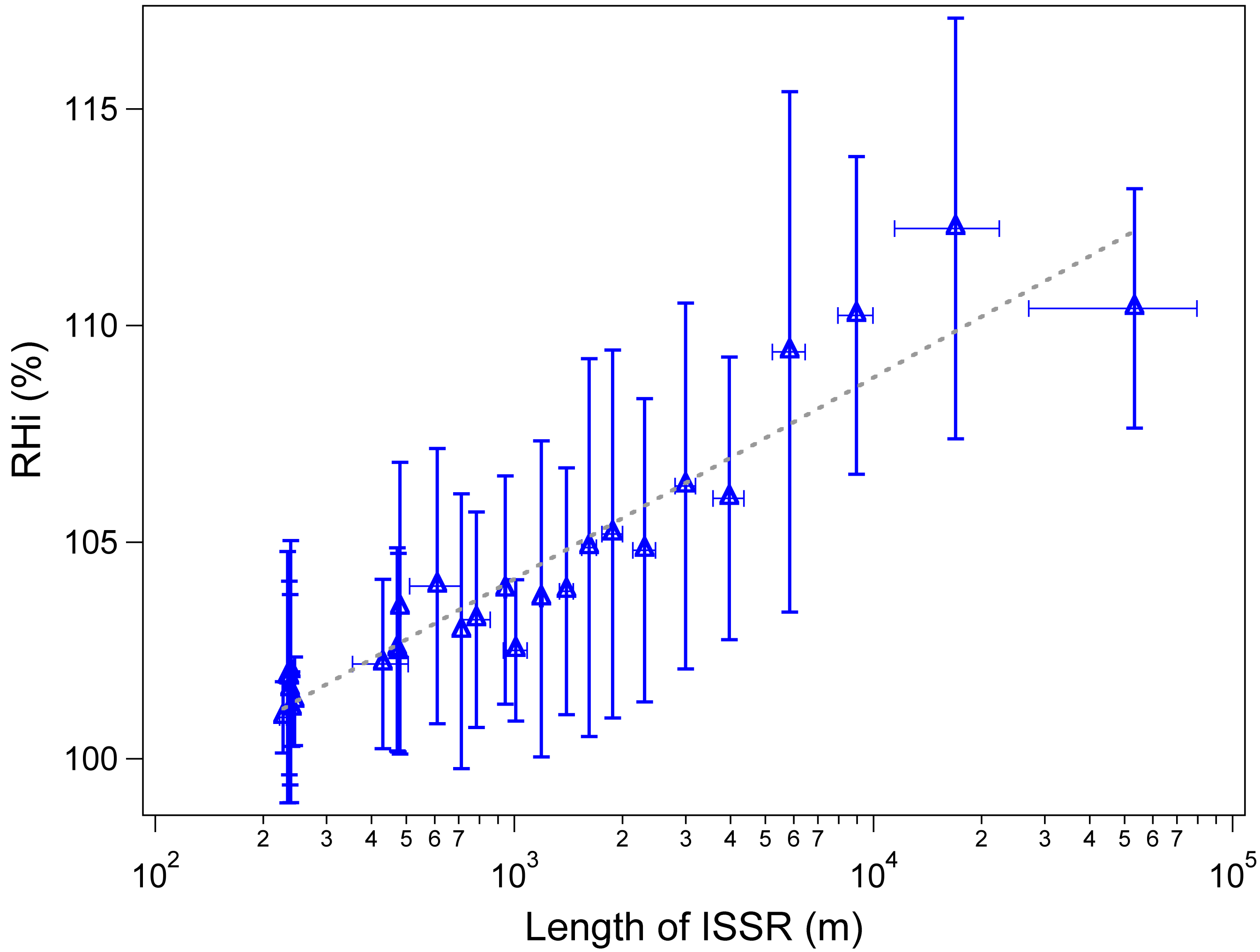


median path length: 2.5 km

Median sizes in HIPPO and START08 all about ~ 1 km horizontally

Is there a size dependence for magnitude of ISSR?

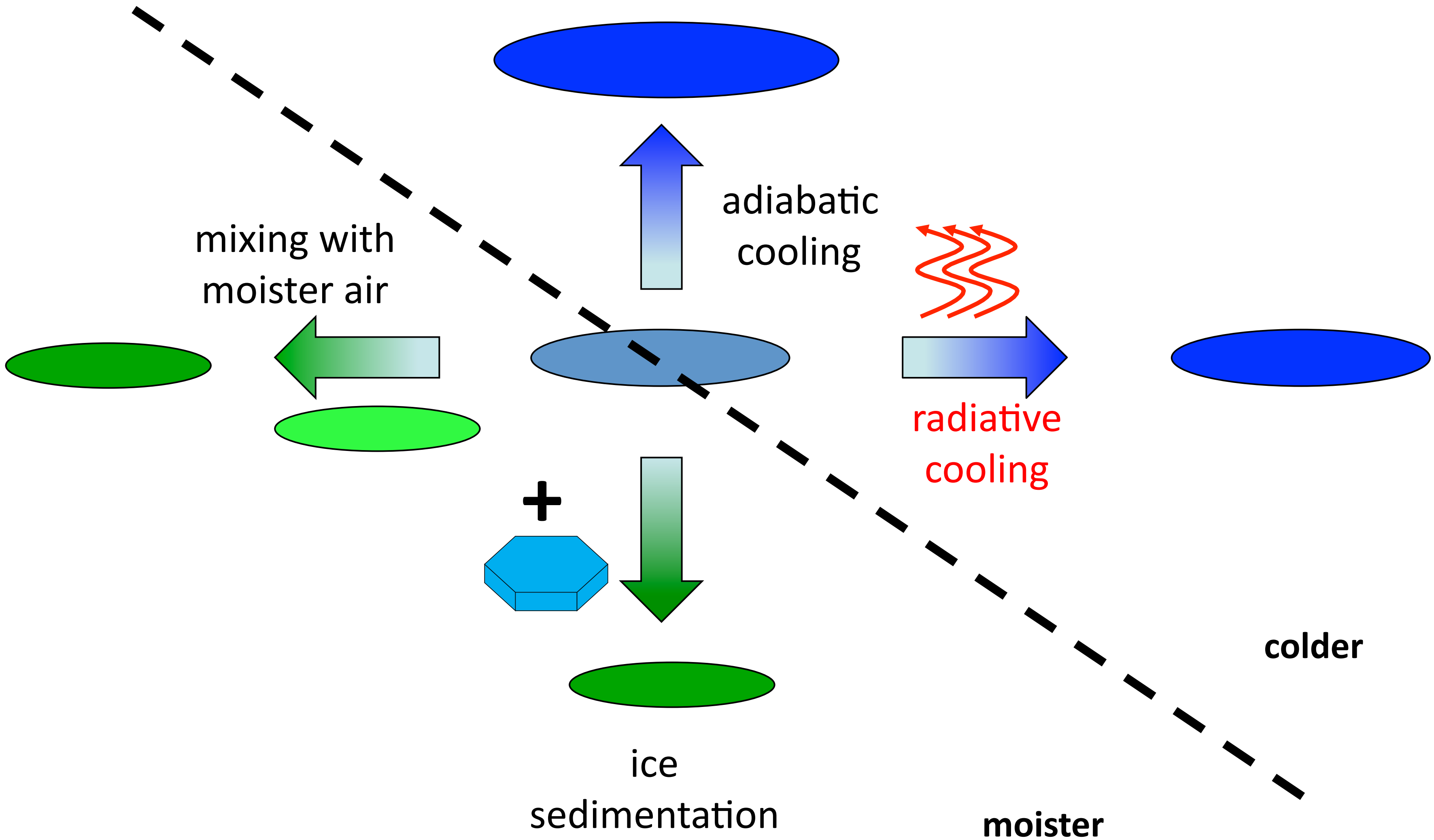
Horizontal scales versus magnitude of ice supersaturation (START08 and HIPPO-1)



RH_{ice} scales with size of ice supersaturated region:

- helps to explain why satellite data (e.g. AIRS) sees fewer ISSRs
- start to linking cloud to satellite scales

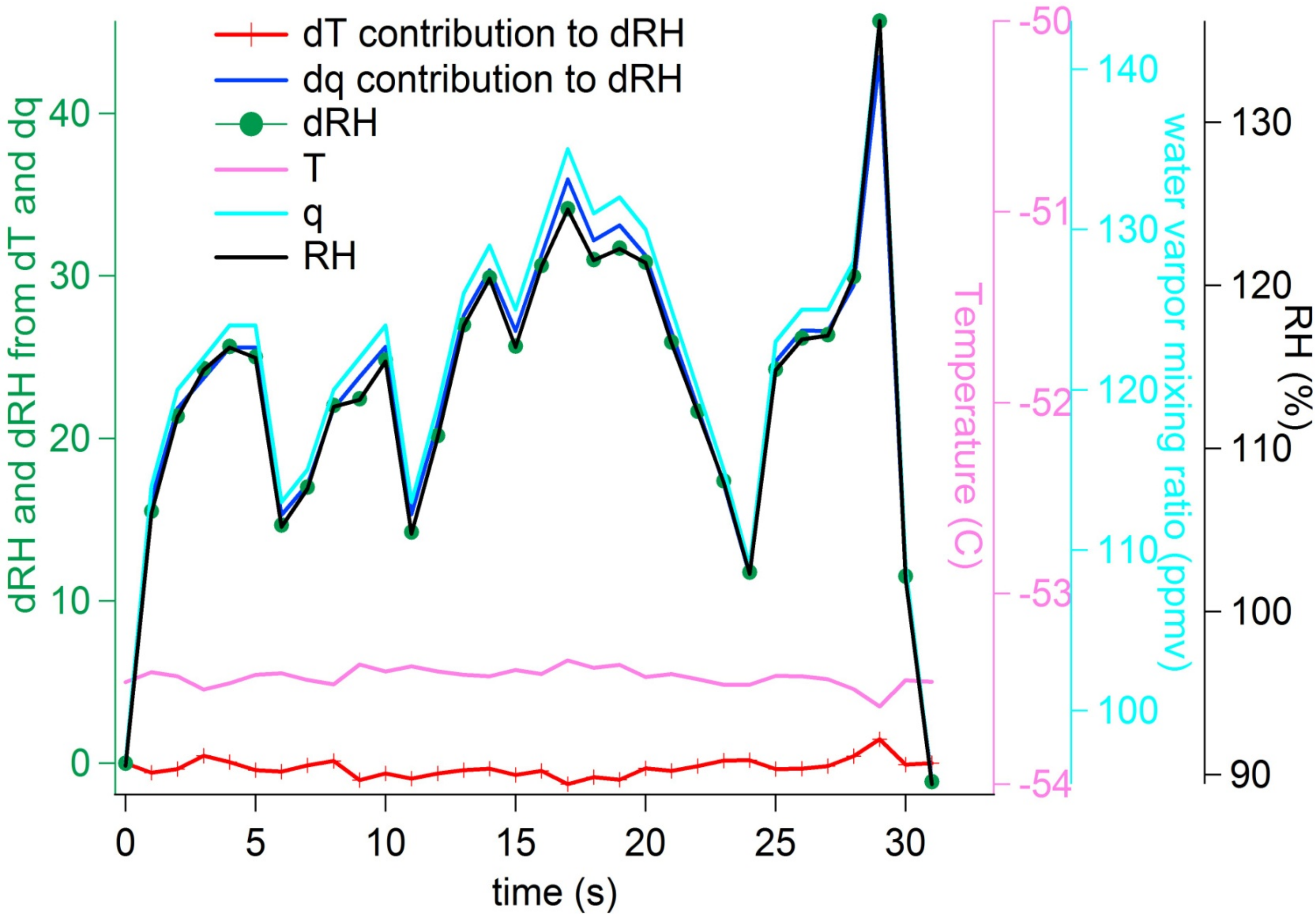
How do ice supersaturated regions form?



Climate and cloud ice nucleation models form cirrus clouds by perturbing (lowering) the temperature field

(Spinchtinger et al., 2005; Kärcher and Burkhardt, 2008; Morrison and Gettelman, 2008; Wang and Penner, 2010)

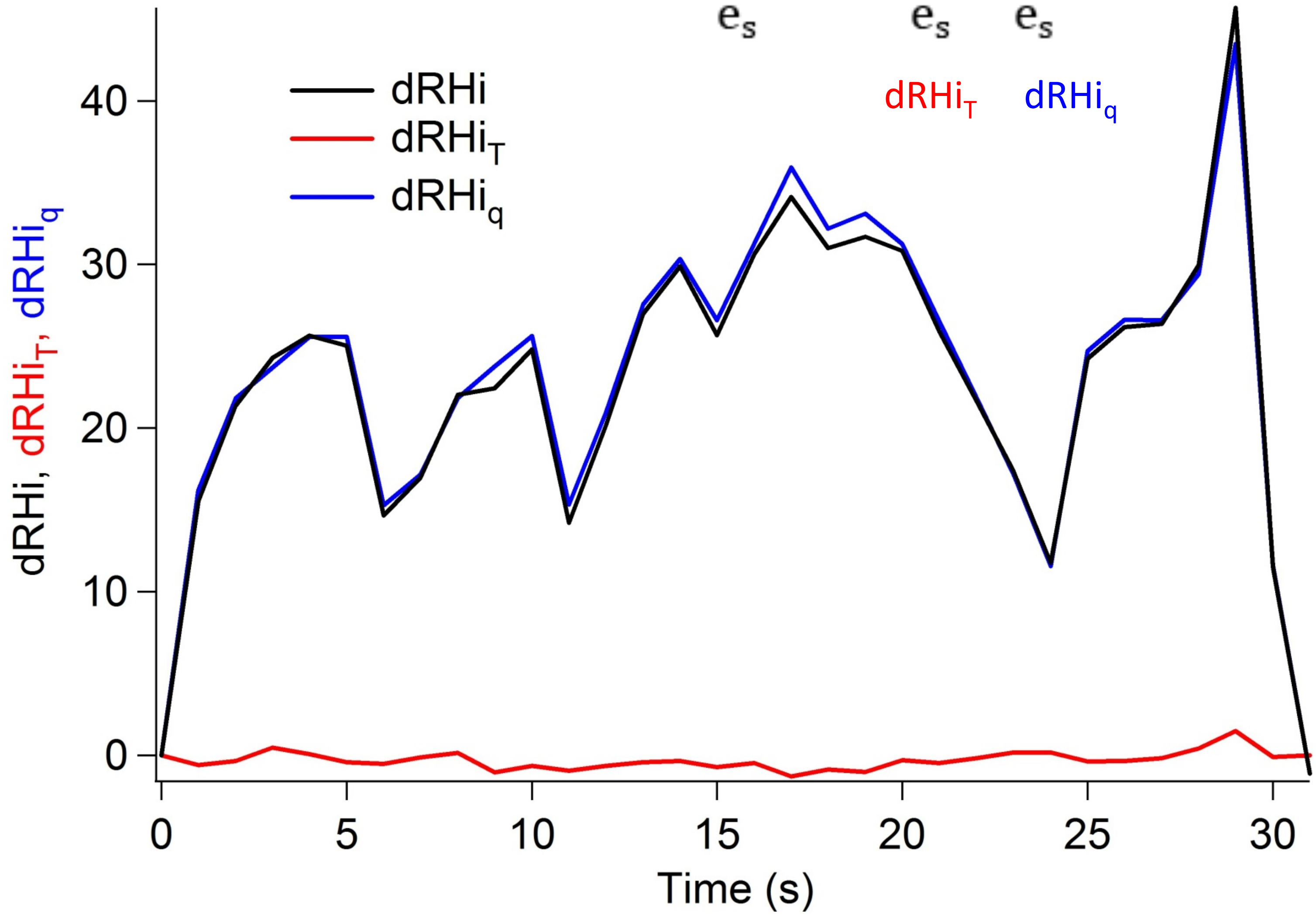
Flight transect of typical ice supersaturation region



RH_{ice} dominated by increase in H_2O, but is this representative?

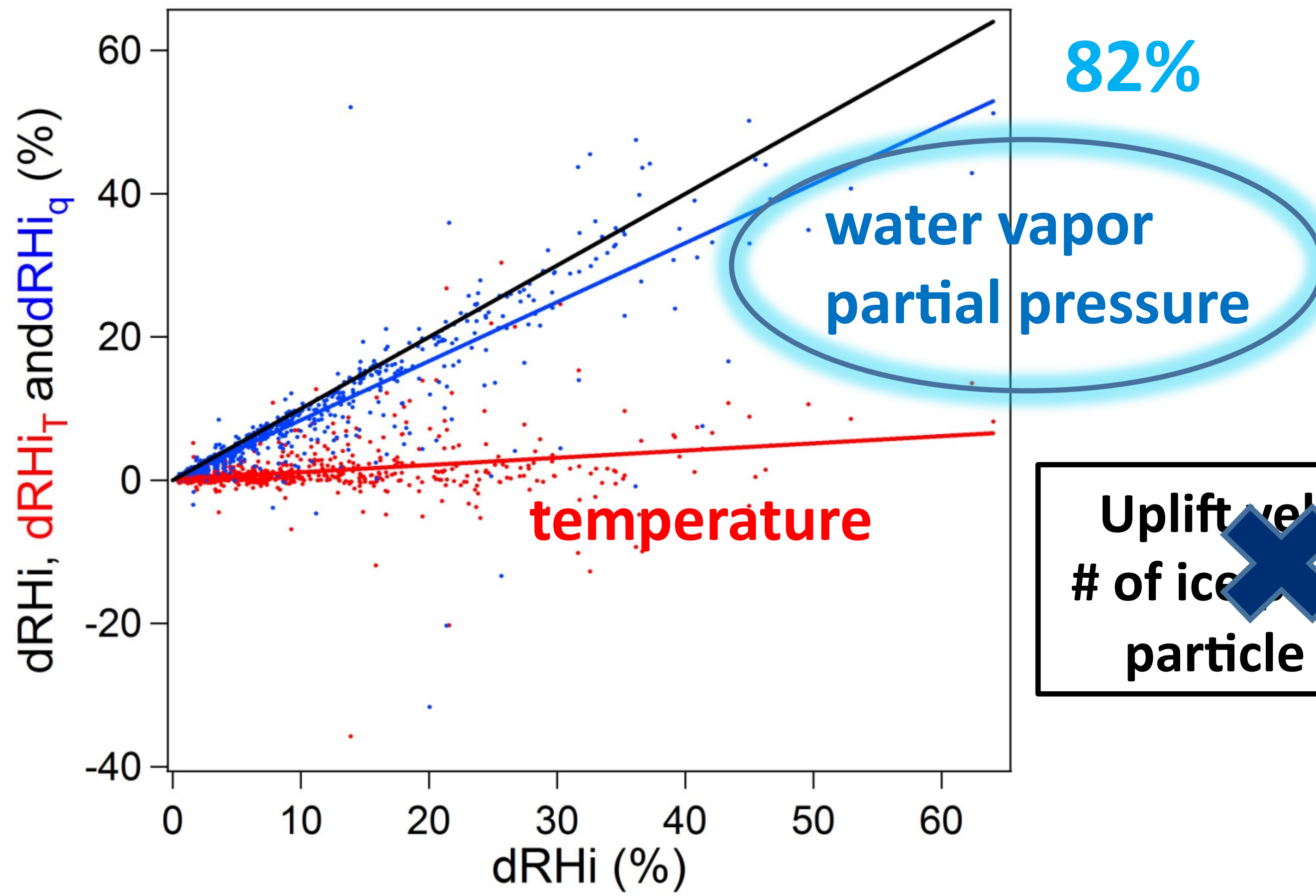
Examining only the dRHi into components from temp. and water vapor

$$dRHi = d\frac{e}{e_s} \approx e\,d\frac{1}{e_s} + \frac{1}{e_s}de$$



Is this case anomalous in that H_2O controls variability in RH field?

