Water vapor in TORERO

Mark A. Zondlo

Dept. of Civil and Environmental Engineering
Center for Mid-Infrared Technologies for Health and the Environment

PRINCETON UNIVERSITY

Minghui Diao, Garnet Abrams, Loayeh Jumbam (Princeton)
Stephan Feuglister; Eric Wood groups (Princeton); Leo Donner (NOAA GFDL)
HIPPO, PREDICT, START08 Science Teams
NCAR EOL Flight and Technical Crews

NSF AGS-1036275, NSF ATM-0840732, NASA NNX09AO51H

TORERO Science Workshop
Boulder, Colorado

November 1, 2011

Cirrus clouds, RH_{ice}, and TORERO

1. What are the characteristics and environmental conditions of ice supersaturated regions in the eastern tropical Pacific?

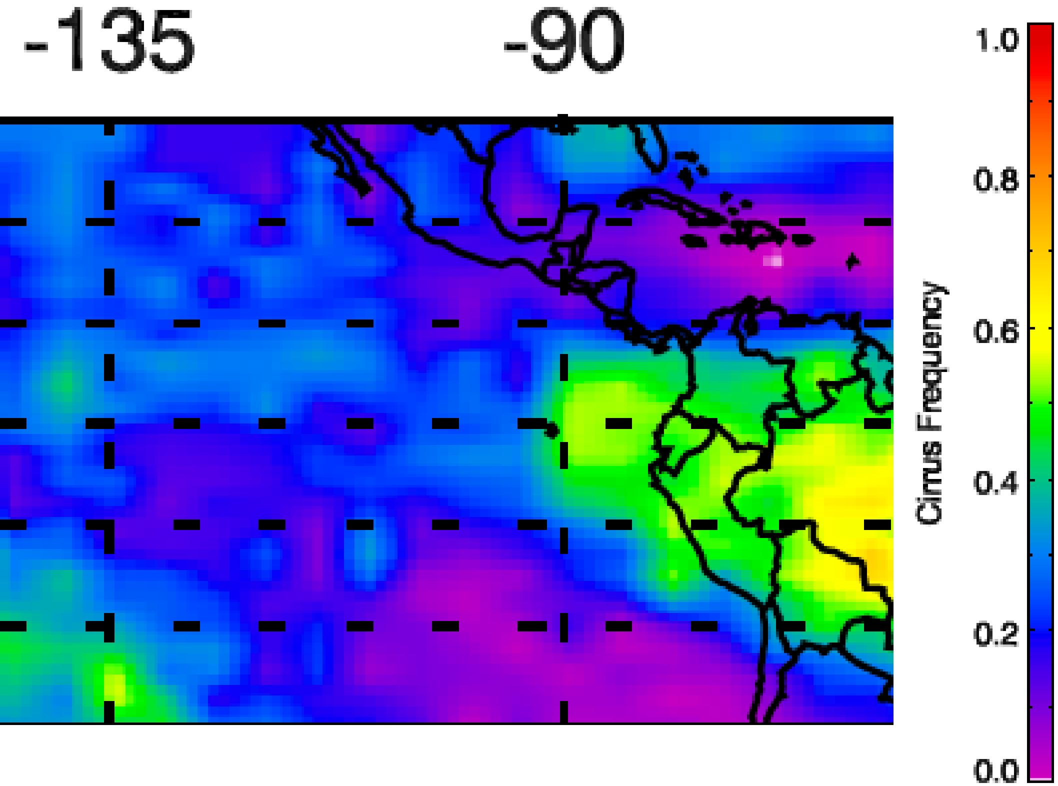
2. Do ice supersaturated regions form in regions of recent deep convection?

3. What governs the distribution of water vapor, especially in the tropics?

4. What is the variability of water vapor in and removed from deep convection?

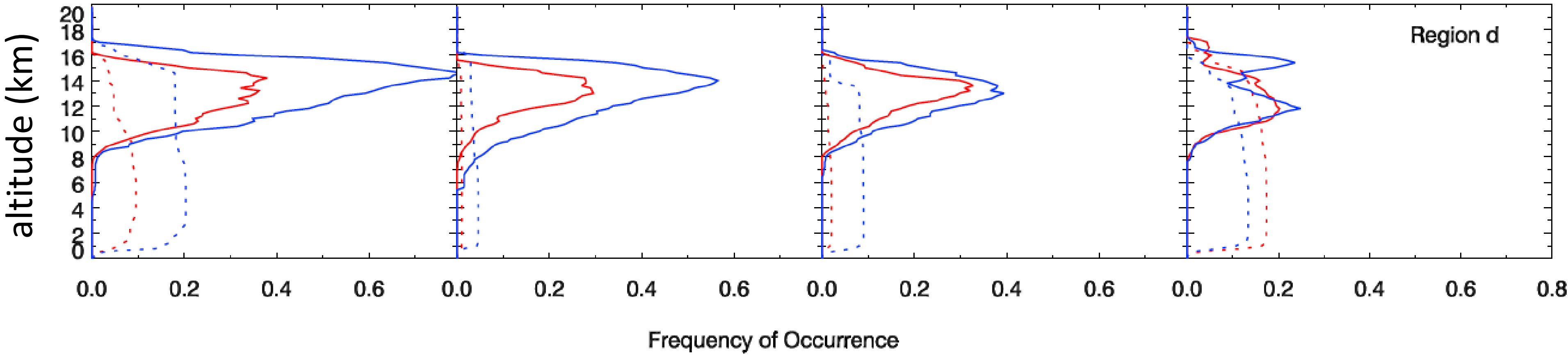
5. How can we link the cloud scales to model grid cell and satellite scales?

Cirrus in tropical eastern Pacific *(Sassen et al., 2009)*

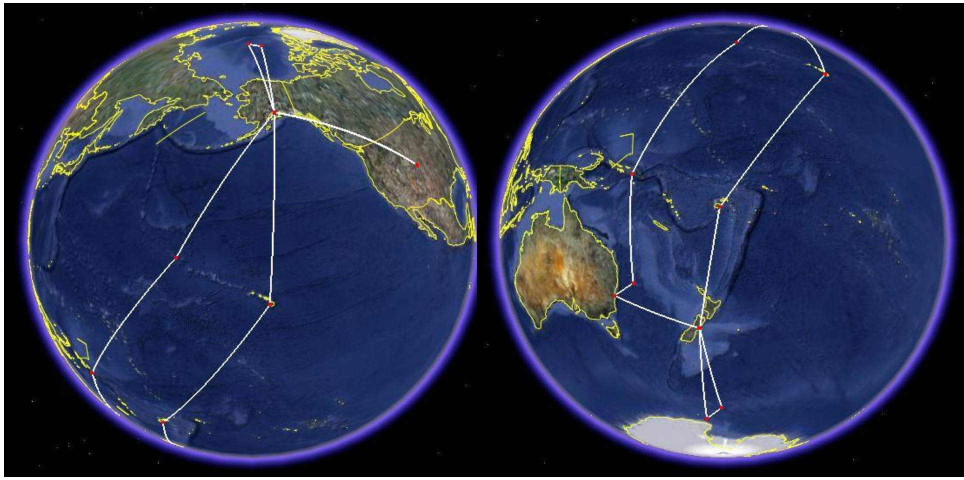


- up to 60% cirrus in DJF
- most frequent in 12-14 km region
- more frequent at night than day

Altitude dependence off Costa Rica (day; night):



Comparison to PREDICT and HIPPO

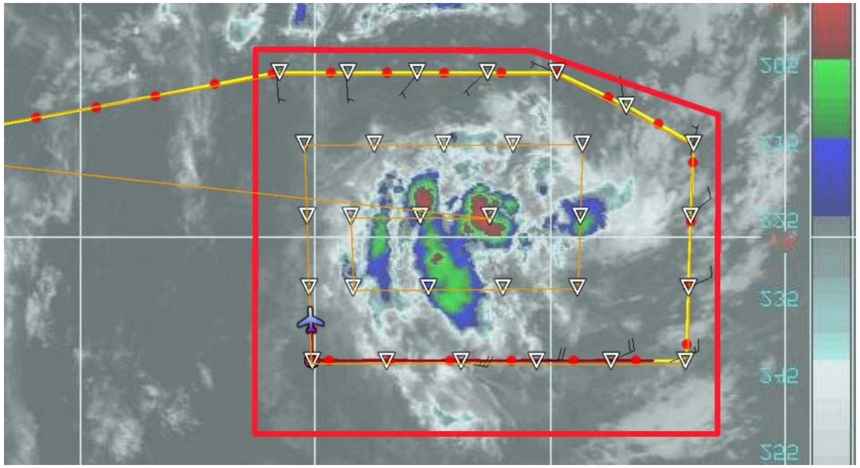


HIPPO:

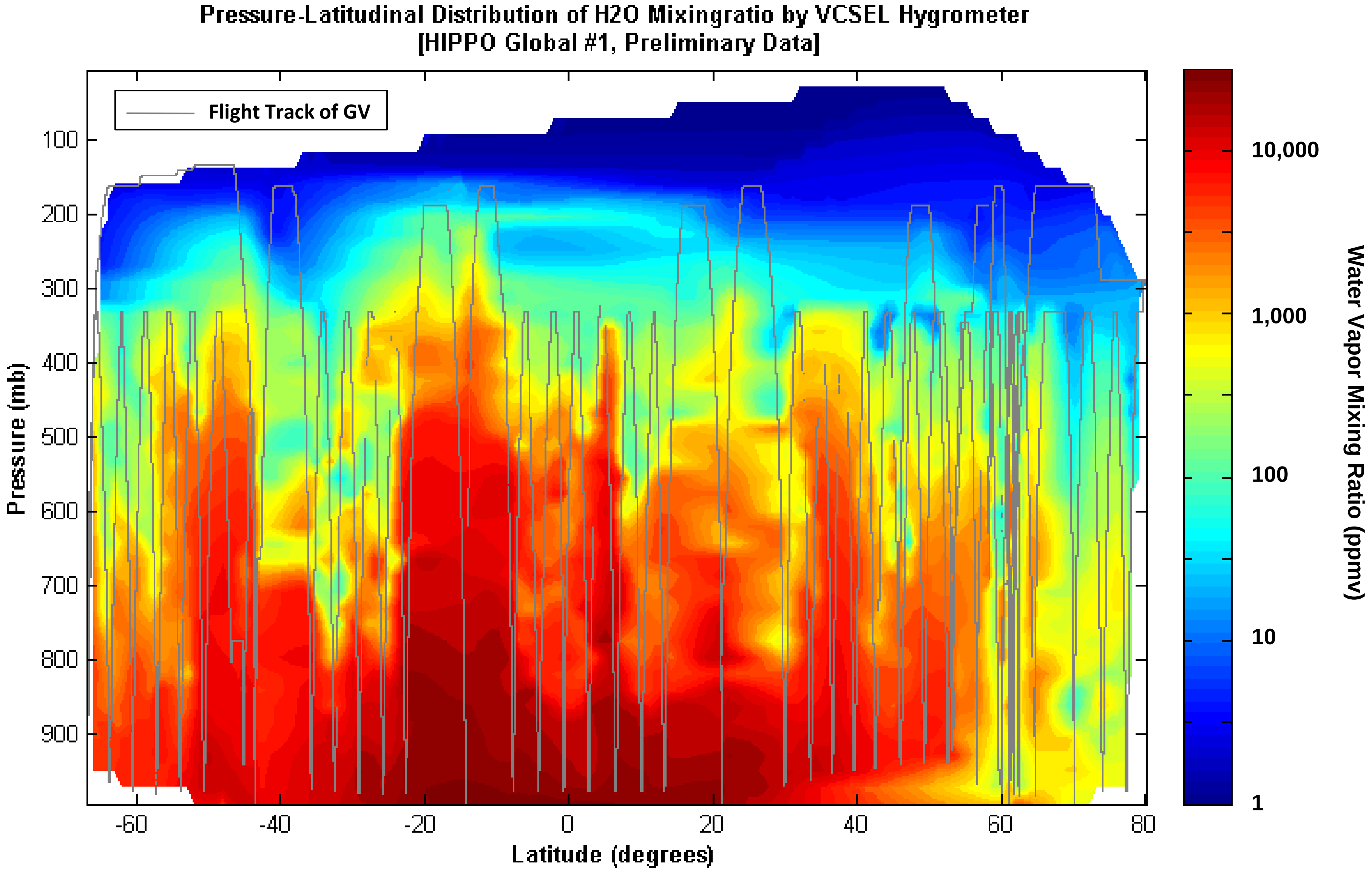
- N/S transect across mainly the central Pacific (all seasons)
- profiled boundary layer to stratos.
- 145 flight hours at T≤-40ºC;
- N=1406 ice supersaturated regions

PREDICT:

- tropical, western Atlantic (Aug./Sept.)
- upper tropospheric dataset almost exclusively (130-200 hPa)
- 93 hrs at T≤-40ºC
- N=5550 ice supersaturated regions



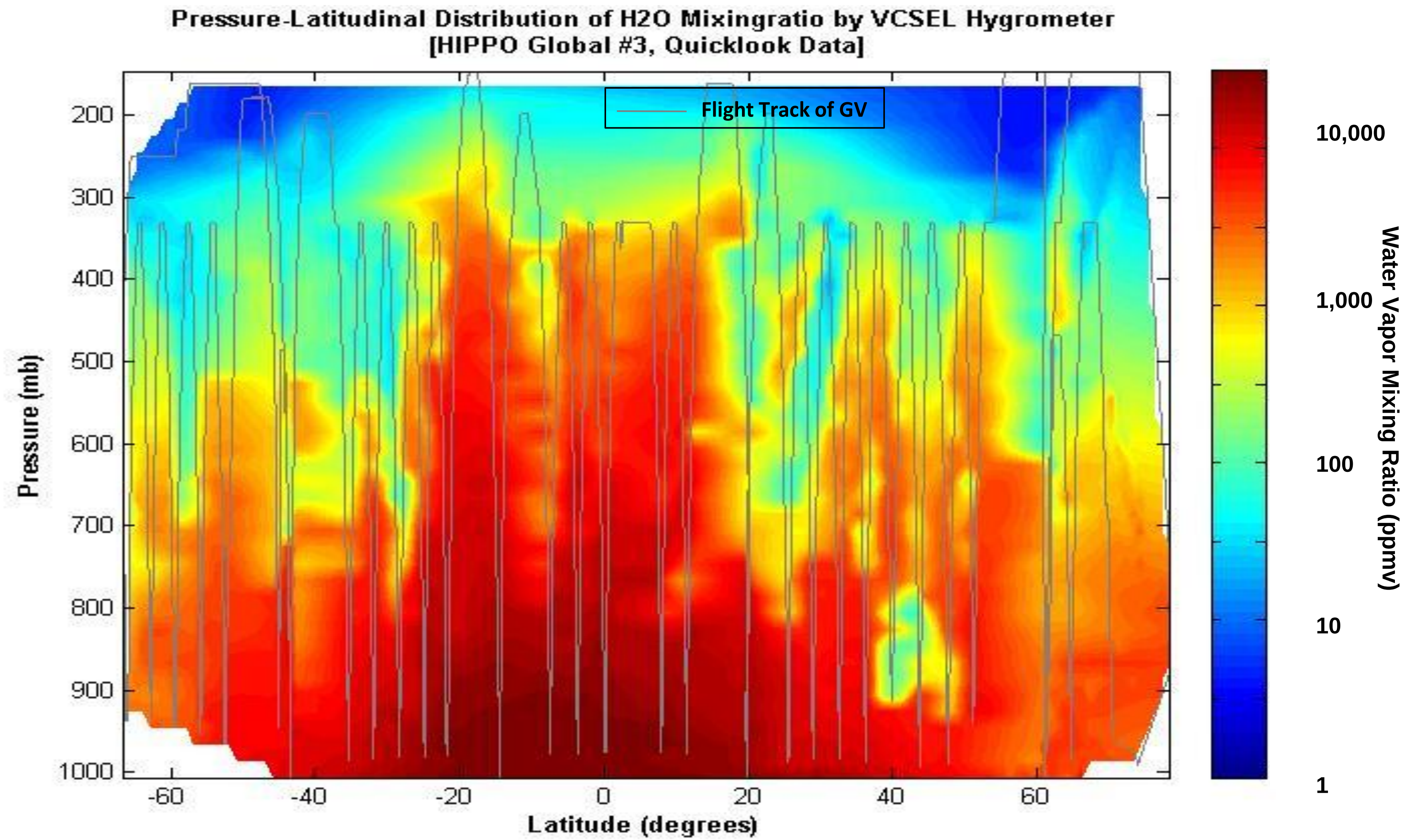
January



Large plumes of water vapor extending vertically

South Pacific Convergence Zone (15°S) > Intertropical Convergence Zone (5°N)