Environmental conditions of ISSRs (START08 and HIPPO-1)



Uplift velocity
# of ice particles
particle size

$d\mathbf{RHi} = d(e/e_s) = 1/e_s * de + e * d(1/e_s)$

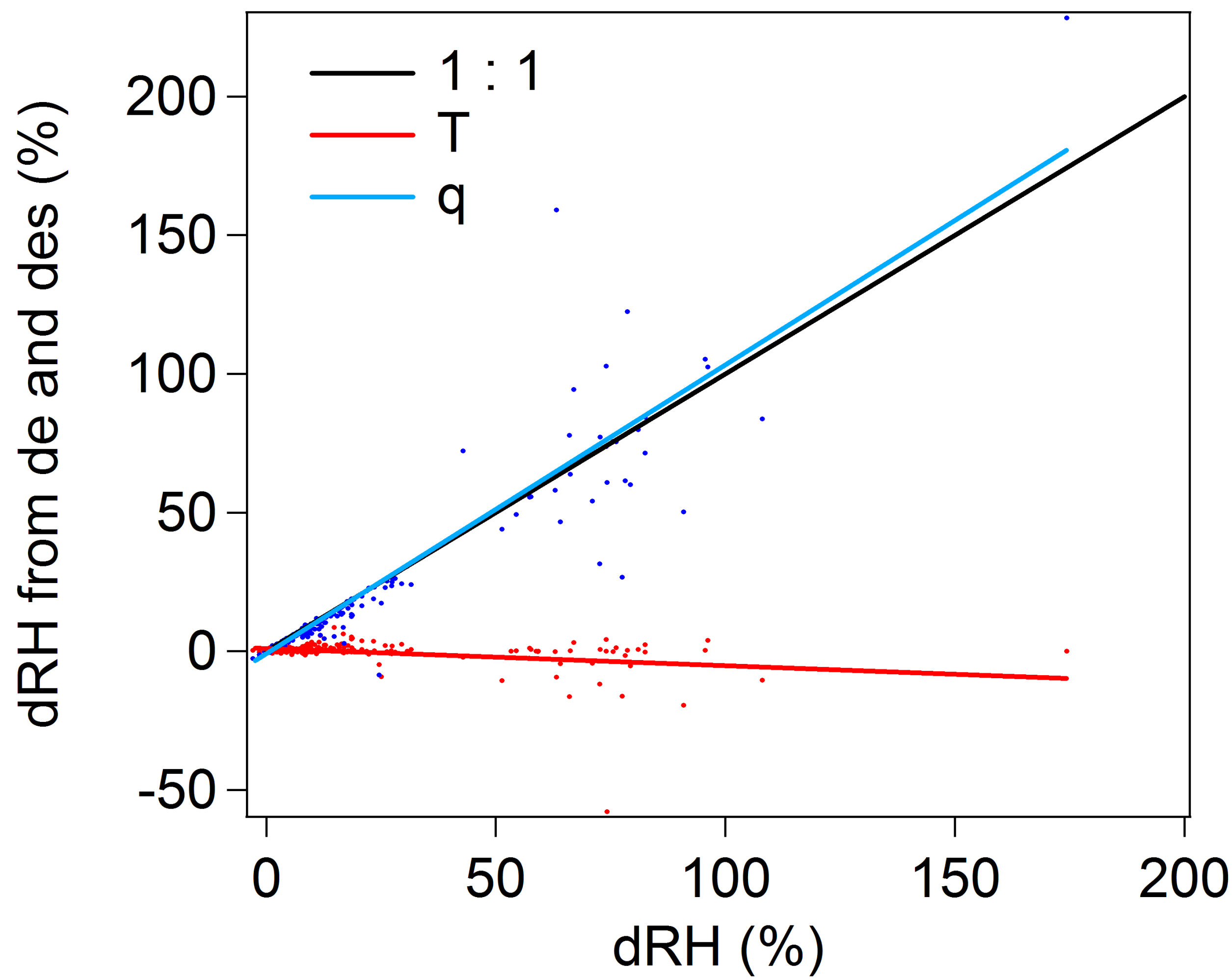
Part 1. Part 2.

$\boldsymbol{de} = d(\text{H2OMR} * \text{Pressure})$

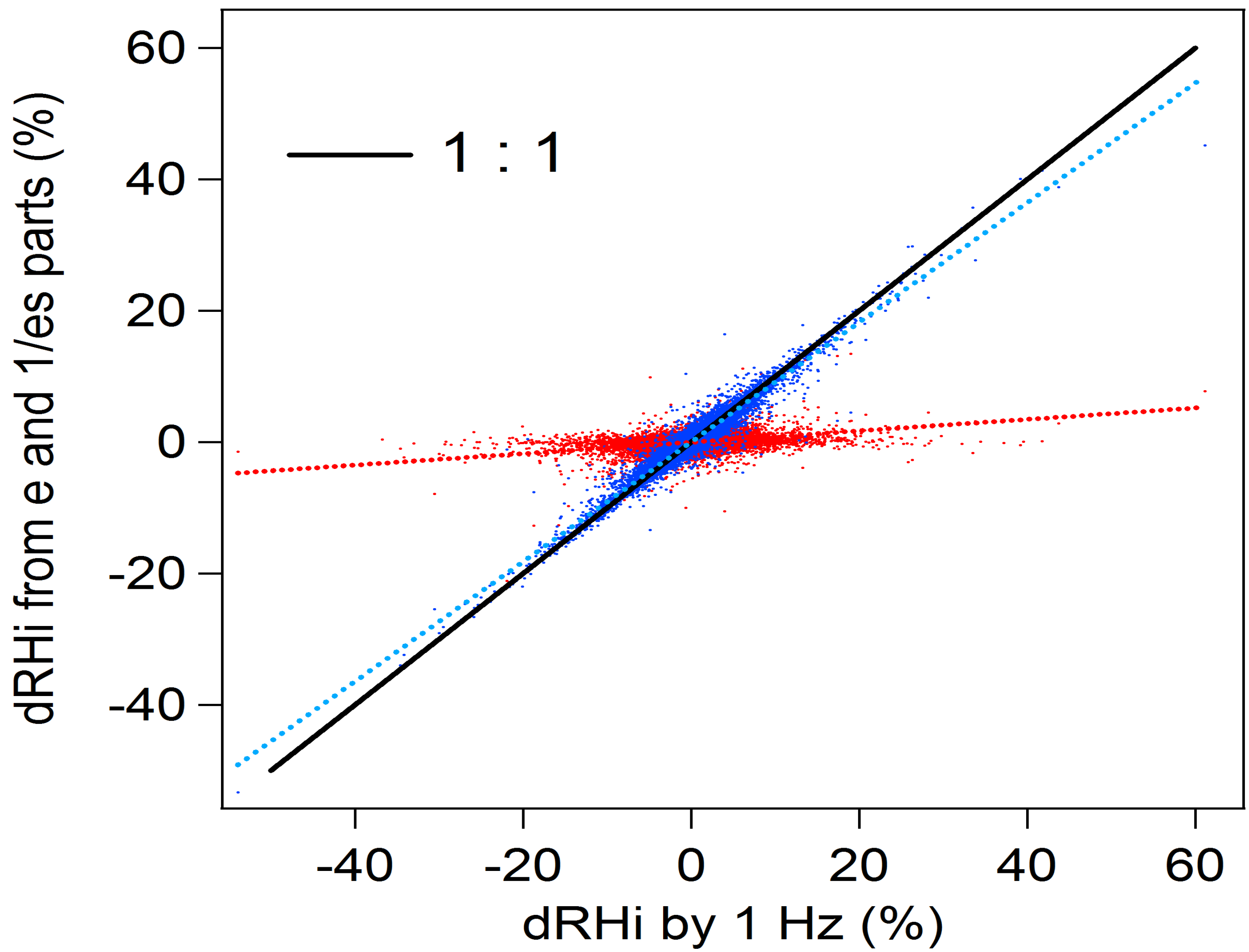
$= \text{Pressure} * \boldsymbol{d}\mathbf{H2OMR} + \text{H2OMR} * d\text{Pressure}$

Part A. Part B.

HIPPO-3: water also dominates

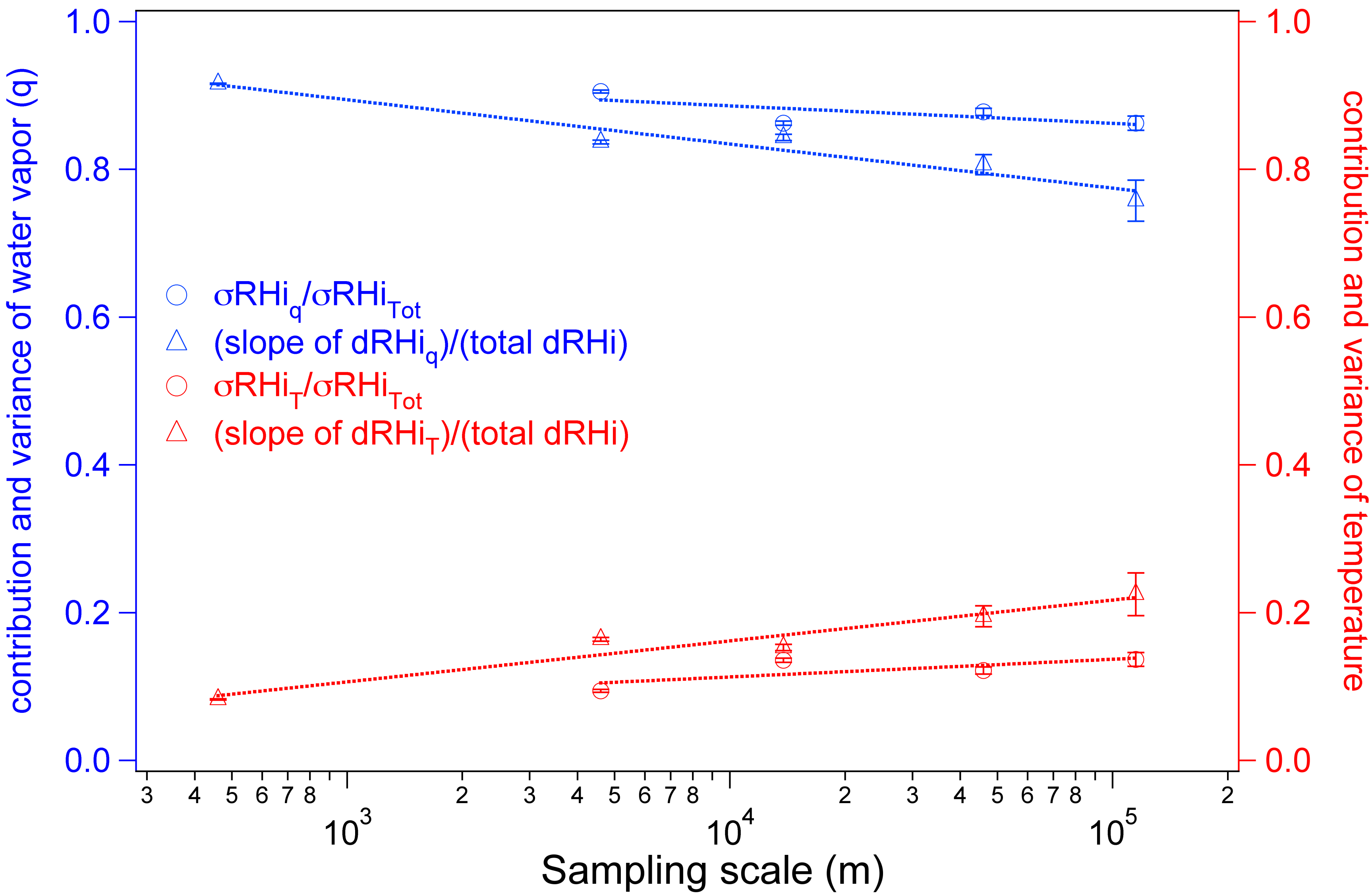


More generally: 1 s RH_{ice} fluctuations due to temp., water vapor (supersaturated <u>and</u> unsaturated conditions: all data)



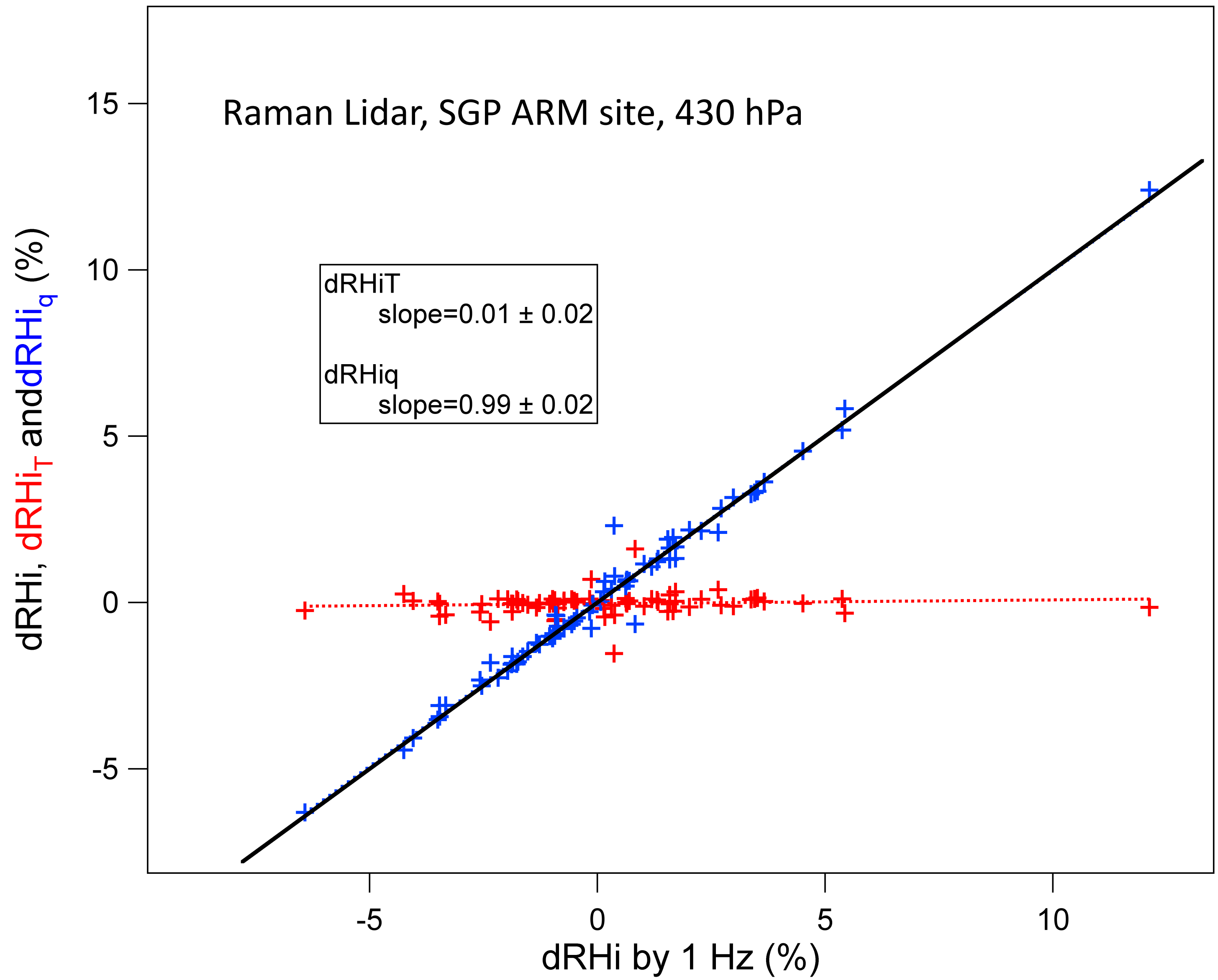
Inhomogeneities of water vapor dominating RH field as opposed to temperature fluctuations on 200 m scales

Scale analyses of RH_{ice} variability



Water vapor fluctuations remain dominant up to 100 km; temperature increasingly becomes important at larger scales

What about the temporal variability of RH_{ice}?



Water vapor variability dominates RHi on temporal scales, too

Ice supersaturation conclusions

- VCSEL hygrometer with global field campaigns on the NSF G-V well-suited to probe ice supersaturation in upper troposphere and extratropical tropopause

  (Zondlo et al., J. Geophys. Res.-Atmos., 2010)

- PDF of RH_{ice} from *in-situ* data depends upon sampling scales

  - small magnitude RH_{ice} more frequently observed than coarser measurements

- Scales of ice supersaturated regions

  - median horizontal lengths ~ 1 km (START08 and HIPPO)

- Magnitude of ice supersaturation shows strong correlation with length scales

  - larger scale measurements biased by higher supersaturations

  - basis for parameterization between remote sensing data and cloud scales

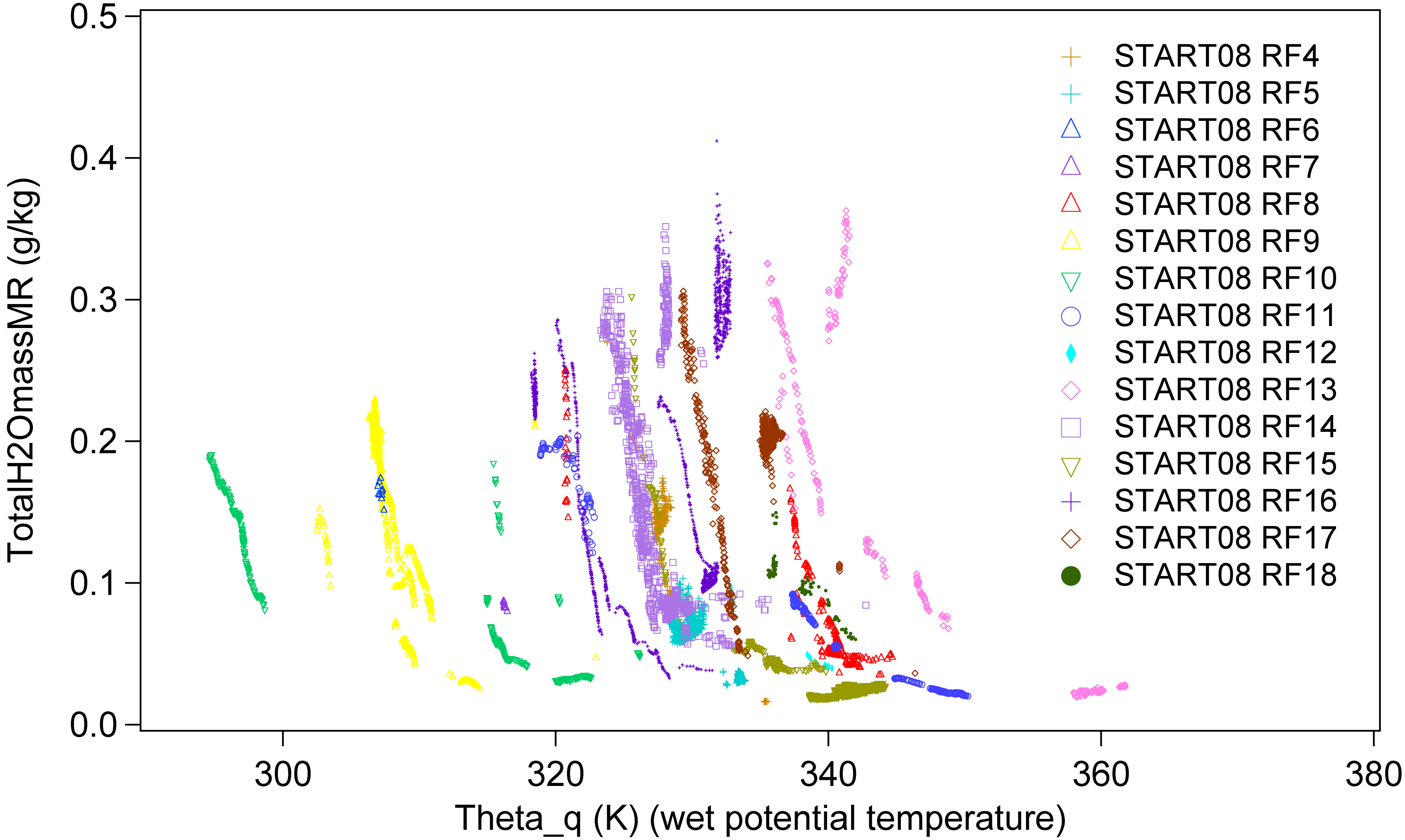
- Inhomogeneity of the water vapor, not temperature, dominates spatial and temporal differences in RH_{ice} field

(~ 90% @ 200m) for ice supersaturation and more generally for all RH_{ice}

Temperature fluctuations become more important at larger scales.

Future work: Comparing AIRS to VCSEL and analyses of PREDICT (tropics)

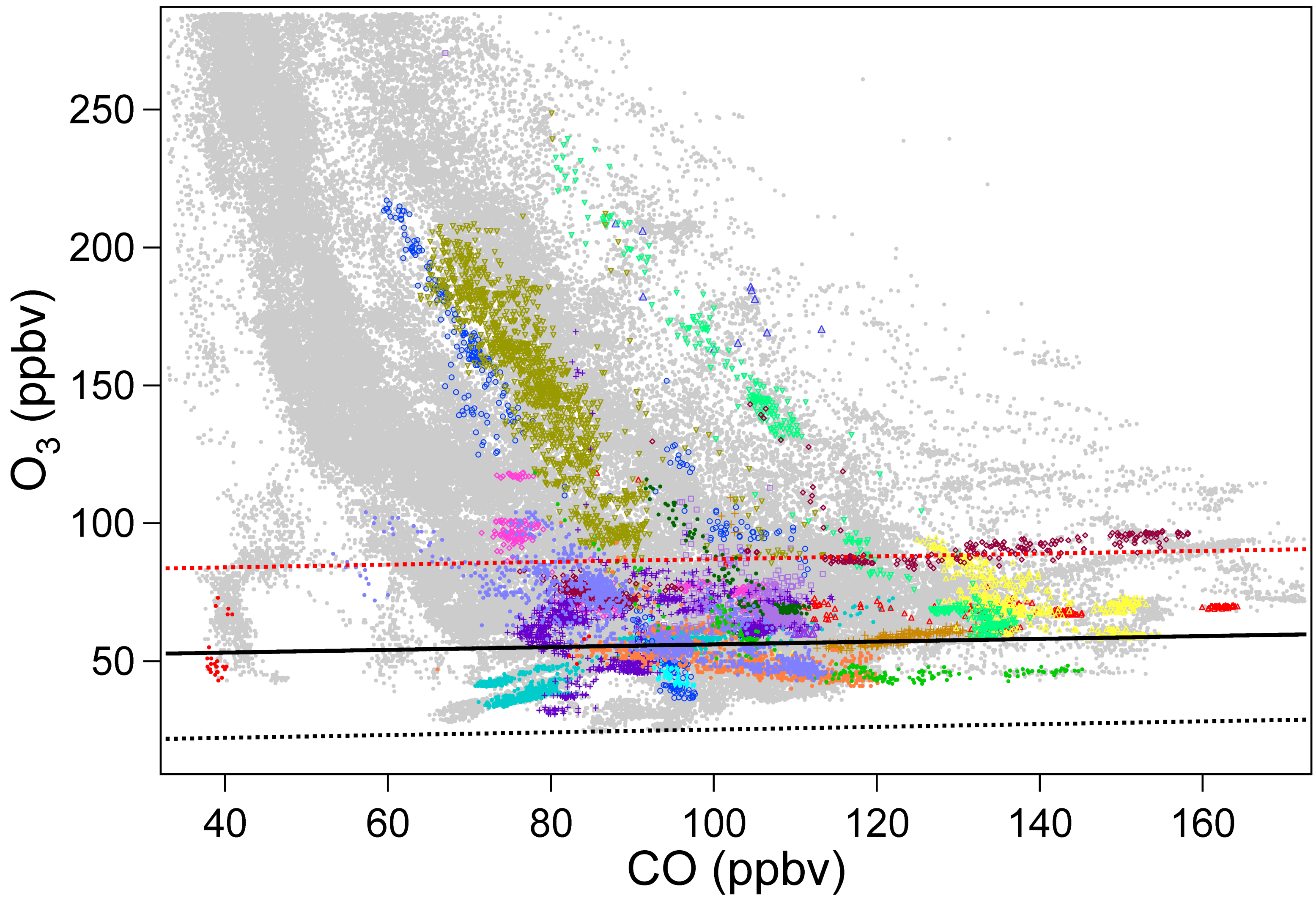
Total water vs. wet potential temperature



Vertical lines represent mixing processes between altitudes

(Paluch, 1979)

Ozone vs. CO tracer plot

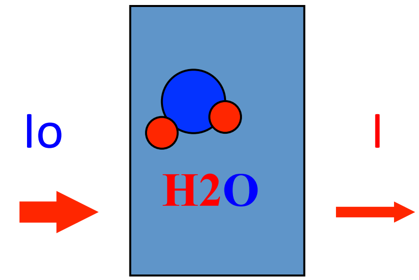


Ice supersaturated regions falling along mixing lines (strat.-trop. and trop.-trop.)

(Pan et al., 2007)

Beer-Lambert law

$$\frac{I(\lambda)}{I_o(\lambda)} = \exp(-\alpha(\lambda))$$



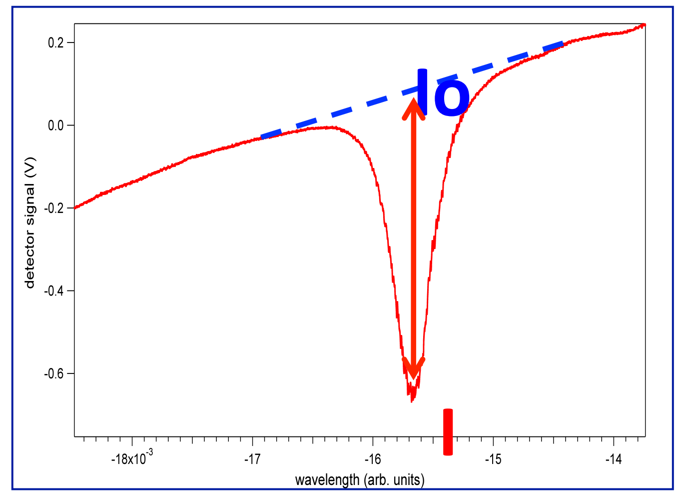
where: $I(\lambda)$ is light intensity after absorption

$Io(\lambda)$ is incident light intensity

$\alpha(\lambda)$ is absorbance

$$a(\lambda) = S(T)\, g(\lambda,T,P)\, N\, l$$

σ = cross section



where: $S(T)$ is the linestrength

$g(\lambda,T,P)$ is the normalized Voigt lineshape function

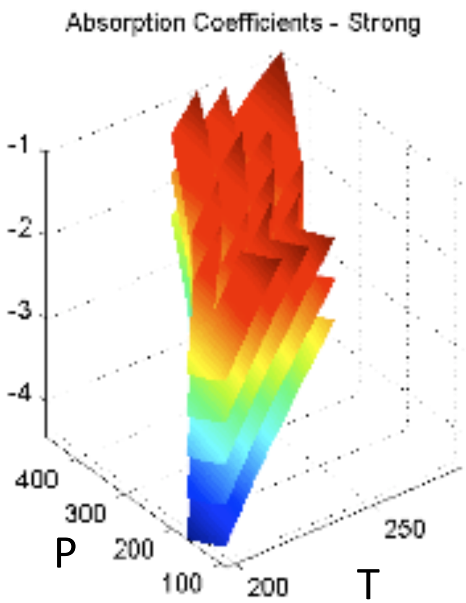
N is the absolute concentration

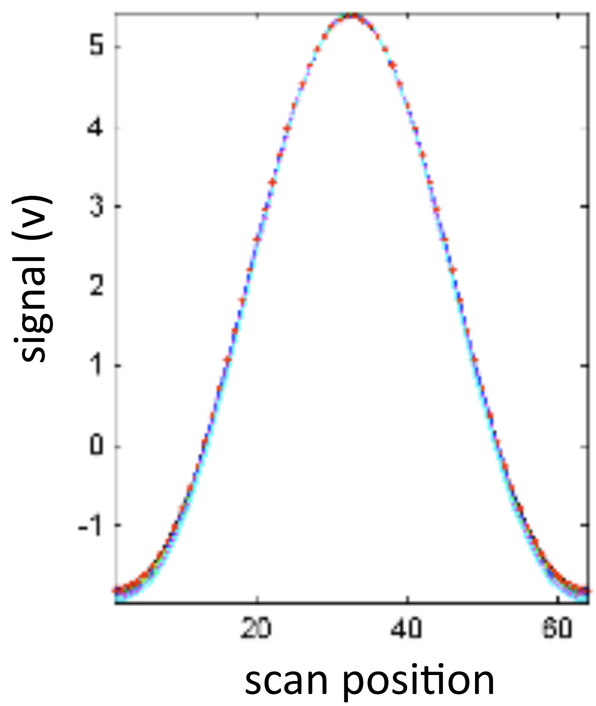
l is the pathlength

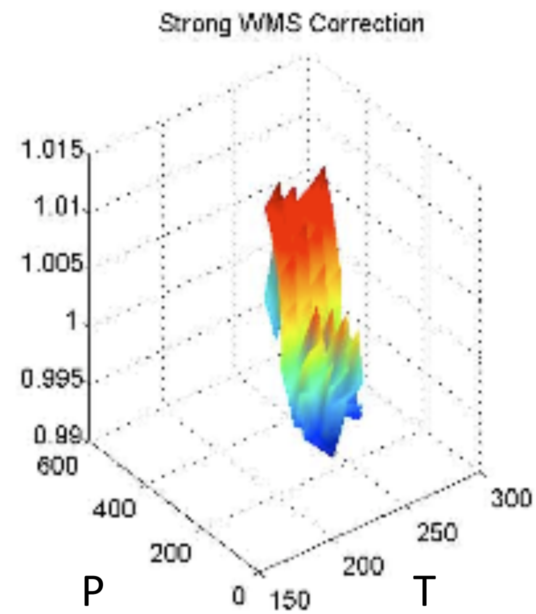
We use wavelength modulation spectroscopy and direct absorption, both based upon the Beer-Lambert law but shifting detection bandwidth into higher frequencies (250 kHz) for better S/N

WMS analysis algorithms

Wavelength modulation spectroscopy (f=250 kHz; 1.5kHz scan rate)
Change modulation depth and scan width as a f(P,T) every second
Normalized peak shape largely invariant
Fit entire trough-to-trough 2f peak shape with stored reference spectrum
Small (< few percent) correction to account for differences from reference condition

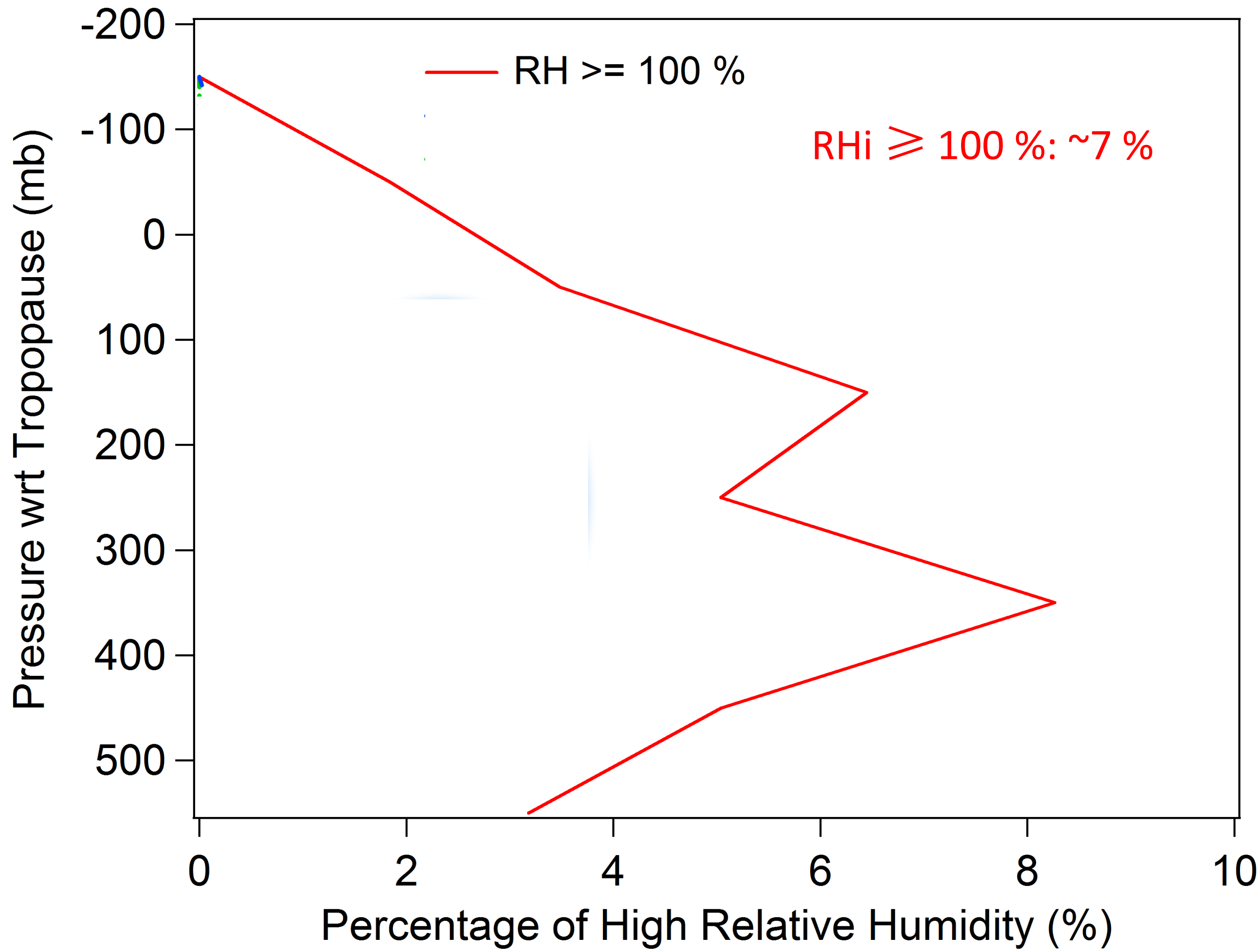






Ref. condition for Aqua-VIT: -63.41ºC, 200 hPa (33.9 ppmv)