April

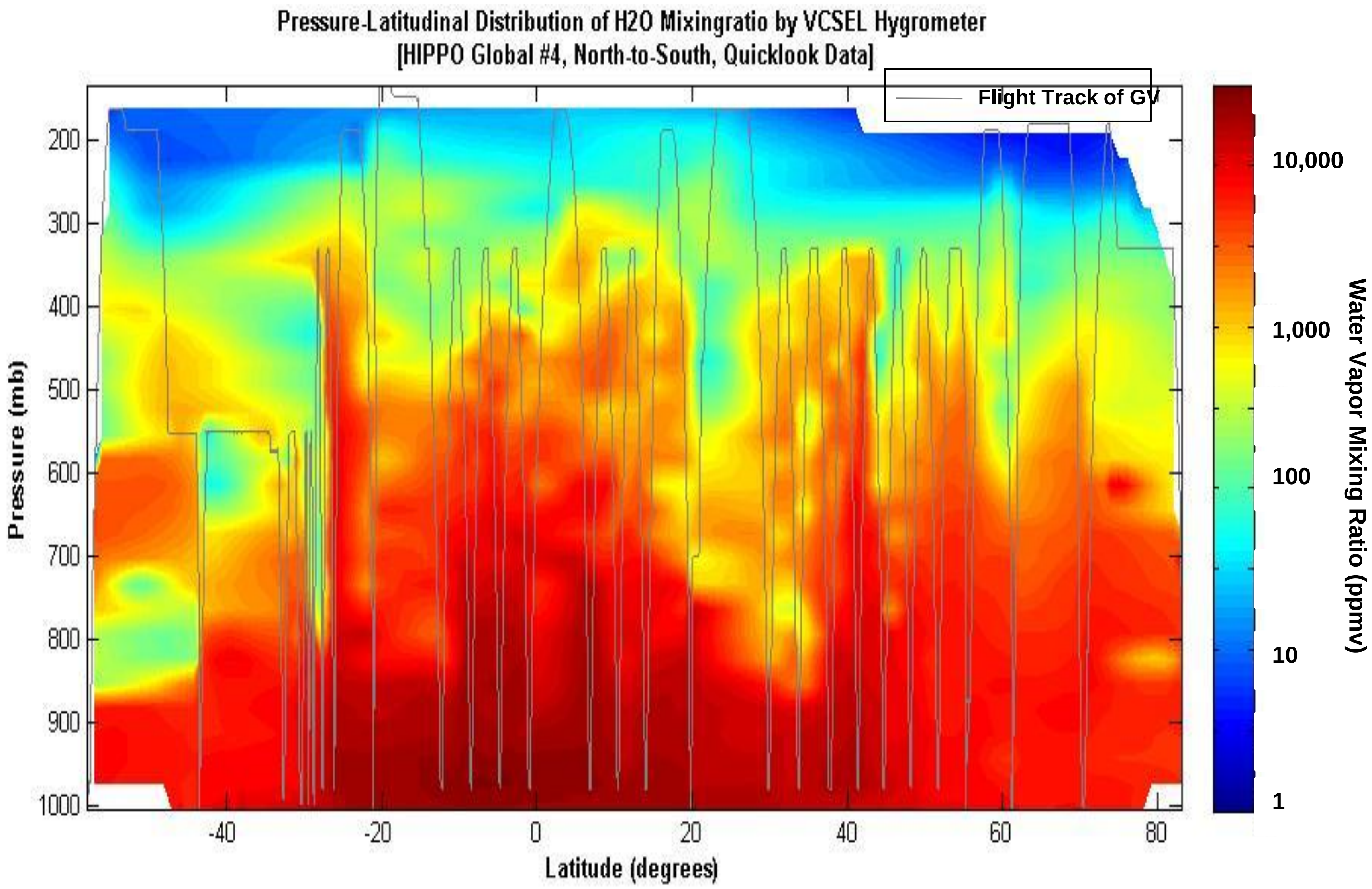


SPCZ is consistently large source of moisture to UT/LS

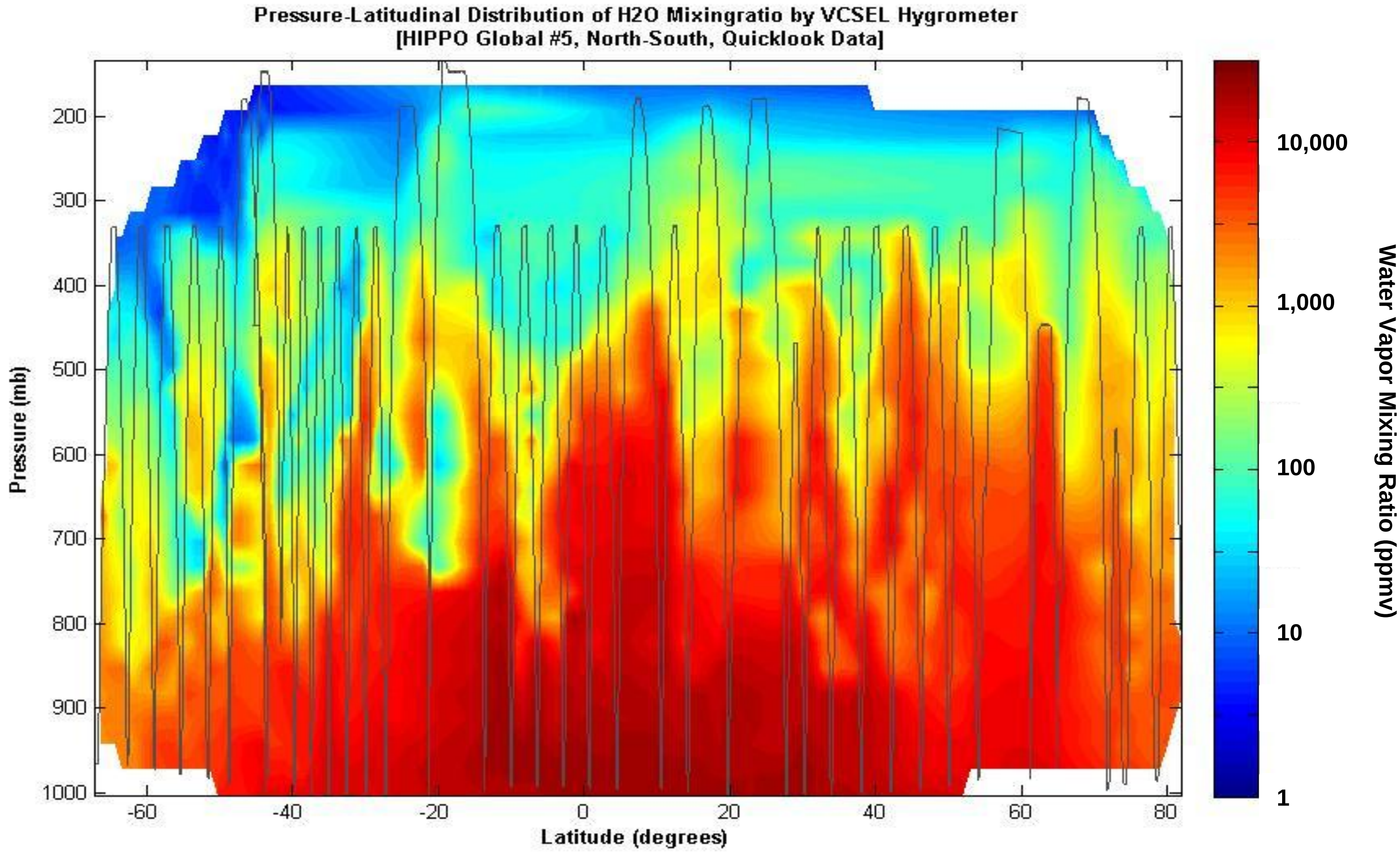
Data consistent with evidence of cirrus cloud backtrajectories *(Fujiwara et al., 2009)*

Other tracers do not show such large SPCZ *(Mari et al., 2003)*

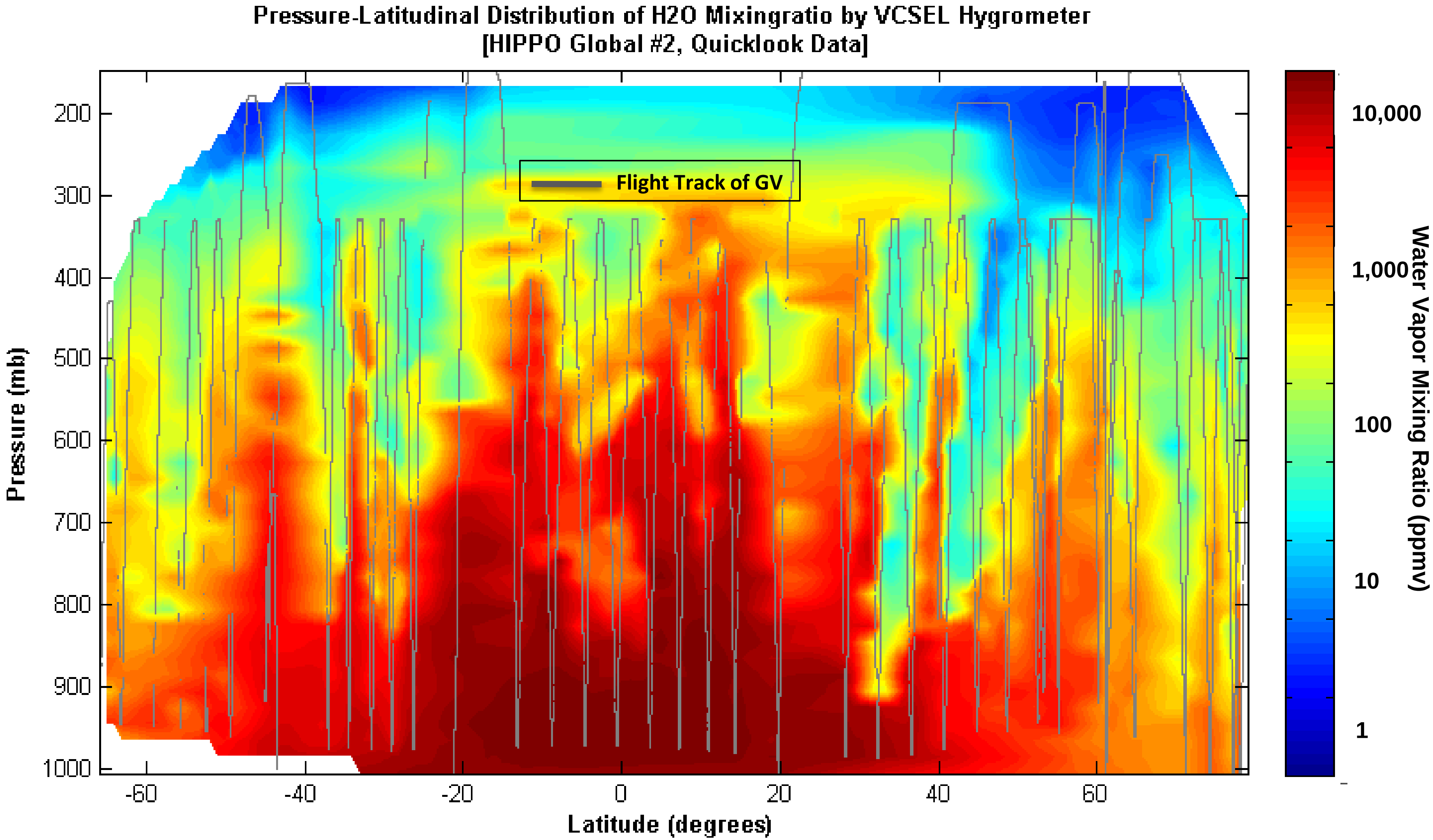
June


Pressure-Latitudinal Distribution of H2O Mixingratio by VCSEL Hygrometer
[HIPPO Global #4, North-to-South, Quicklook Data]
Flight Track of GV
Pressure (mb)
200
300
400
500
600
700
800
900
1000
-40
-20
0
20
40
60
80
Latitude (degrees)
10,000
1,000
100
10
1
Water Vapor Mixing Ratio (ppmv)