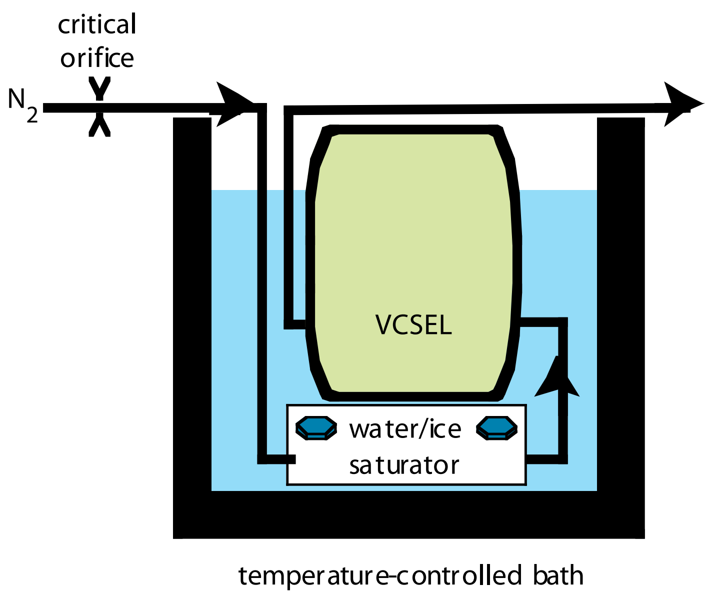
Vertical distribution of ice supersaturation

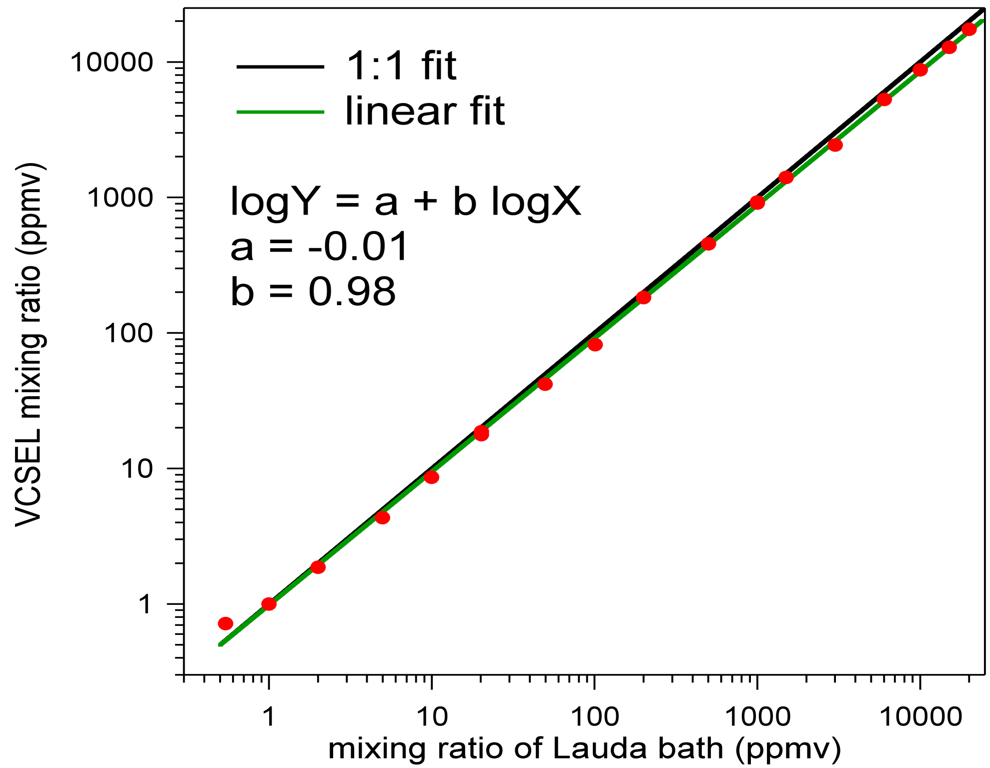


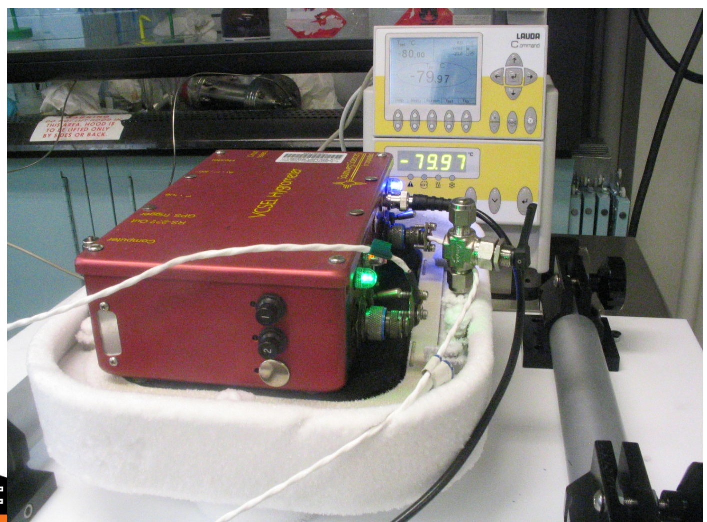
AIRS frequency of supersaturation at midlatitudes (40°–60°N) : 6.5 %

Calibrations at UT/LS temps. and pressures

c) saturated flow directly into immersed VCSEL



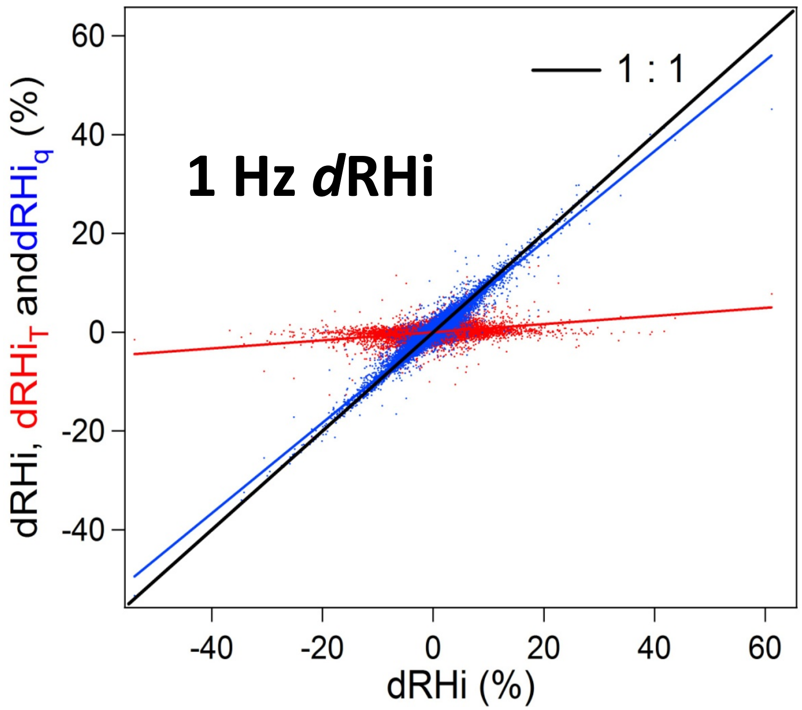


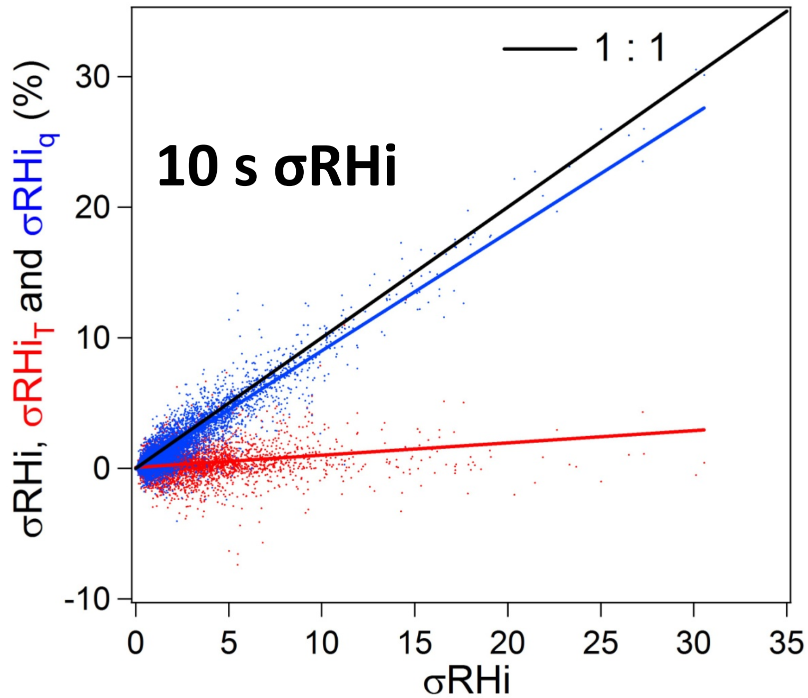


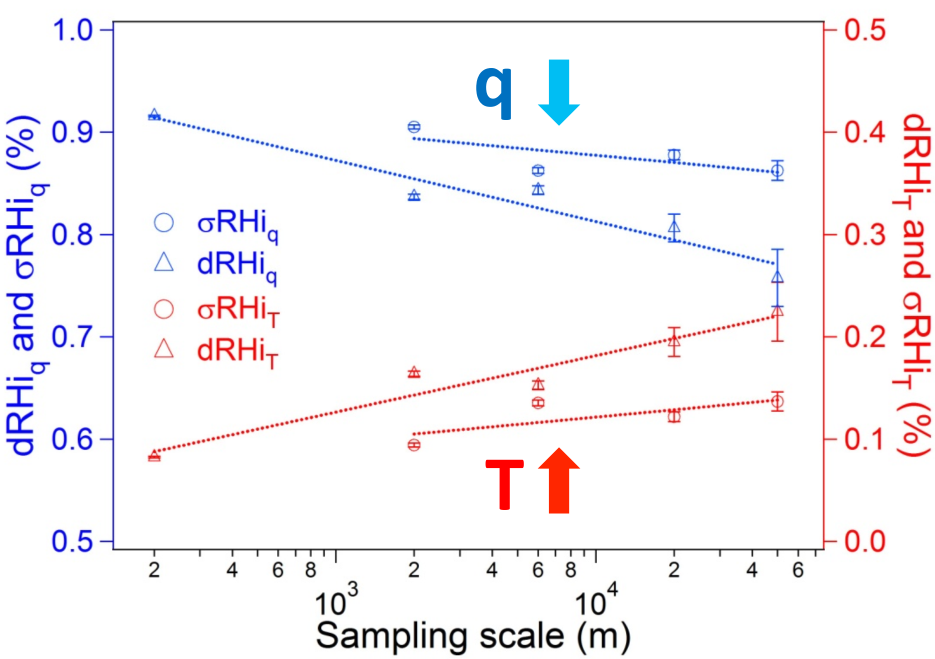
orthogonal methods to verify these results

2-10% agreement with research grade sensors

(AquaVIT, NOAA balloon, NASA DC8, – Zondlo *et al.*, 2010)



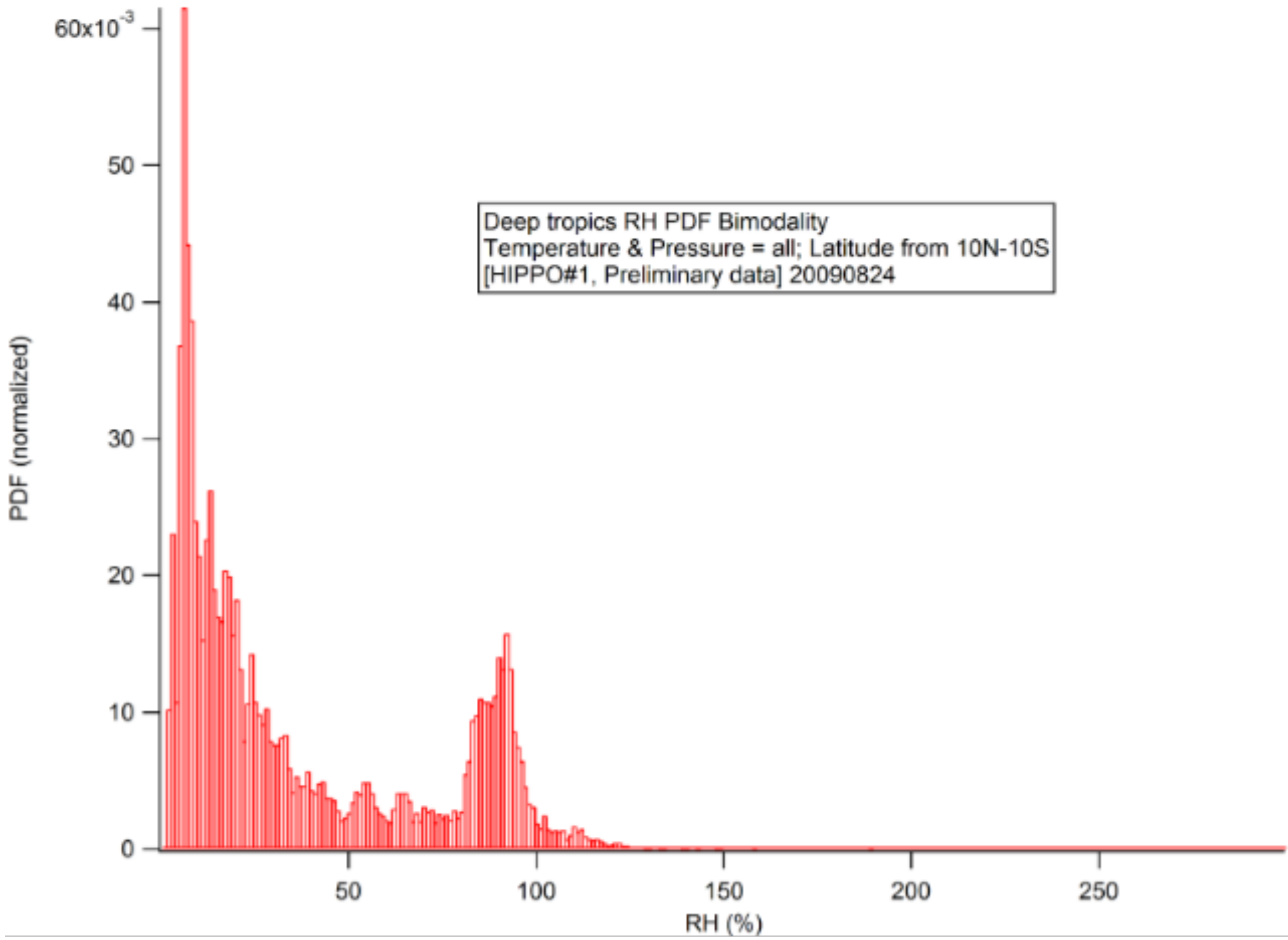




Scale analyses of RHi variability:

Variability of water vapor partial pressure dominates RHi variability (200 m ~ 50 km)

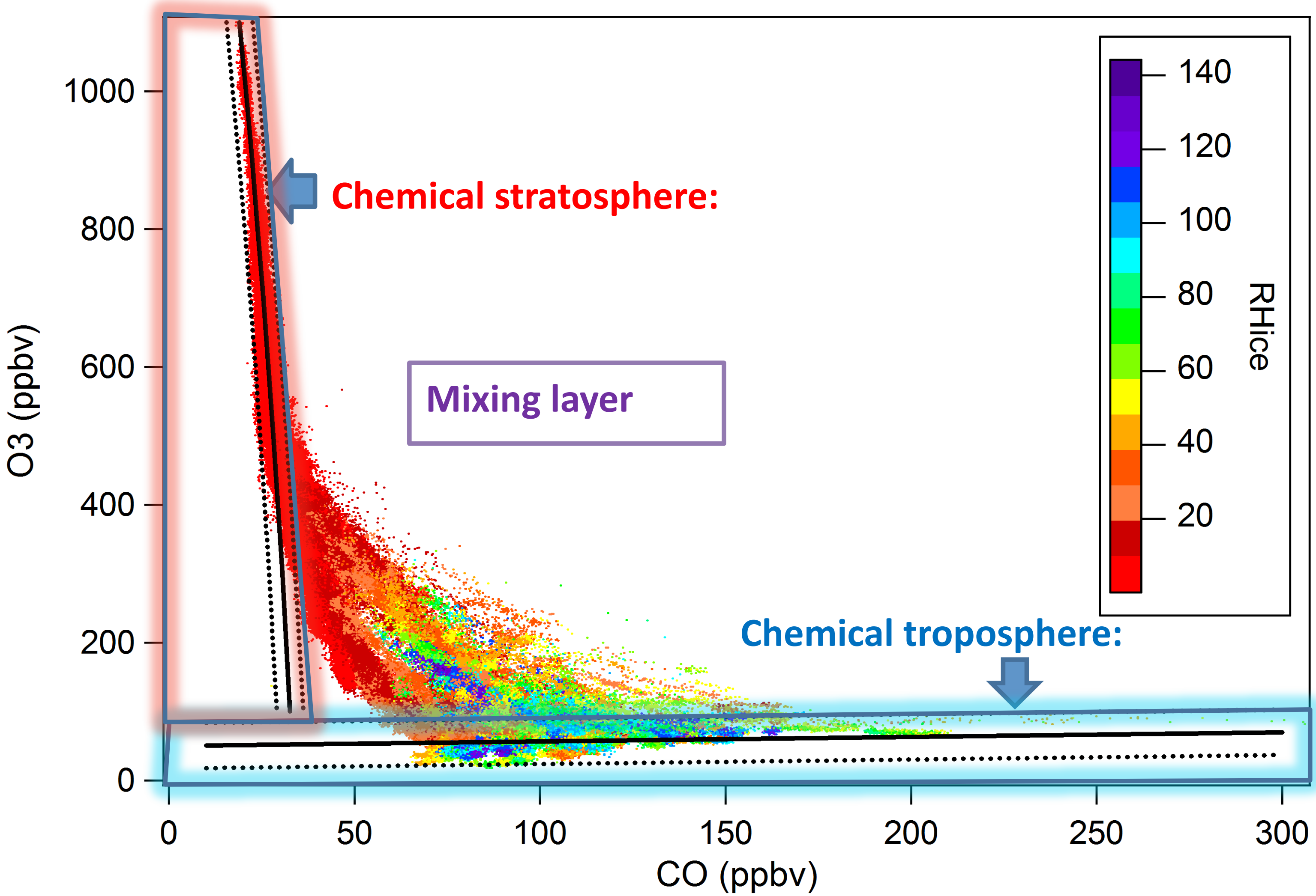
RH bimodality, deep tropics, HIPPO Global



Peak at 13% and 93% RH_{ice} in excellent agreement with AIRS data that show clear sky peak of 10-20% and clouds 75-95%

(Kahn et al., JGR, 2009)

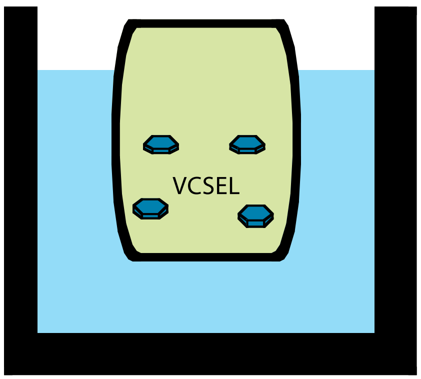
Ice supersaturation in chemical tropopause



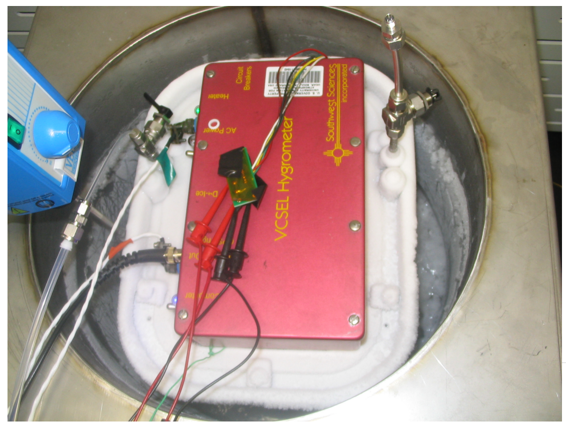
Most ice supersaturation occurs at or below chemical tropopause

Calibrations at UT/LS temps. and pressures: Method B

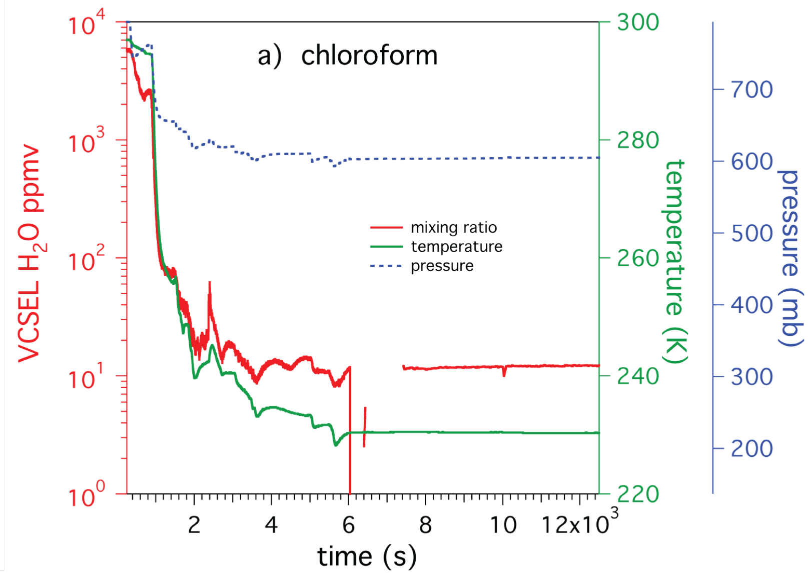
d) VCSEL isolated in cold bath

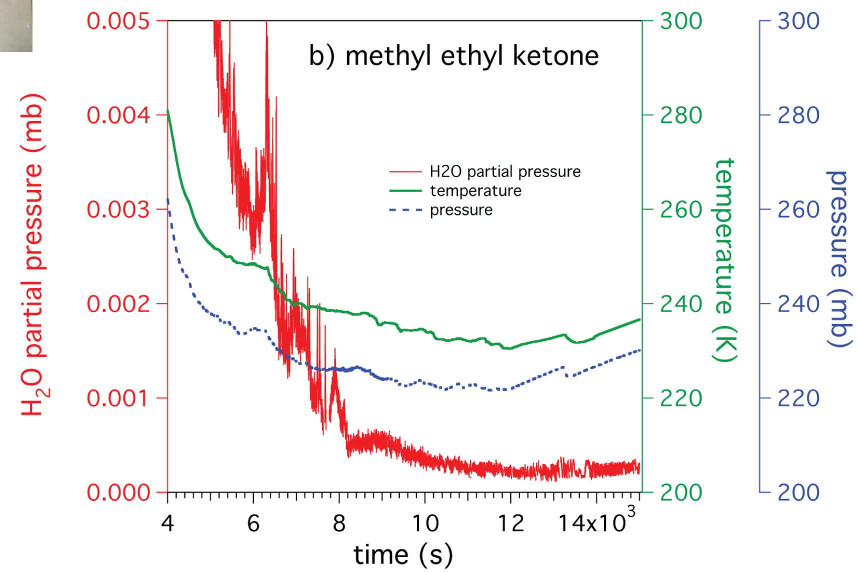


temperature-controlled bath



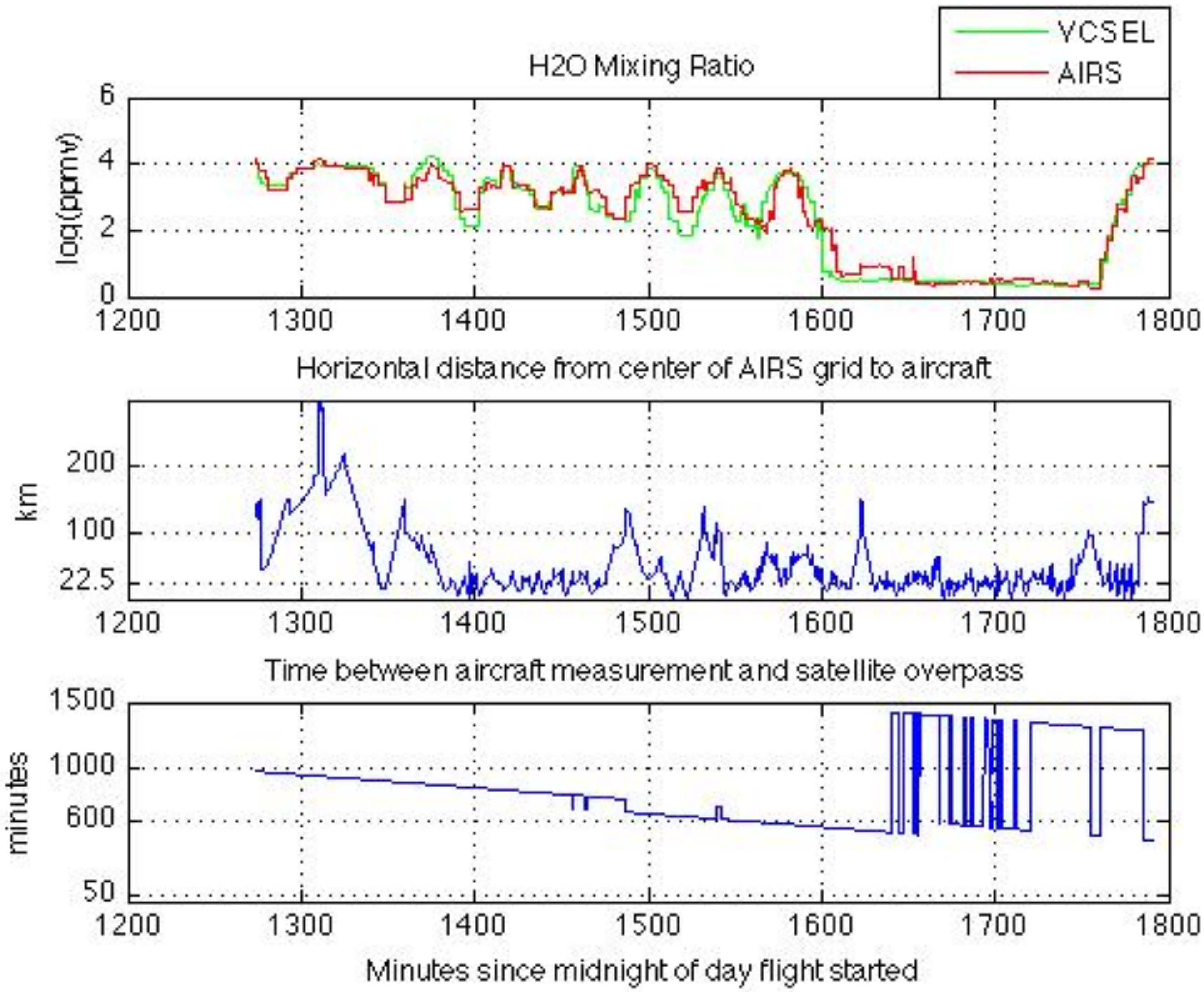
organic (melt. temp.)	nominal	VCSEL (ppmv)
chloroform (-63.41°C):	11.23	11.7 ± 0.2
2-butanone (-86.64°C):	0.77	1.07 ± 0.21
acetone (-94.7°C):	0.18	0.50 ± 0.30





Overall, four orthogonal methods agree to within 5% for > 10 ppmv H_2O; systematic biases minimized due to small design, unique methods

HIPPO #1, RF07: Christchurch to 67 S and back



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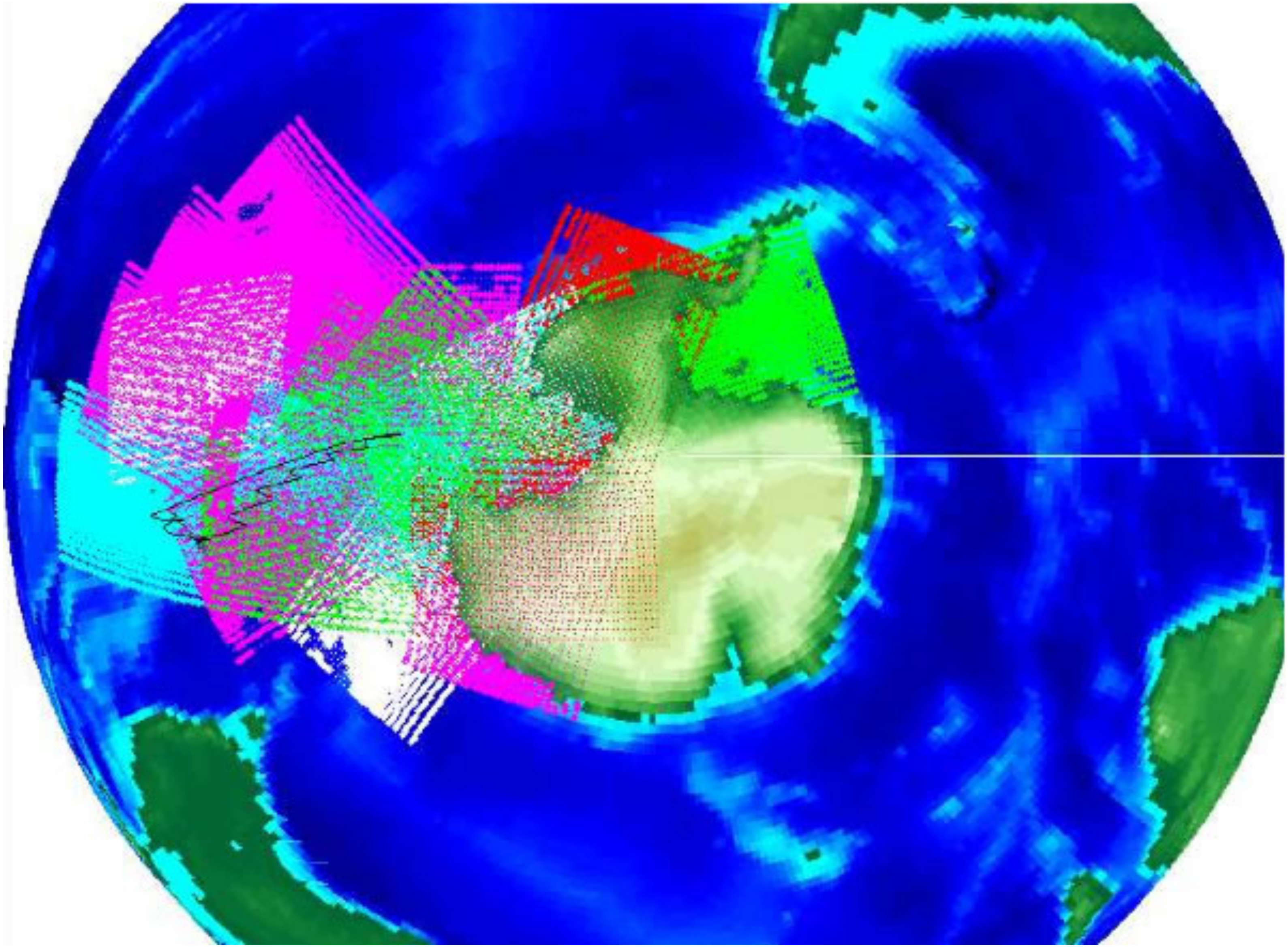
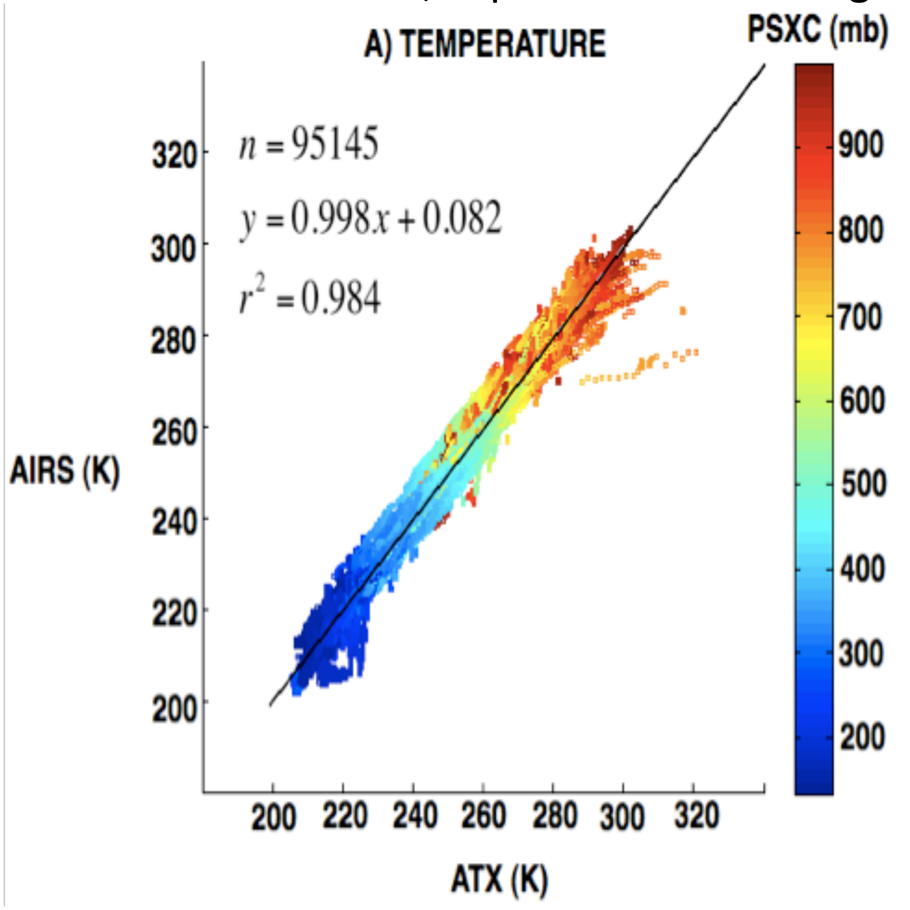
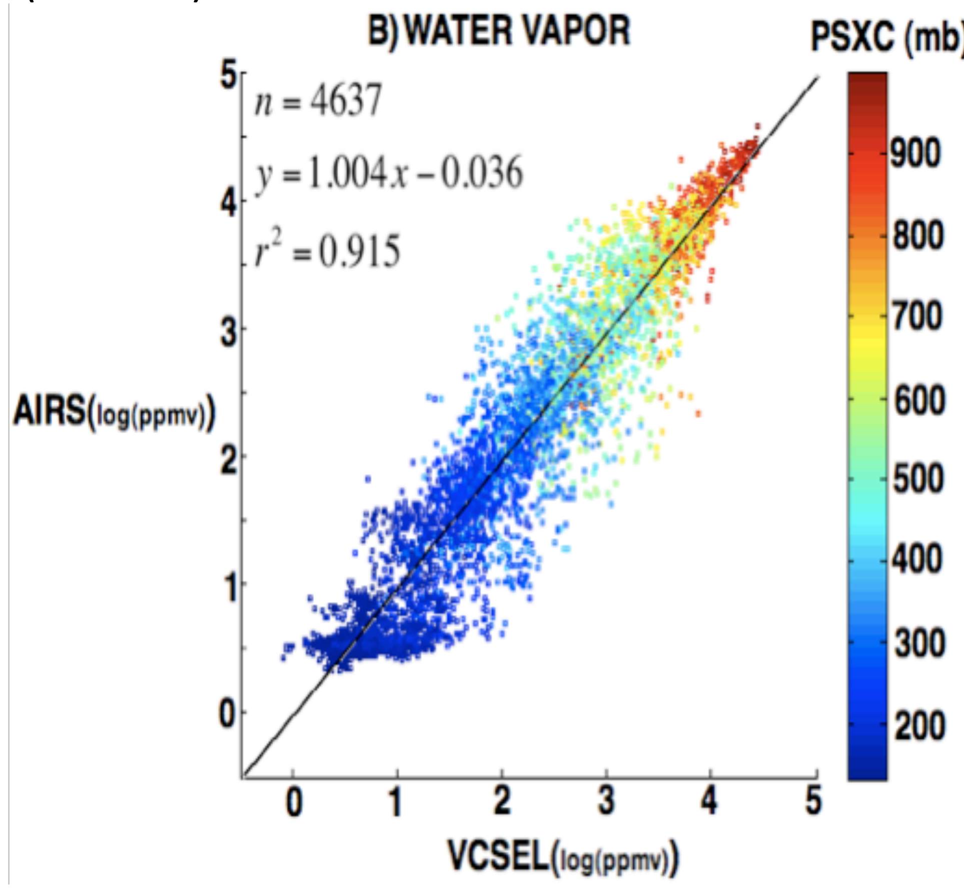


All START08/HIPPO data: AIRS/AMSU-A/VCSEL comparison

v. 5, level 2 standard product, aircraft data averaged to 5 s (~ 1 km); PGood temp.; Pbest H_2O
criteria: coincident space, time; then, coincident in space but within 1, 2, 3, 6 ,12 hrs; if no criteria fulfilled, expand next nearest grid (22.5 km) and restart coincident in time