August

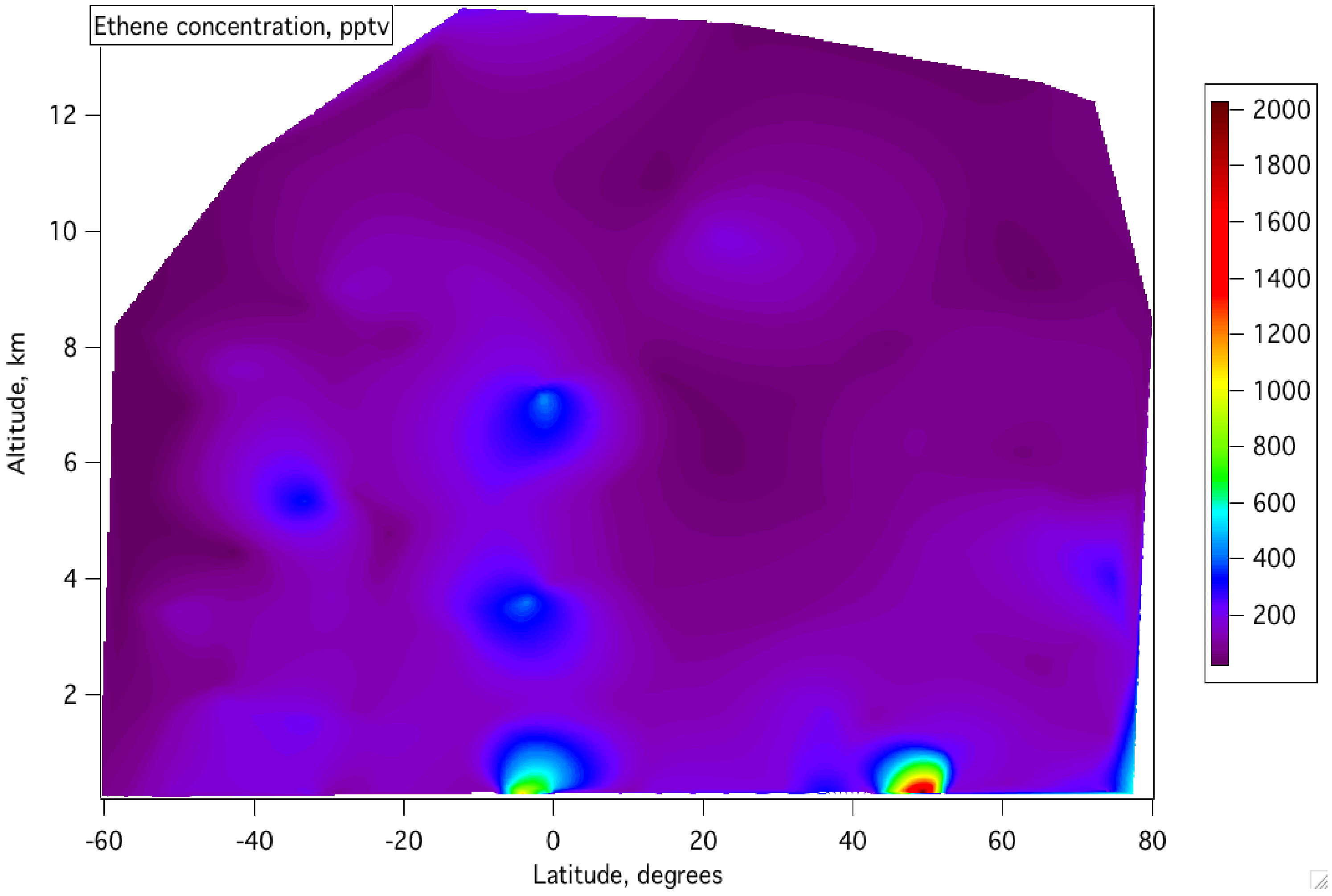

Pressure-Latitudinal Distribution of H2O Mixingratio by VCSEL Hygrometer
[HIPPO Global #5, North-South, Quicklook Data]
Pressure (mb)
200
300
400
500
600
700
800
900
1000
-60
-40
-20
0
20
40
60
80
Latitude (degrees)
10,000
1,000
100
10
1
Water Vapor Mixing Ratio (ppmv)

November

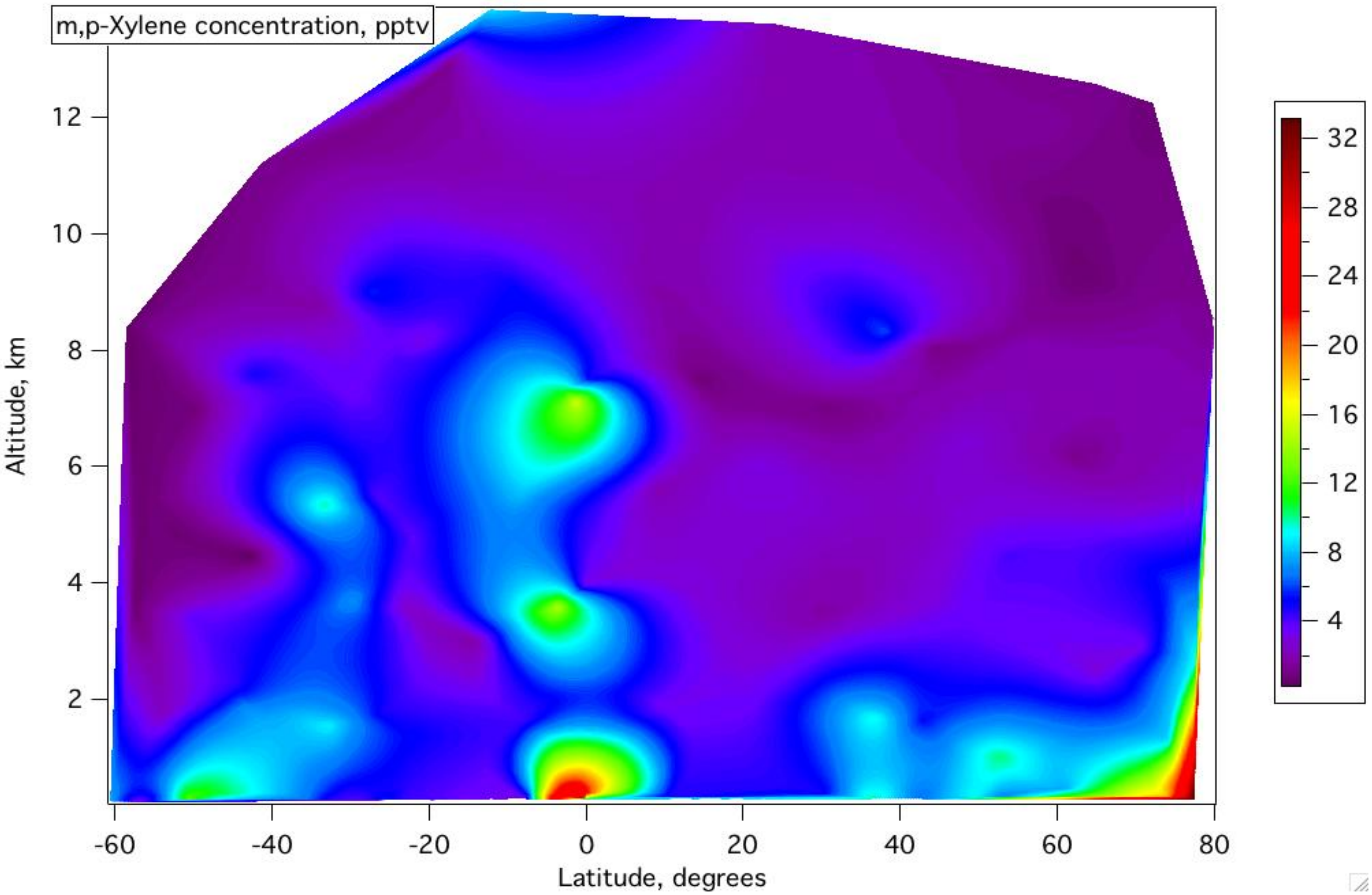


At any given time, there is tremendous variability in the distribution of water vapor including sharp horizontal gradients and large plumes extending vertically in all regions

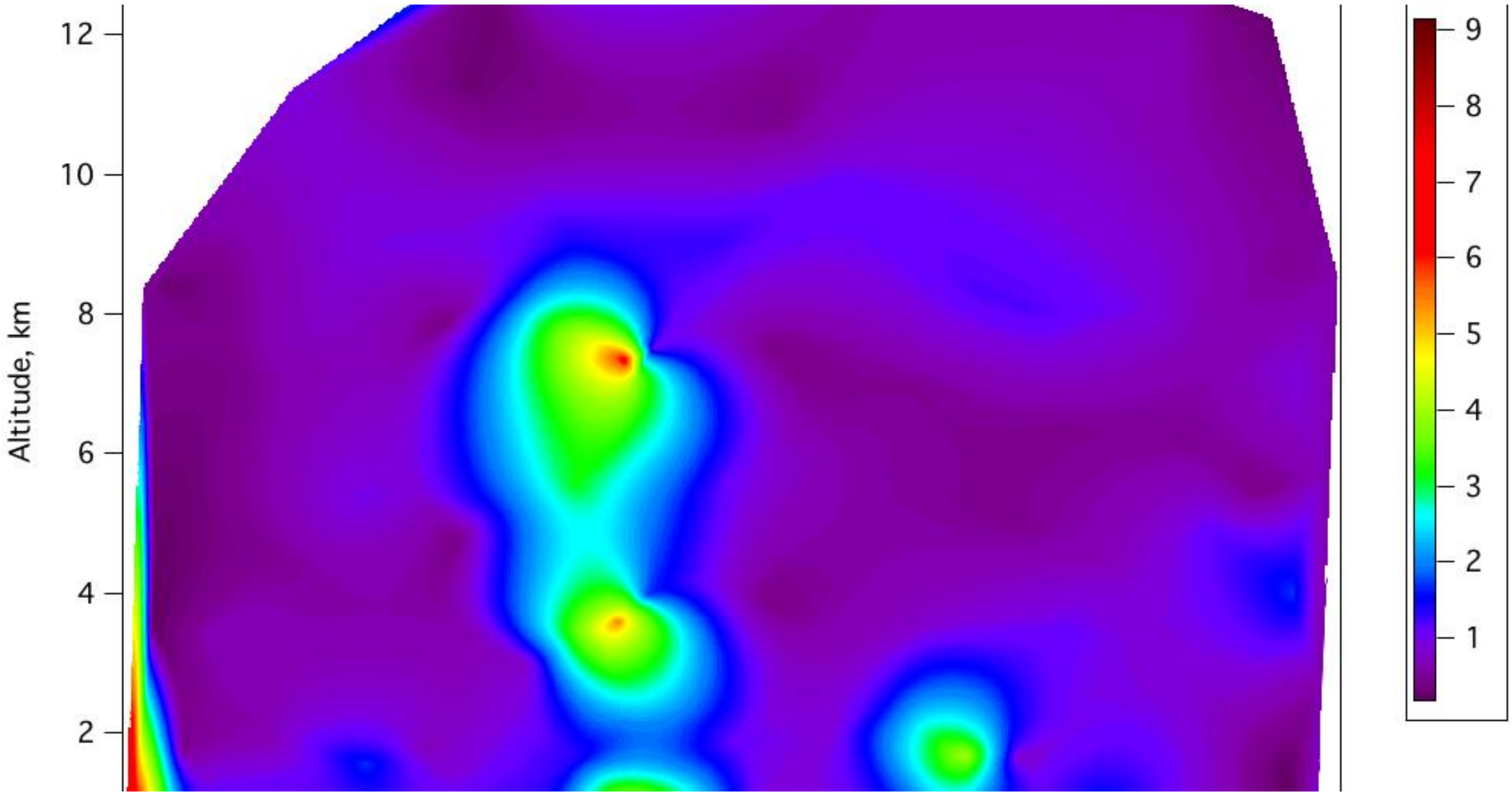
ethylene, HIPPO #1
(E. Atlas)



xylene, HIPPO #1
(E. Atlas)



isoprene, HIPPO #1
(E. Atlas)



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%

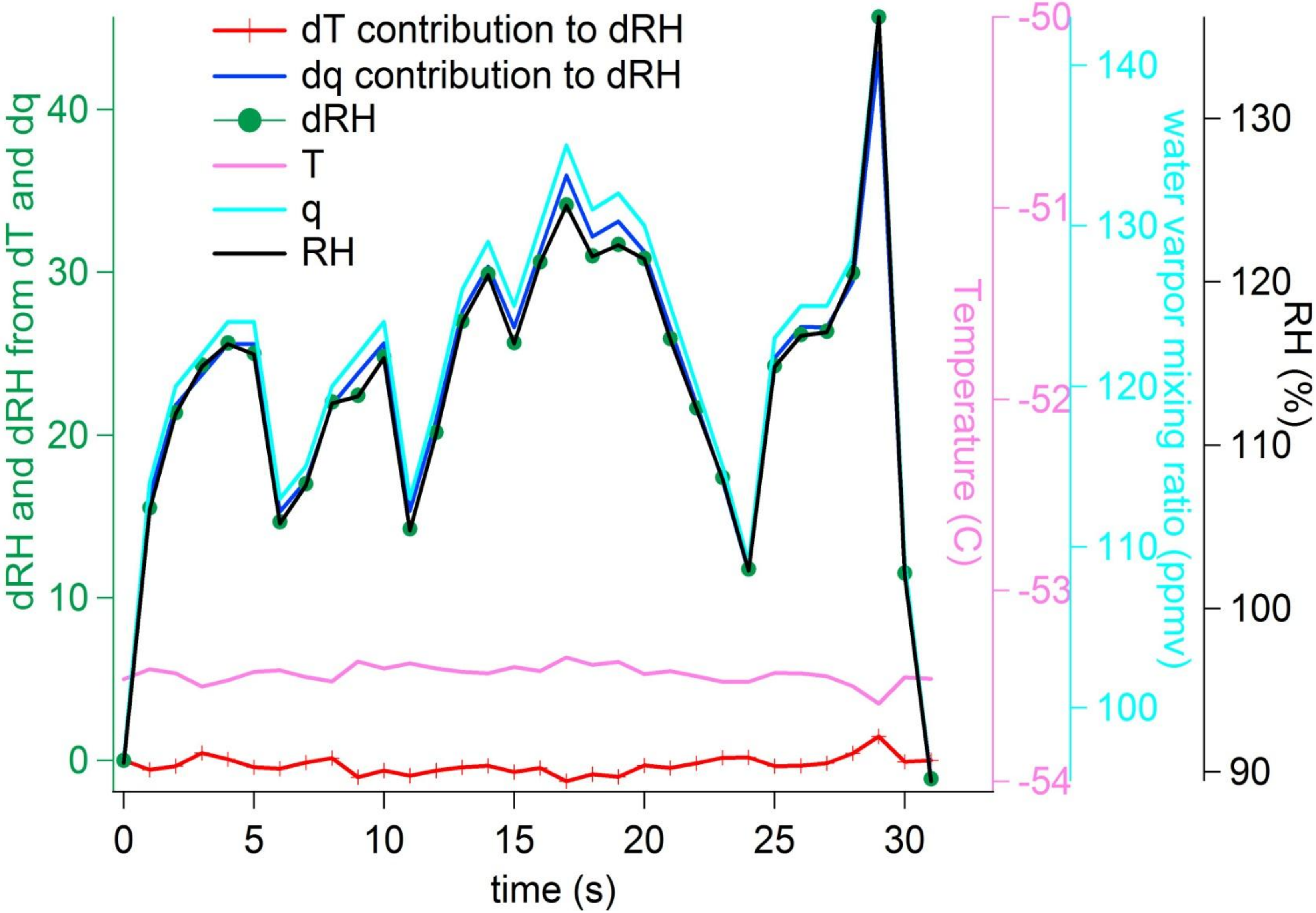
[To avoid mixed phase clouds, restrict analyses to ice supersaturation when T ≤ -40°C]

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}) *(Fussina et al., 2007)*
4. Improves ice cloud parameterizations *(Gettelman et al., 2010; Salzmann et al., 2010)*

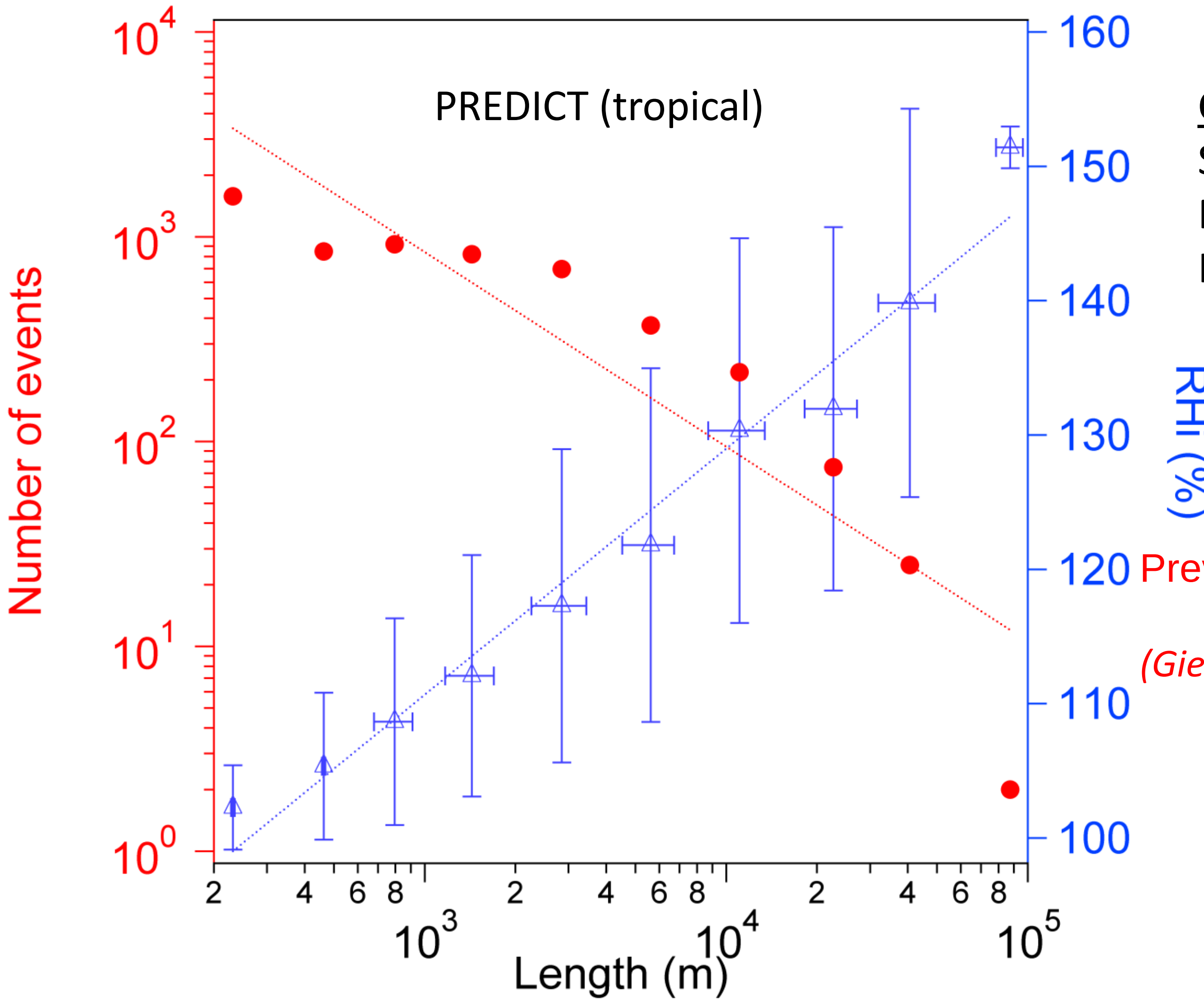
• ice supersaturation poorly measured in upper trop. / lower strat.
• antecedent conditions before cirrus cloud formation
• no measurements at cirrus clouds scales (~1 km, Wood et al., 2011)