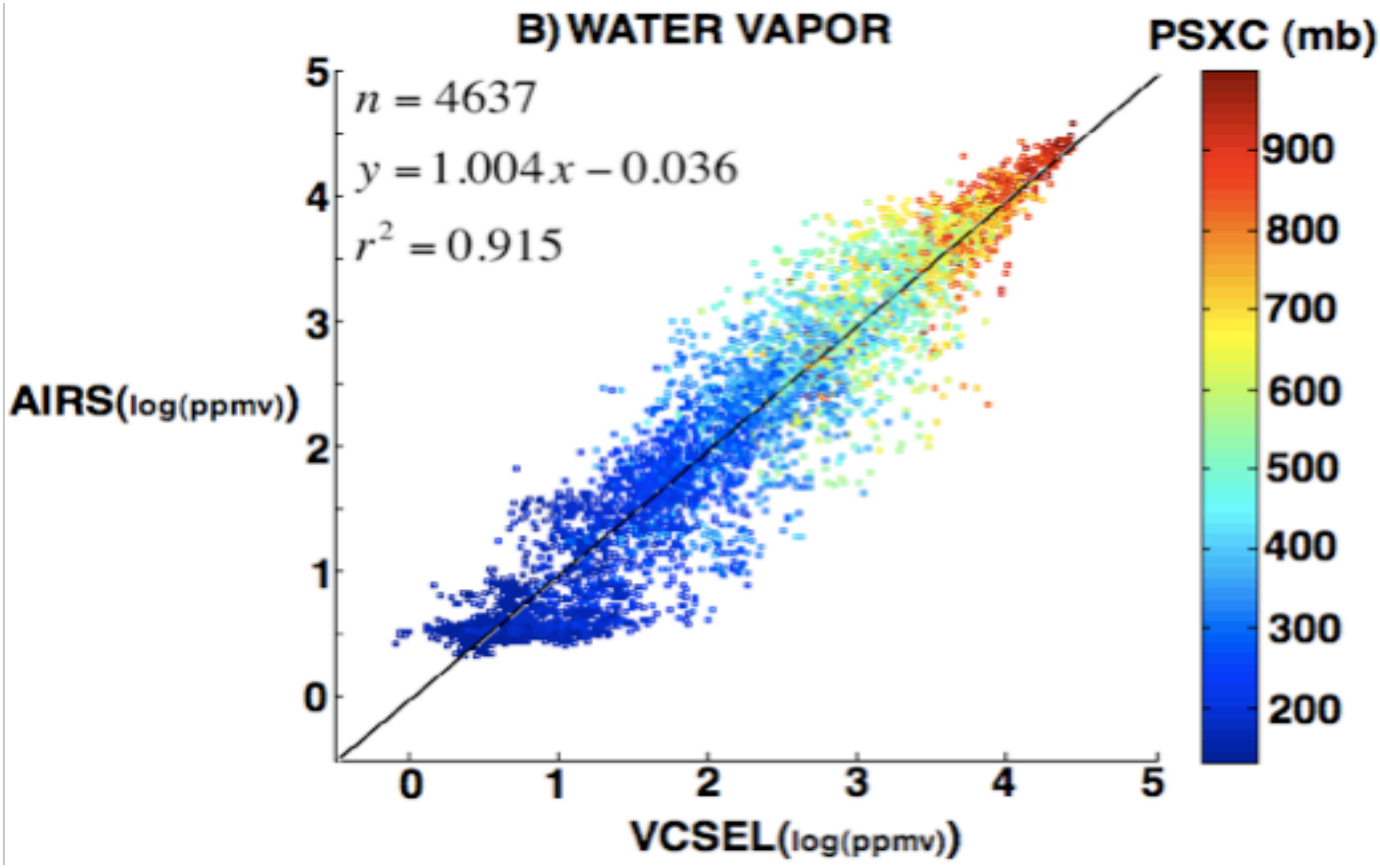


Very good agreement between AIRS and VCSEL, will be basis for further studies to put the aircraft campaigns onto a more global scale (space/time/vertical)

Gettelman et al., 2004: 5 hour average of aircraft data, within 24 hours

r^2(temp)=0.97; r^2 (H_2O)=0.83

All START08/HIPPO data: AIRS/VCSEL

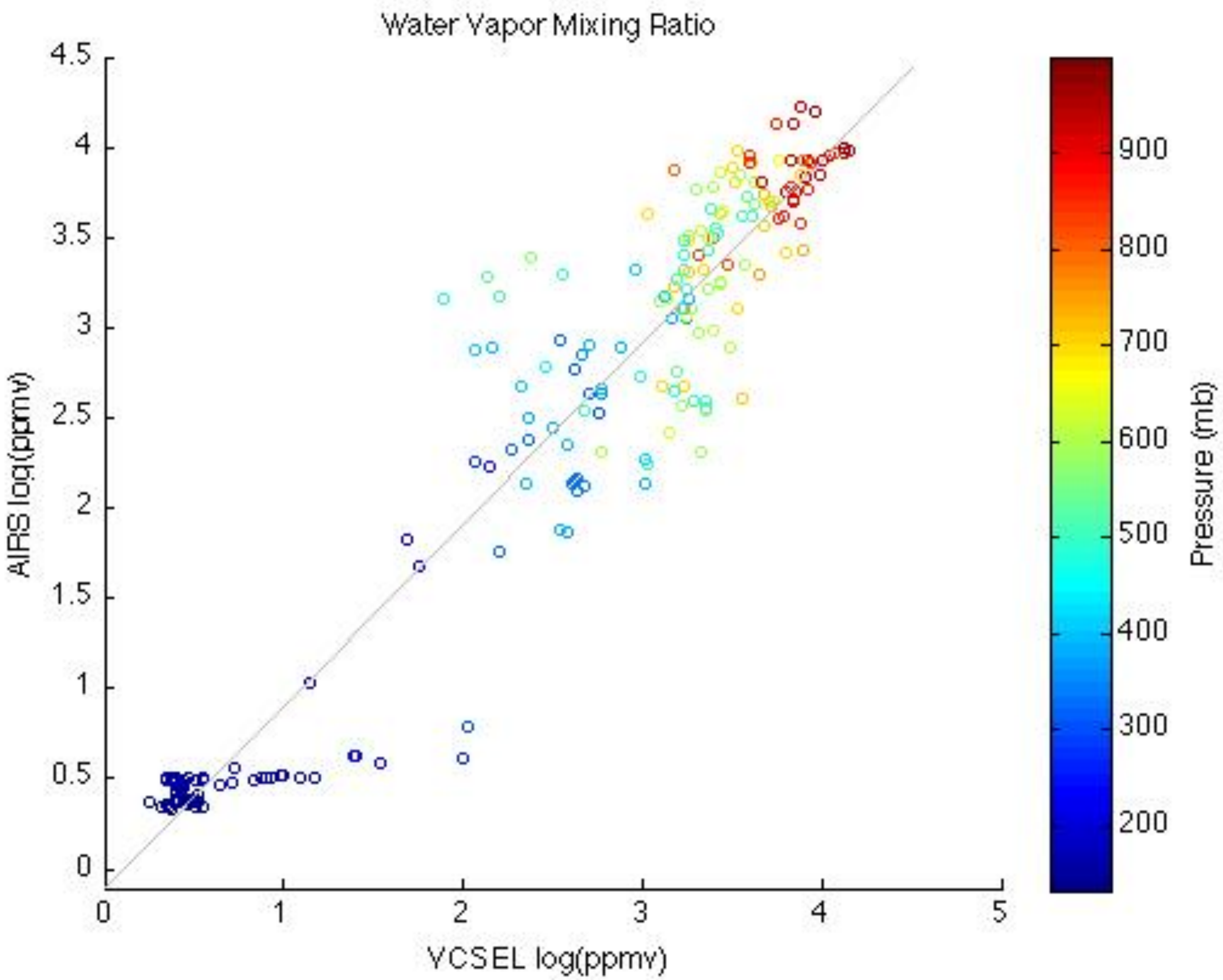


Excellent agreement with AIRS, will be basis for further studies to put the aircraft campaigns onto a more global scale

HIPPO #1, RF07: Christchurch to 67 S and back

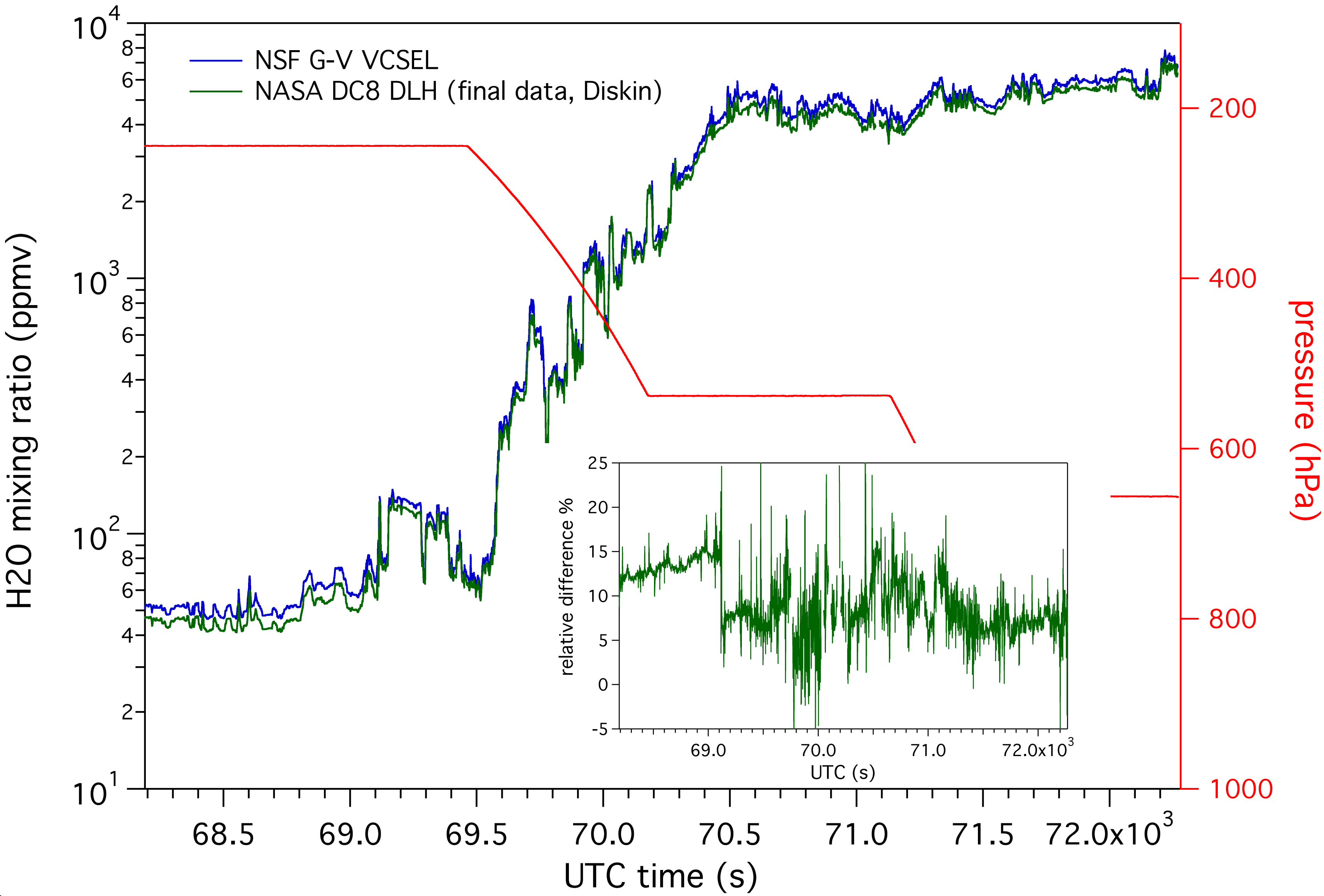
R=0.97

m=1.01



Most comprehensive validation of AIRS in far southern latitudes

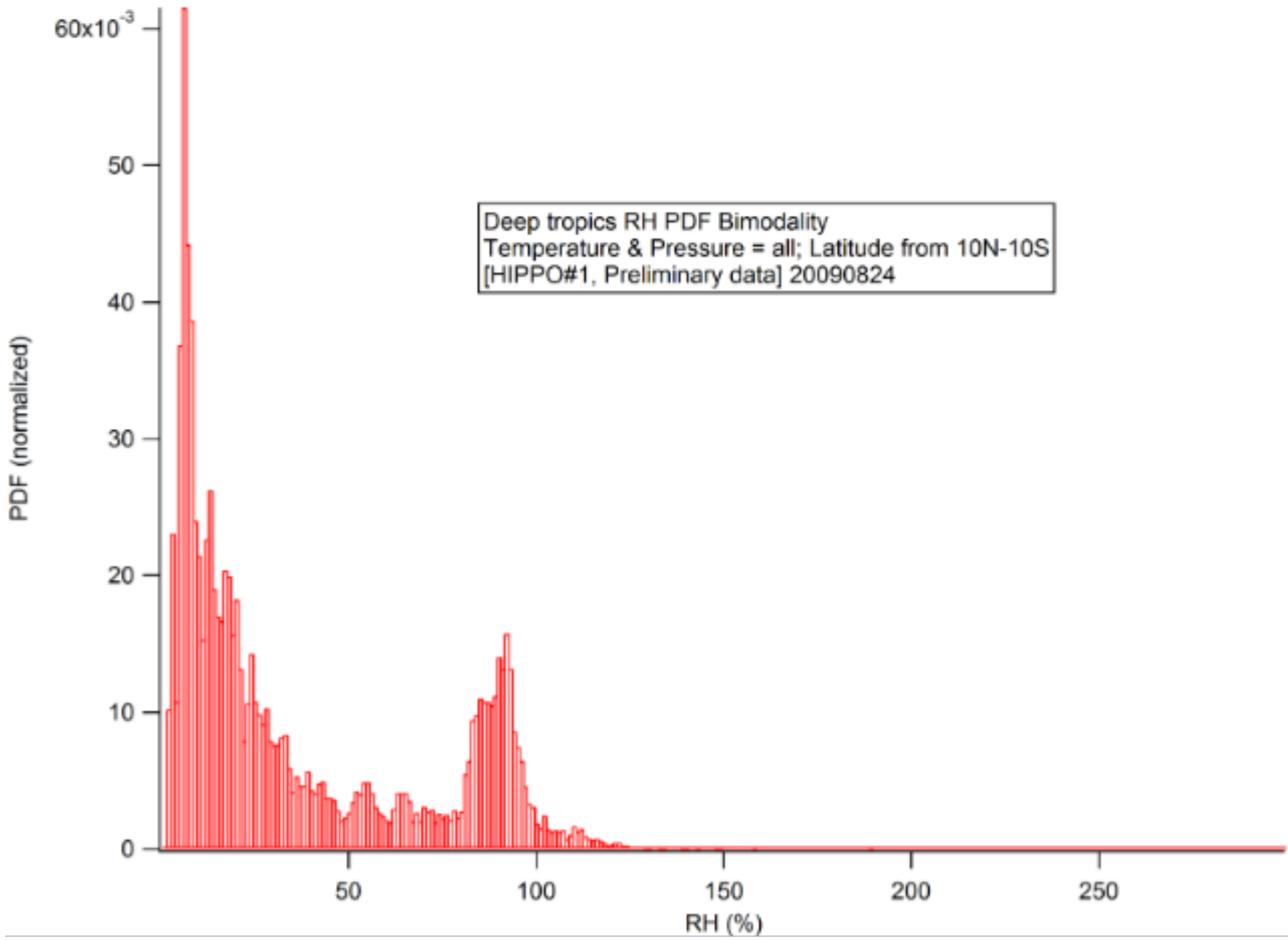
RF 17: G-V VCSEL and DC-8 DLH intercomparison



~ 8% higher than DLH on average

(within sampling and instrument uncertainties)

RH bimodality, deep tropics, HIPPO Global

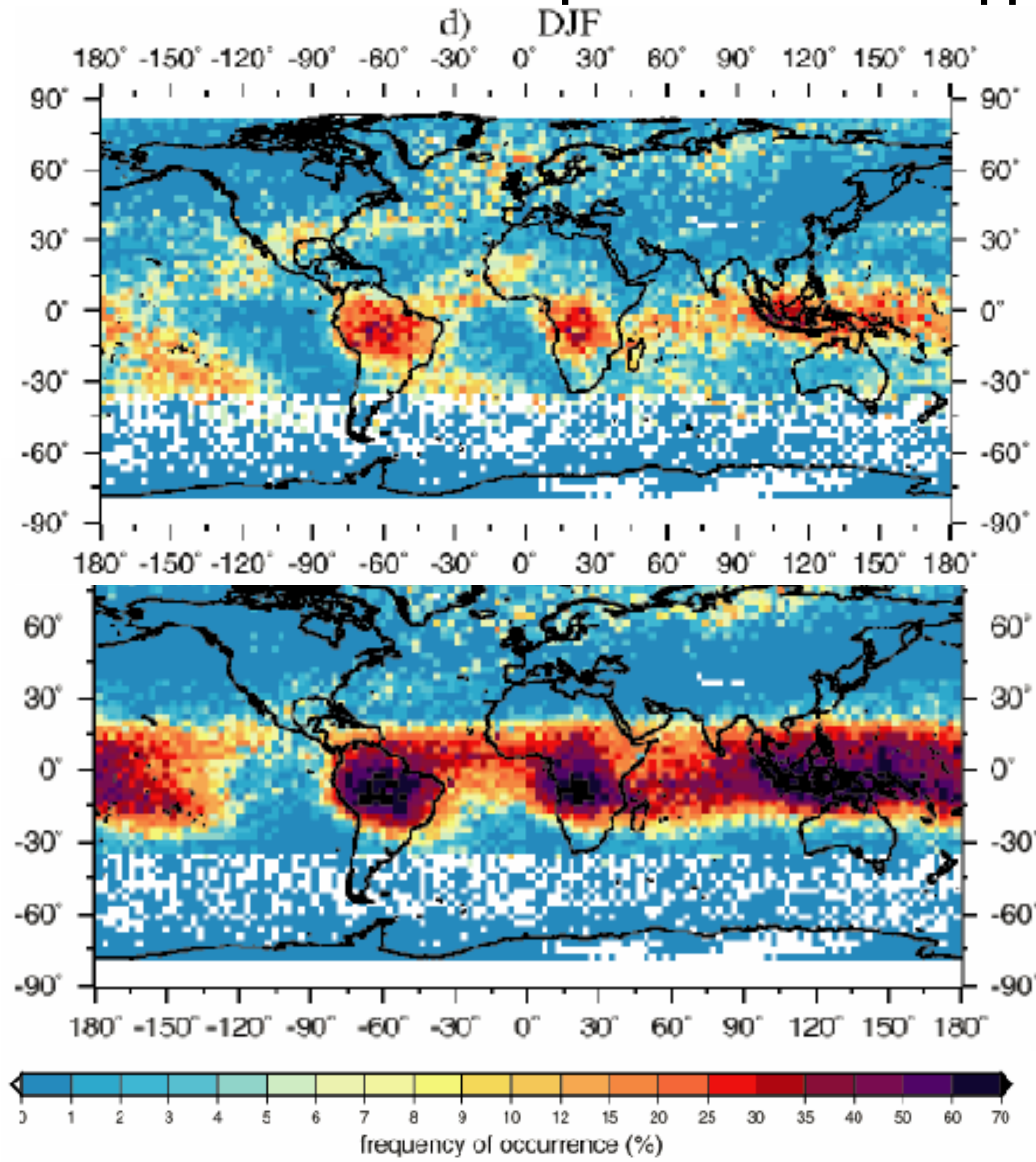


Peak at 13% and 93% RH_{ice} in excellent agreement with AIRS data that show clear sky peak of 10-20% and clouds 75-95%