Flight transect of typical ice supersaturation region



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

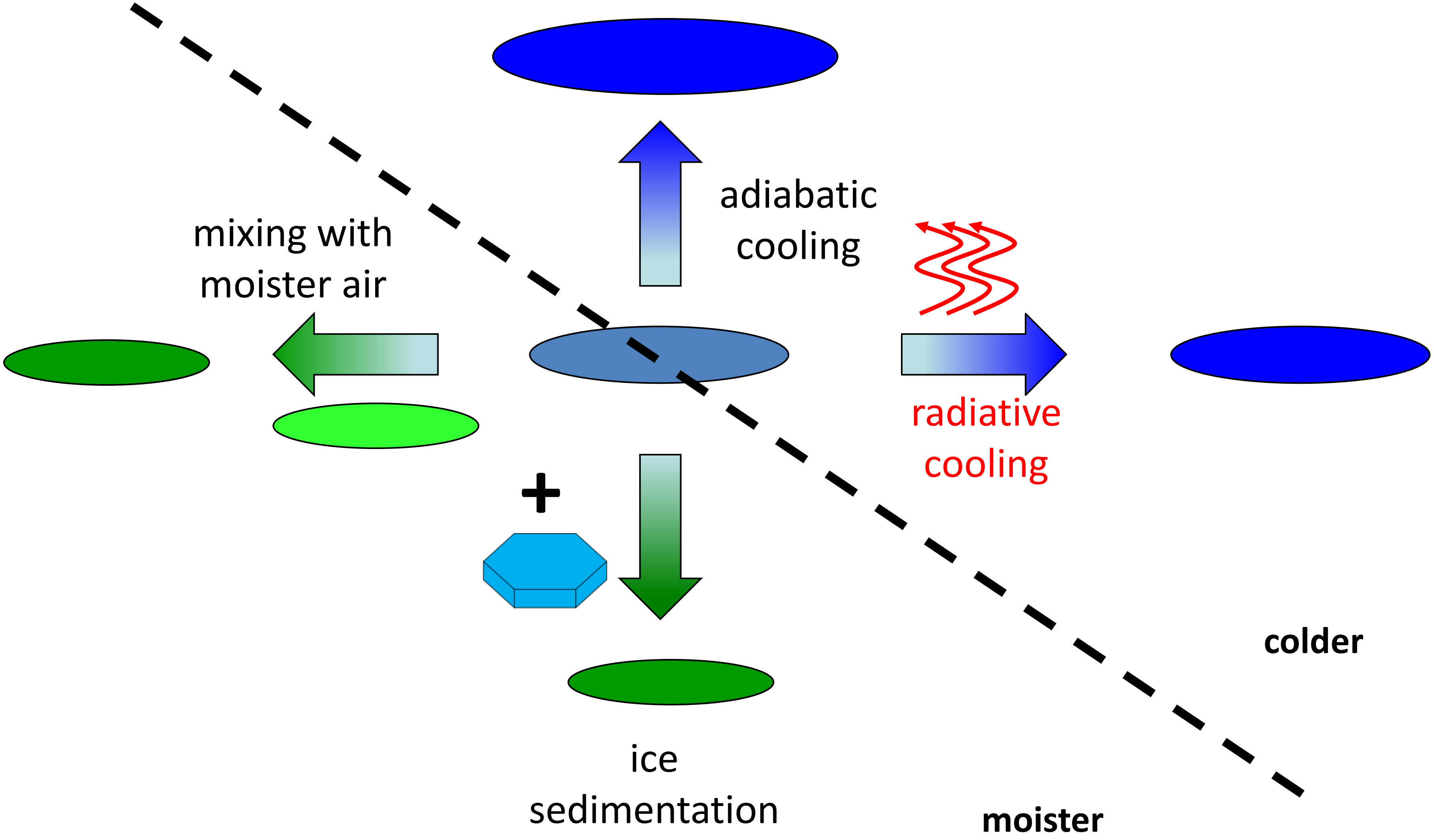
Size distribution of ice supersaturated regions



Campaign	Median size (km)
START08	0.9
PREDICT	0.7
HIPPO	0.9

- ice superaturated regions are very small (~ km)
- larger sized ice superaturated regions have higher supersaturations (bias in remote sensing data)?

How do ice supersaturated regions form?



Climate and cloud ice nucleation models form cirrus clouds by perturbing (lowering) the temperature field – but no observational basis!

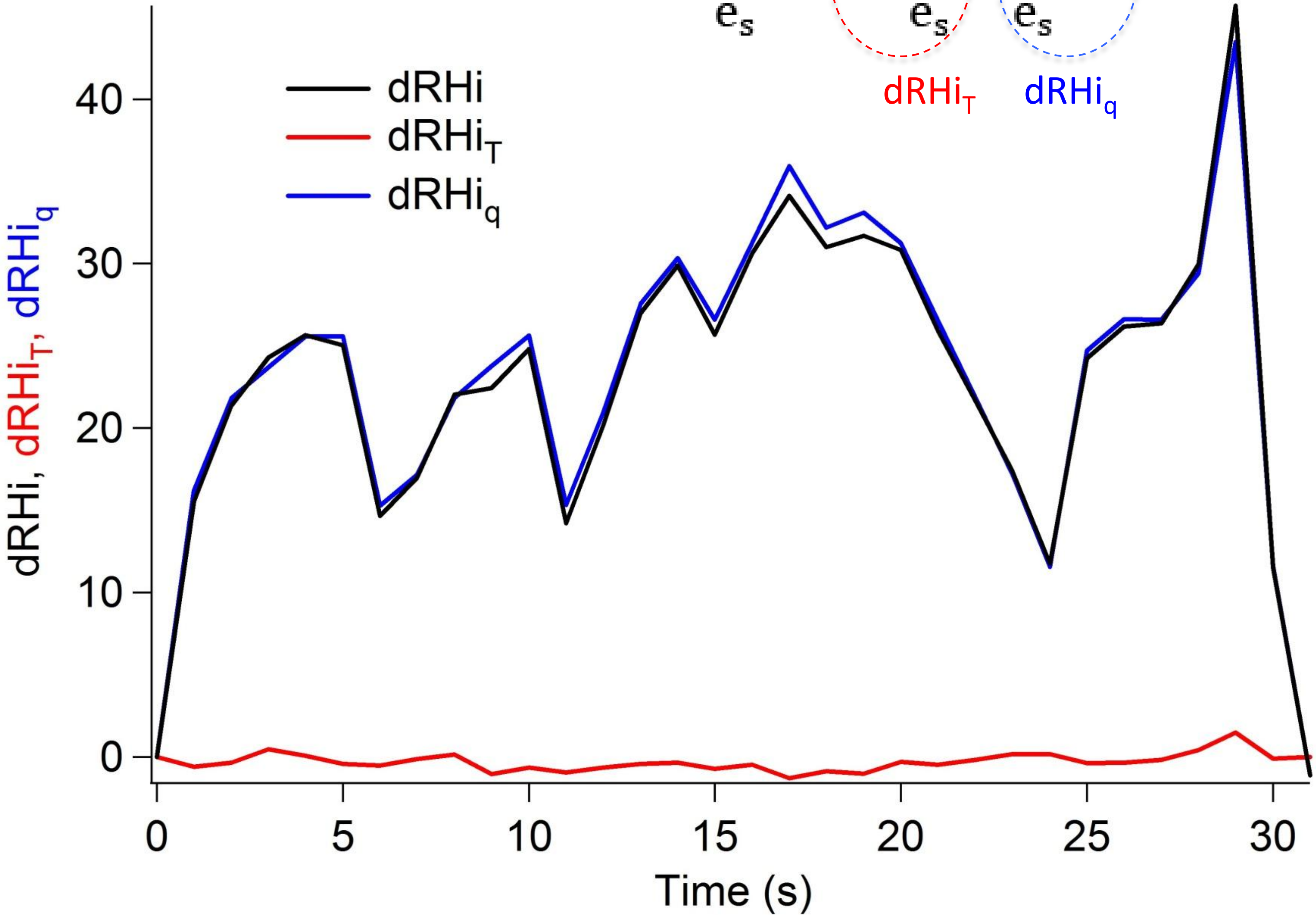
(Spichtinger et al., 2005; Kärcher and Burkhardt, 2008; Morrison and Gettelman, 2008; Wang and Penner, 2010)

Ex: Ice supersaturated region

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

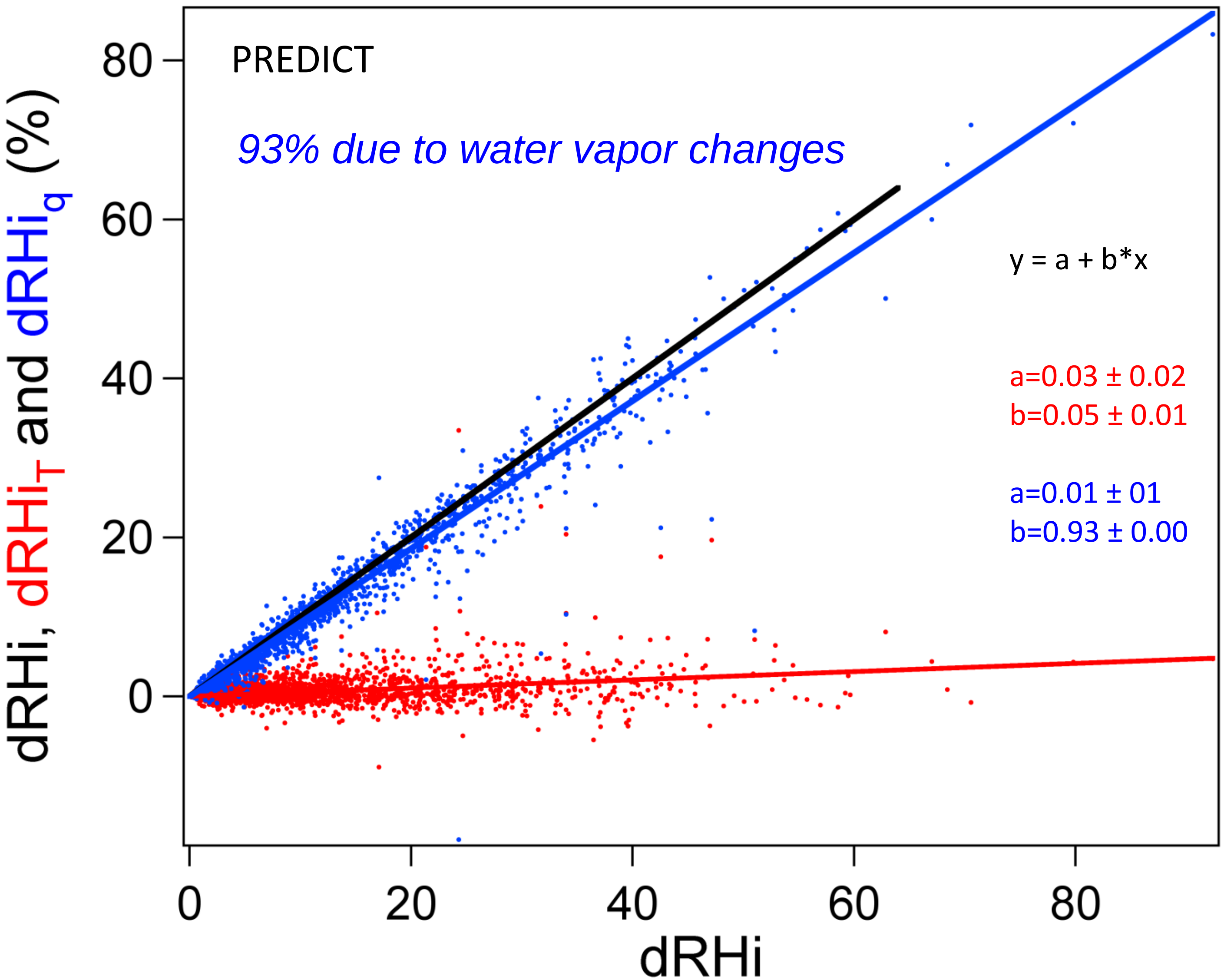
$$dRHi = d\frac{e}{e_s} \approx e\, d\frac{1}{e_s} + \frac{1}{e_s}de$$

$dRHi_T$ $dRHi_q$



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

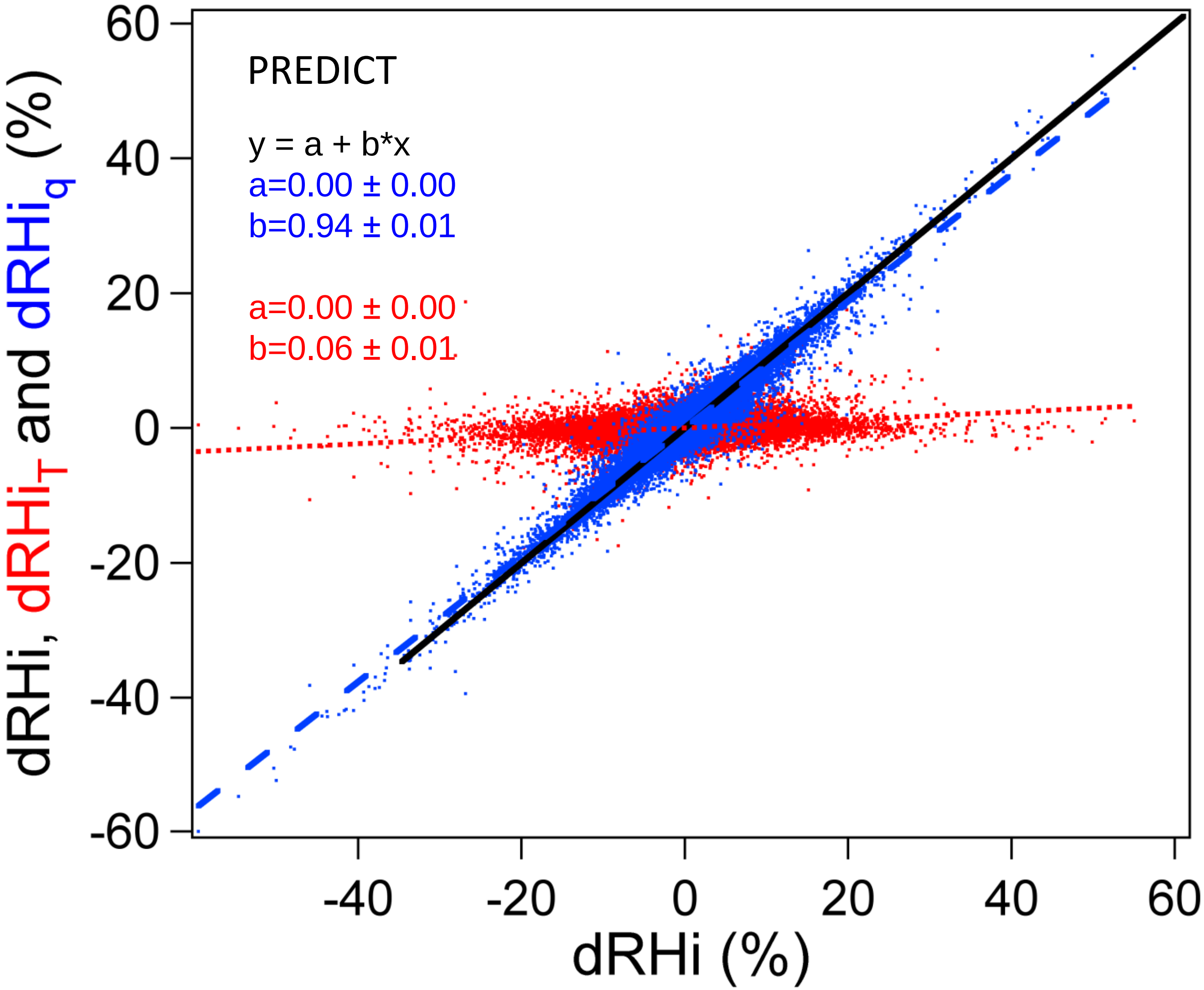
Environmental conditions of ISSRs
(i.e. how do ISSRs differ from their adjacent environments?)