(Kahn et al., JGR, 2009)

MLS ice supersaturations in upper troposphere

(Spichtinger et al., ACP, 2003)



215 hPa

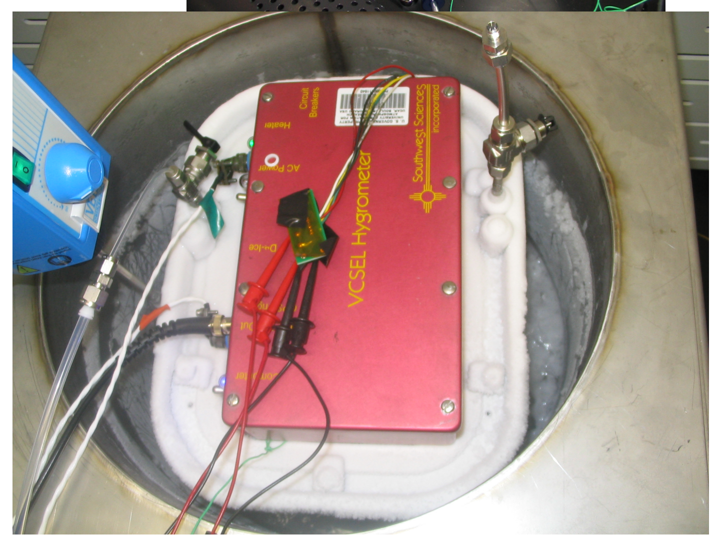
147 hPa

Calibrations: organic phase change, baths

1. Seal sensor in ambient air (no flow)
2. Immerse cell in organic, phase change baths
3. Housing cools to bath temperature
4. Frost forms inside housing (giant cold finger)

<u>Advantages</u>

Representative conditions of T, P, and mixing ratio of UT/LS
Reproducible, well-known bath temperatures
Stable temperature (phase change)
Ability to obtain near zero (e.g. ethanol, -114 C)
Bias from outgassing flow lines, residual H_2O minimized



<u>Caveats</u>

Is the ice vapor pressure at bath temperature?
How long does it take to reach equilibrium?
Is the solvent bath at constant temperature (T gradients)?
Is the cell leak free?

This method was first tested in AquaVIT, used in START08 and HIPPO for low values (chilled mirror, flow dilution for higher)

Ice supersaturation (ISS)

$$ISS = RHi - 1 = e / e_s - 1$$

e: water vapor pressure (water vapor number density, air pressure)

e_s: saturated water vapor pressure wrt ice (temperature)

(Murphy and Koop, 2005)

RH(ice)=120% same as supersaturation=20%

[To avoid mixed phase clouds, restrict analyses to ice supersaturation when T < -40°C]

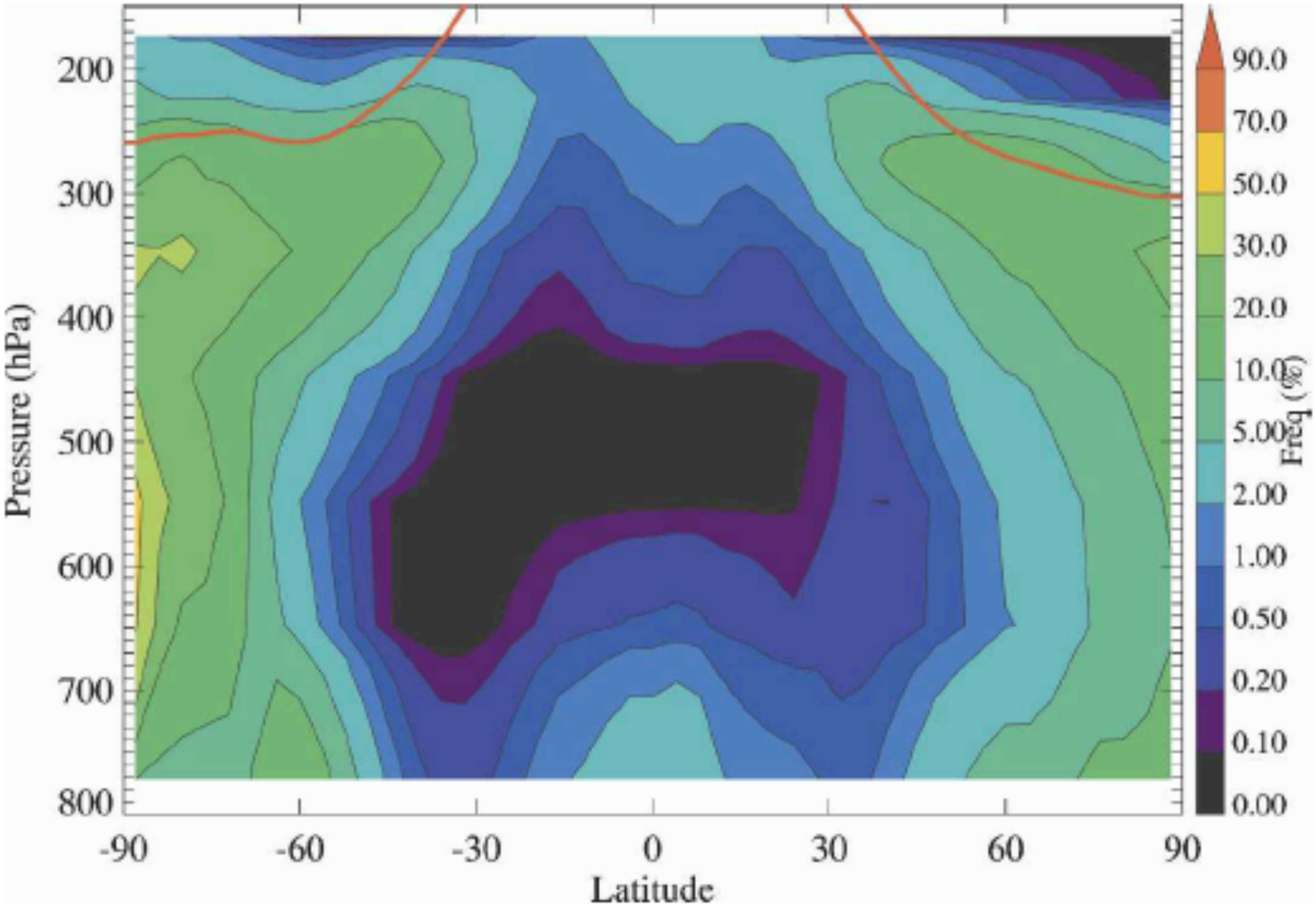
Significance of ice supersaturation:

1. Birthplace of cirrus clouds (typically ~ 120-160% RH_{ice})
2. Controls the amount of water vapor into stratosphere *(Peter et al., 2008)*
3. Large radiative forcing (regionally 10s W m^{-2})
4. Improves ice cloud parameterizations *(Gettelman et al., 2010; Salzmann et al., 2010)*

Ice supersaturation poorly measured in upper troposphere/lower stratosphere (UT/LS)

AIRS supersaturation climatologies

(Gettelman et al., 2006)

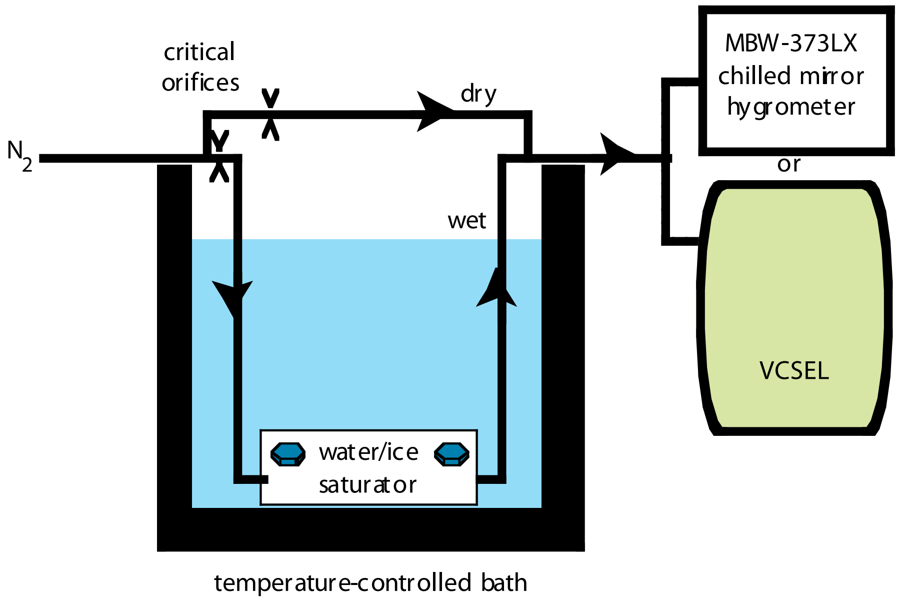


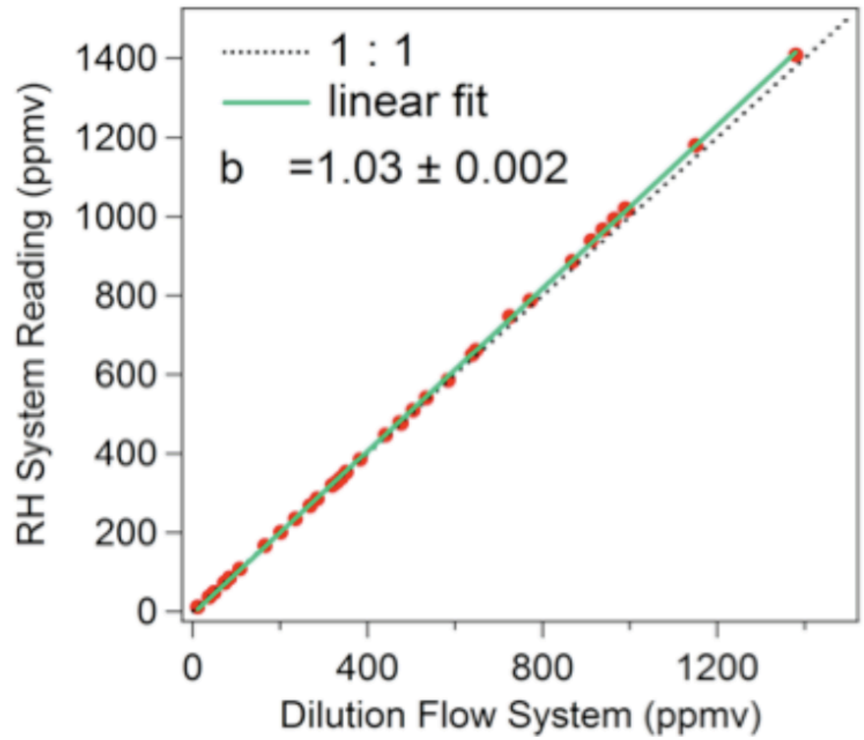
Large frequencies of ice supersaturation in polar regions and near tropopause

What are the scales, magnitudes, and frequencies and environmental conditions of ice supersaturated regions from high-resolution aircraft data?

Calibrations: 2) calibrations at sub-saturated conditions

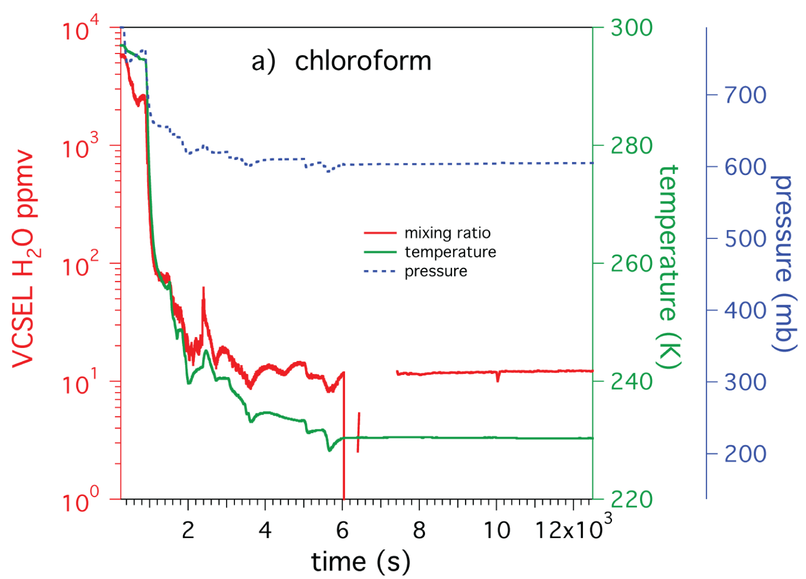
b) saturated/dry flow directly into VCSEL outside bath





mix "dry" and "wet" flows, excellent agreement > 20 ppmv
do not use this method below ~ 100 ppmv because of unknown amount of H_2O in "dry" nitrogen (typically 1-5 ppmv)

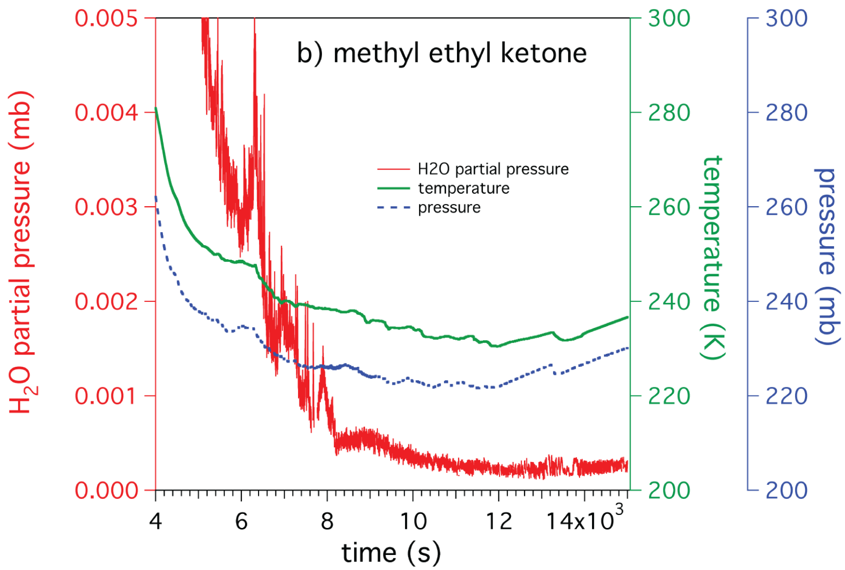
Organic-liq. N_2 slush bath calibrations



a) chloroform (-63.41°C)

nominal 11.23 ppmv

VCSEL=11.74 ± 0.16 ppmv



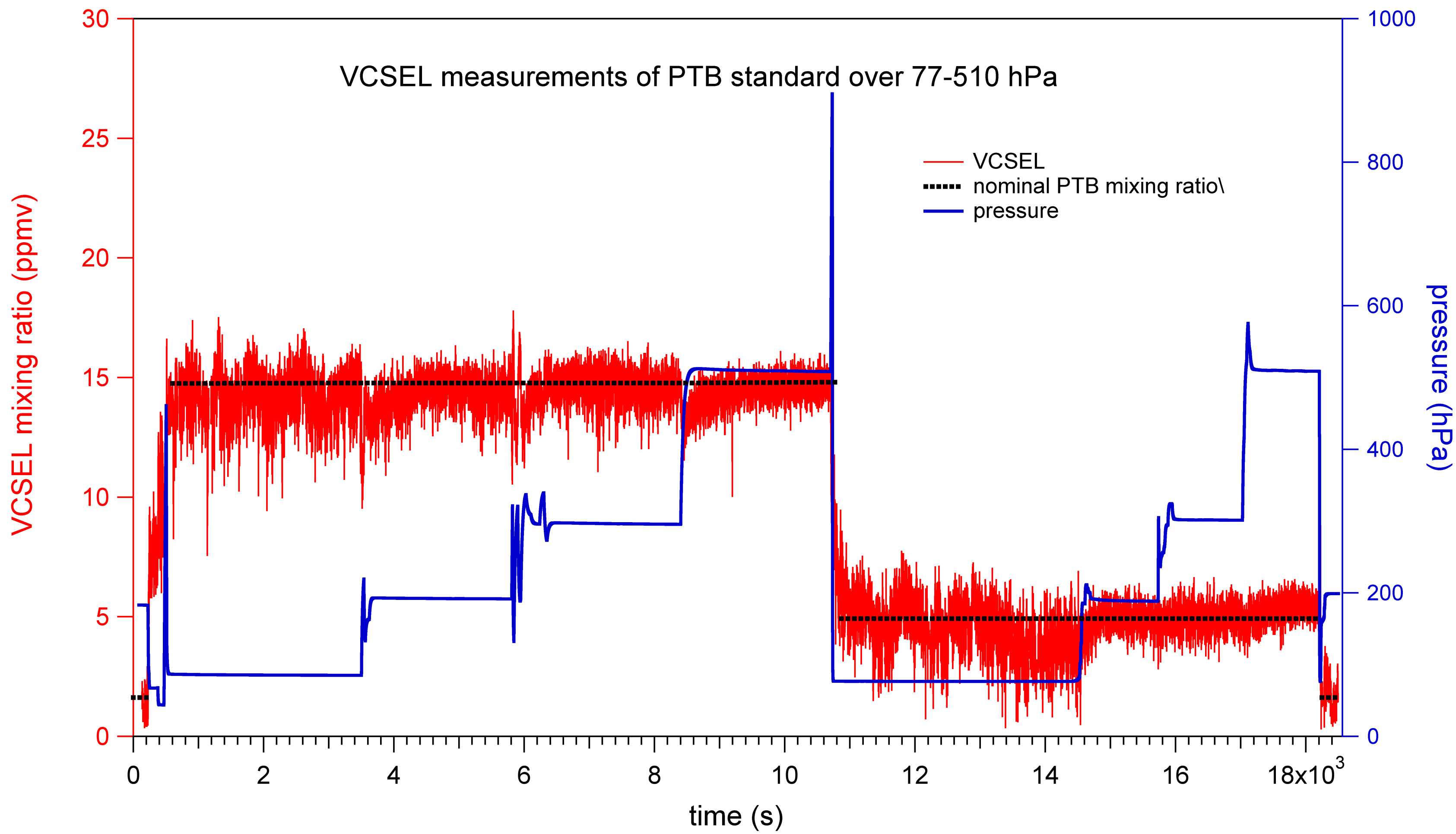
b) 2-butanone (-86.64°C)

nominal = 0.77 ppmv

VCSEL=1.07 ± 0.21 ppmv

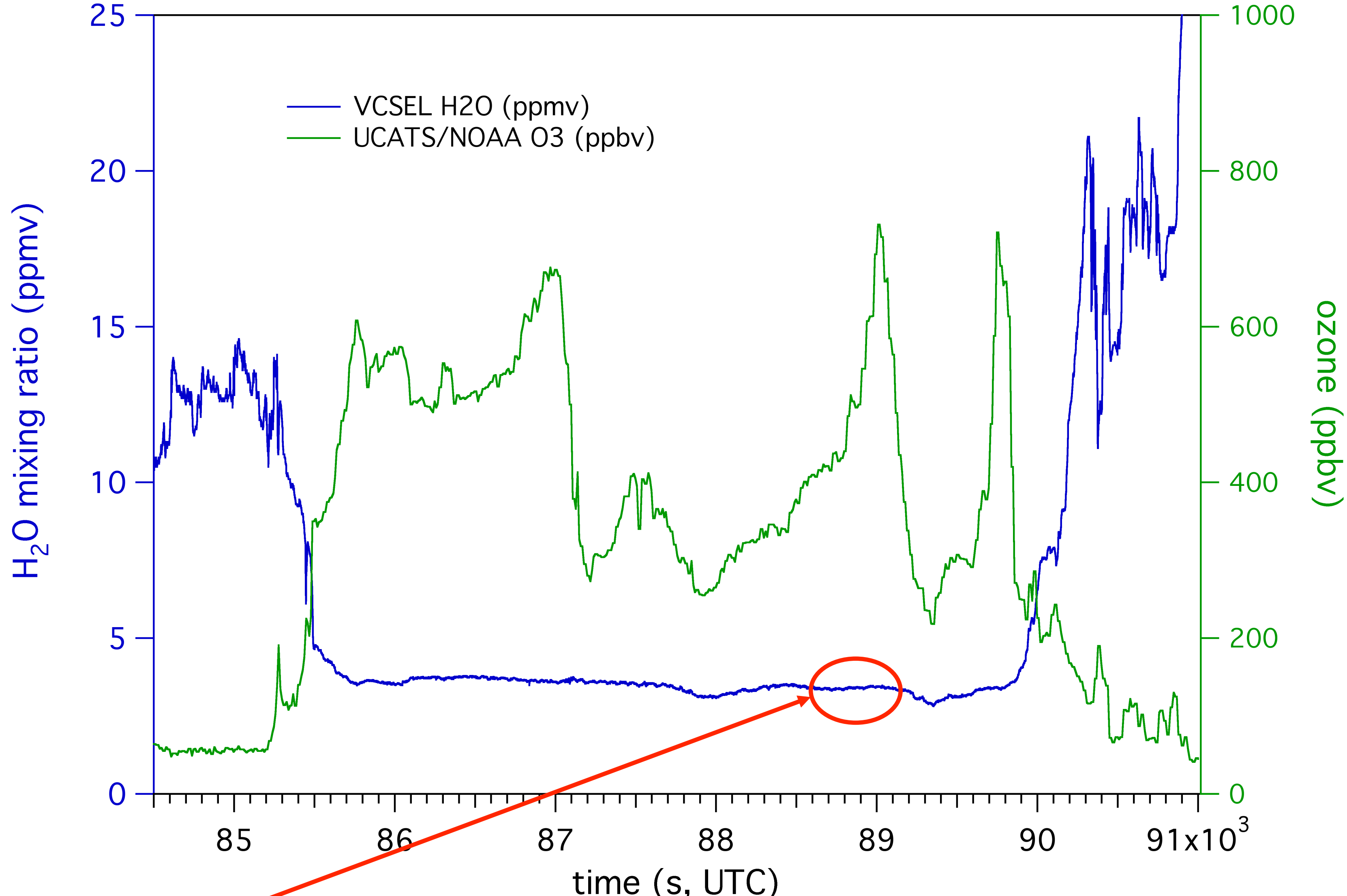
Acetone (-94.7°C: nominal 0.18 ppmv; VCSEL= 0.5 ± 0.3 ppmv)

AquaVIT blind intercomparison (AIDA chamber)

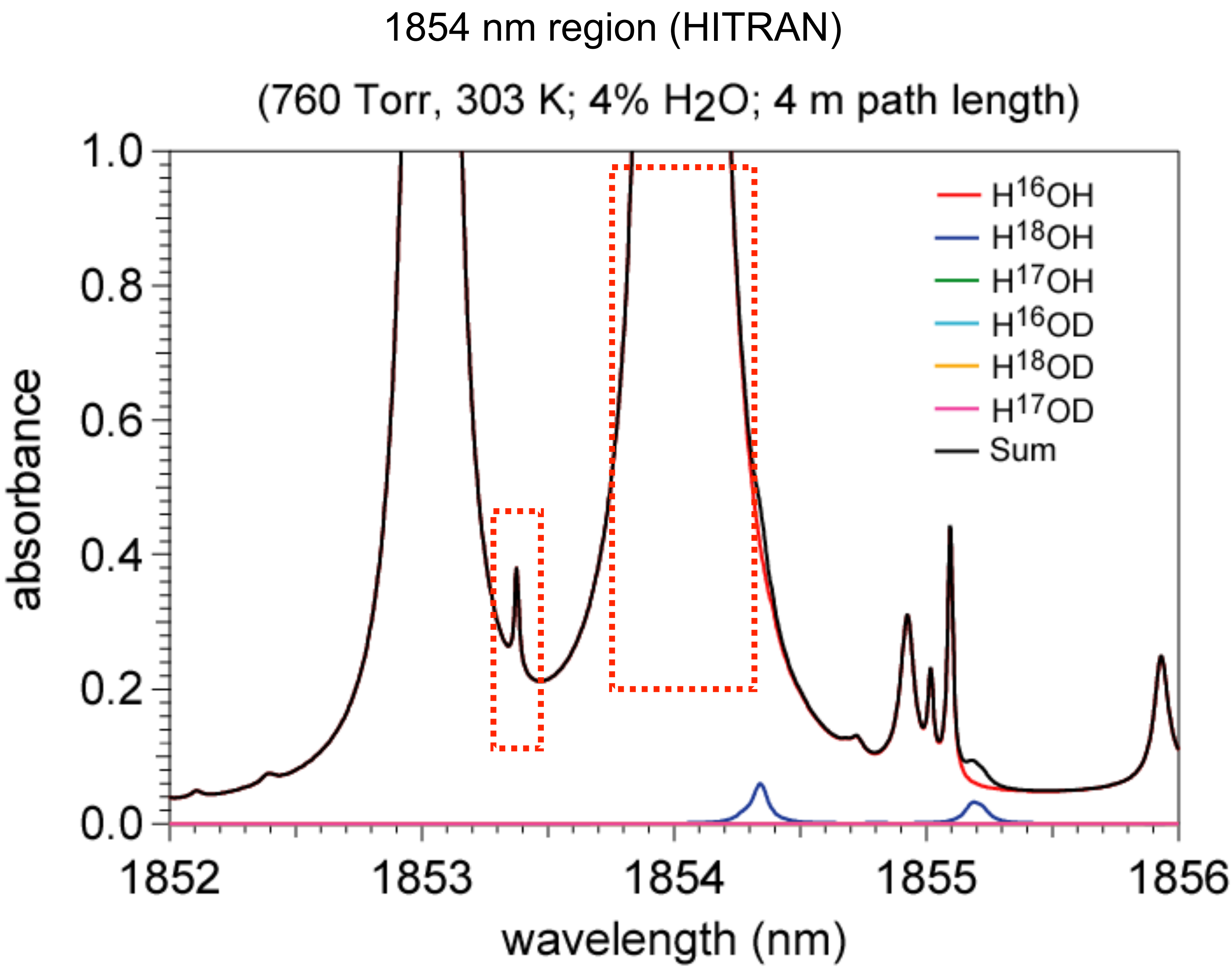


Double-blind AquaVIT intercomparison agreed 2-8% from 4.79 to 14.5 ppmv over range of pressures

In-flight performance
(HIPPO #1, RF03: stratosphere)

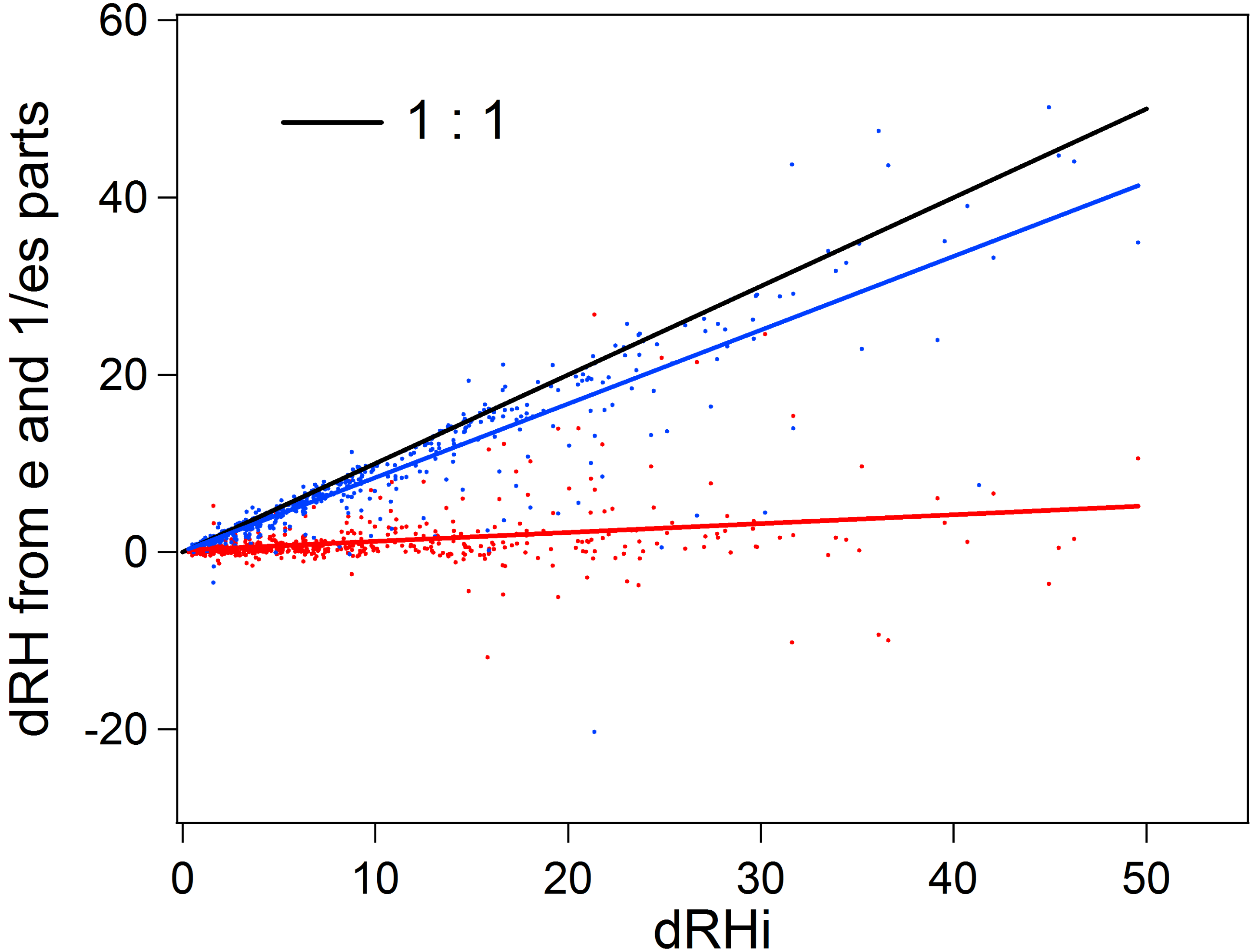


⇒ 1 Hz precision, 2σ = 1.8% at 3.39 ppmv (204 K, 162 hPa)



⇒ transition between lines around -30 C frost point

Comparison of inside/outside ice supersaturated regions

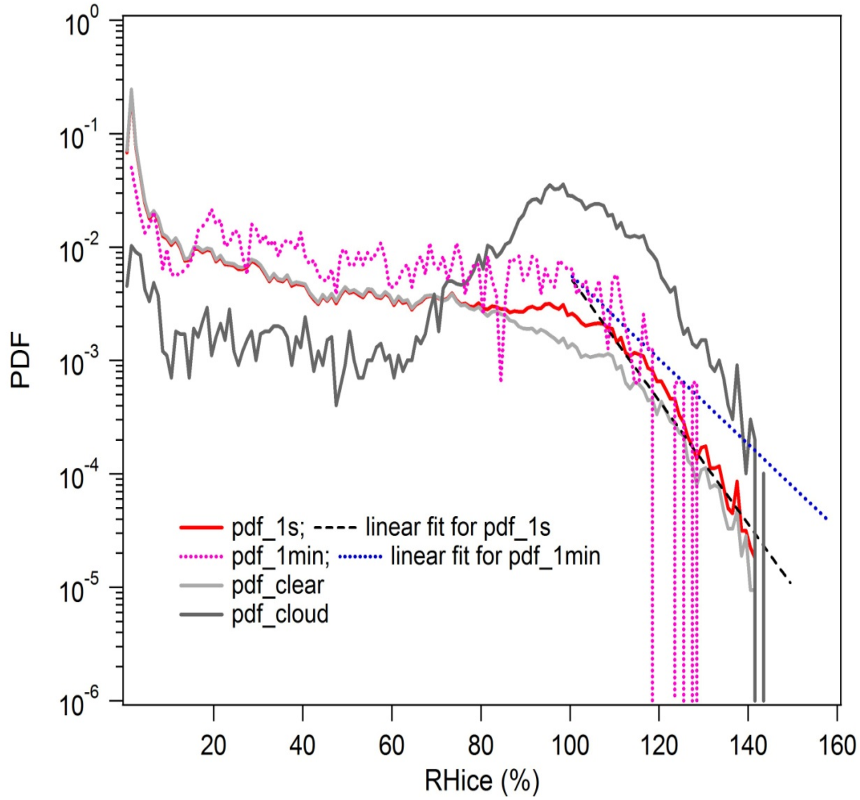


Changes in water vapor dominate ISSRs

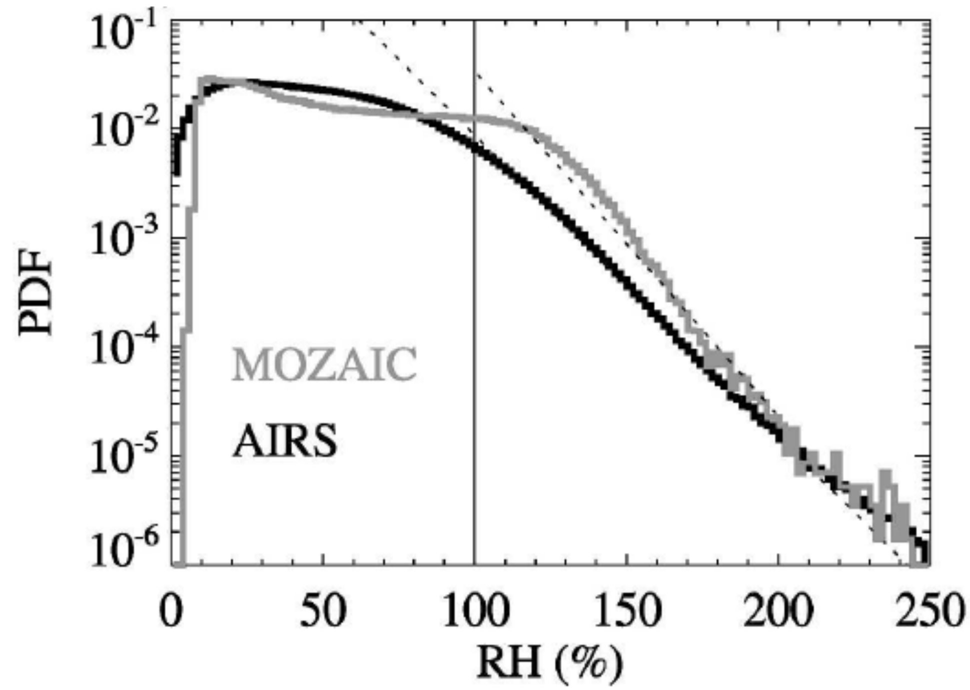
Can we generalize this to other relative humidities?

Comparison to AIRS and MOZAIC

VCSEL 1 s avg. data: -0.13
1 min. data: -0.09



Midlatitudes 600-200mb (100 < RH < 200)
AIRS exponent b = - 0.06
MOZAIC exponent b = - 0.07



AIRS data in black,
MOZAIC data in dark gray
(Gettelman et al., 2006)

AIRS / MOZAIC see many more larger ISSRs than the G-V data
Faster removal of ice supersaturated regions in G-V data;
related to scale differences or sampling protocols?