Water contribution:
HIPPO: 90%
START08: 84%

Increases in water vapor are the dominant reasons that distinguish ISSRs from their adjacent subsaturated environments

Subsaturated conditions dRHi, T≤-40ºC

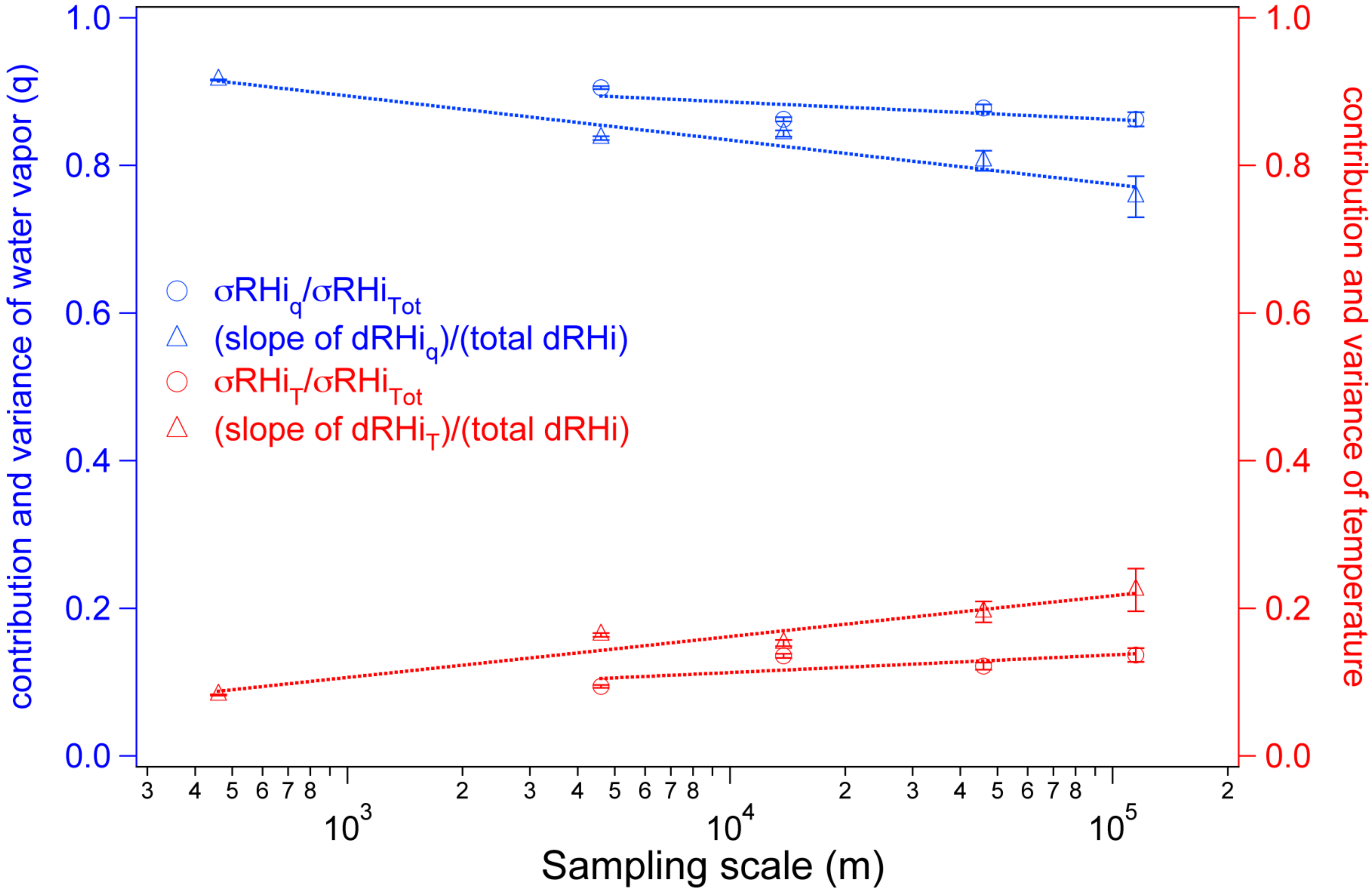


PREDICT: 94%
START08: 89%
HIPPO: 92%

• ***At fine scales (0.2-100 km), changes in water vapor – as opposed to temperature - dominate the spatial distribution of the relative humidity field***

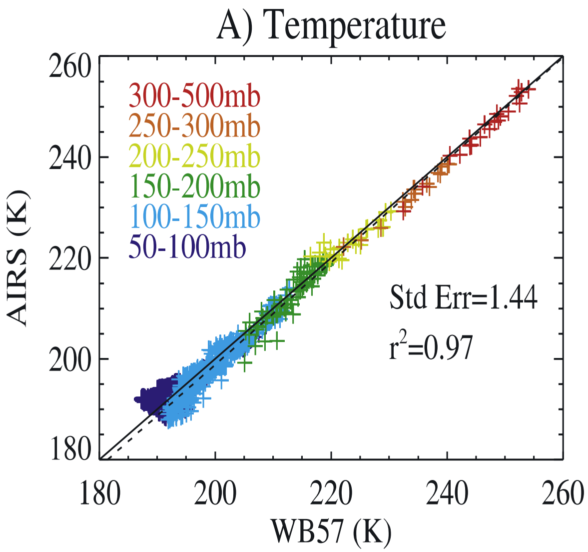
• ***Valid for both tropical and extratropical locations***

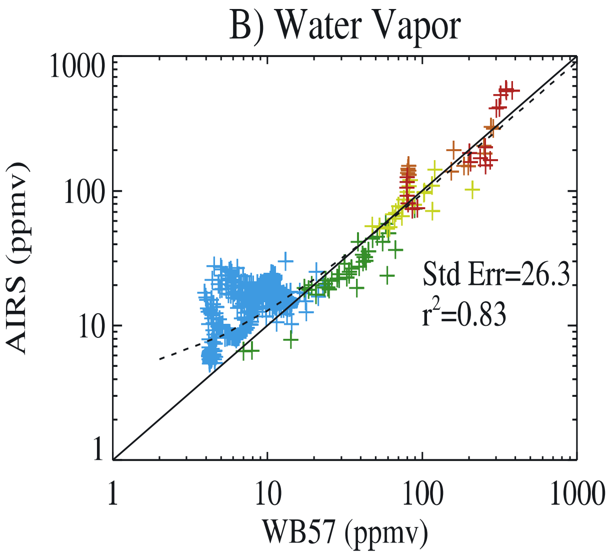
Scale analyses of RH_{ice} variability



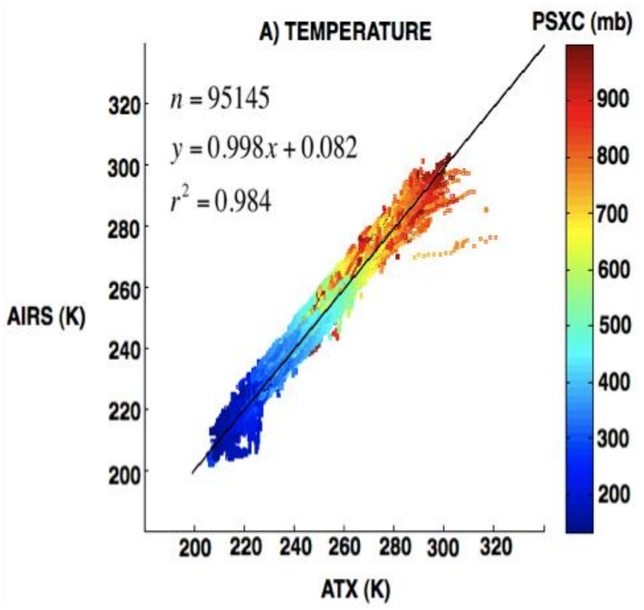
Water vapor fluctuations remain dominant up to 100 km; temperature increasingly becomes important at larger scales

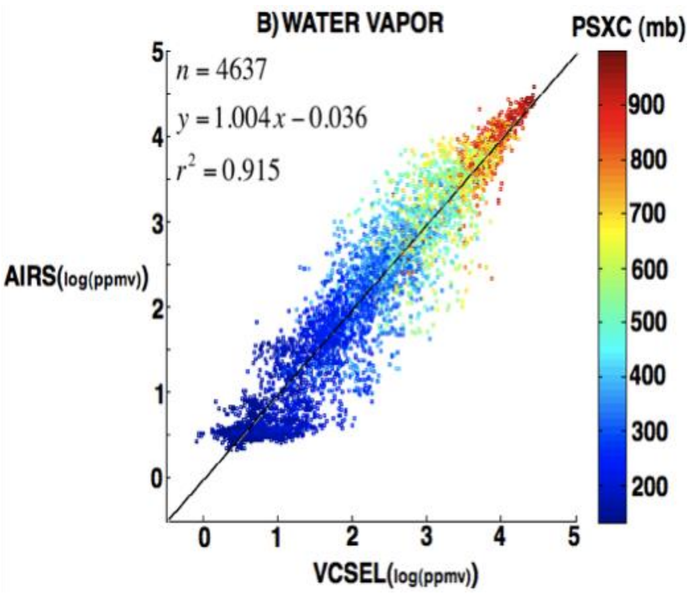
Aircraft / AIRS intercomparisons





- Gettelman et al. 2004 compared satellite and aircraft data (±12 hrs; ~ 300 km) for pre-AVE (r^2=0.83); also bias at < 10 ppmv





- VCSEL and AIRS with much tighter windows (<3 hrs; <150 km) show better agreement (r^2=0.92) and no apparent bias (HIPPO)

- Link TORERO aircraft data to larger scales with AIRS/aircraft syntheses

Summary

1. Water vapor and ice supersaturation (HIPPO and PREDICT)
   - Ice supersaturated regions are very small (km)
   - Water vapor fluctuations strongly control the upper tropospheric and lower stratospheric relative humidity fields at cloud scales
   - Satellite measurements are biased toward larger and higher ice supersaturation (*Diao et al., Nature*, in revision)

2. For TORERO, we expect the above results to also hold but we'd like to look at:
   - Do ice supersaturated regions form in regions of recent convection? (use tracers) (Hypothesis #1, 3: deep convective transport; fast reactive species groups)
   - Linking RH_{ice} variability measurements from cloud (sub-km) to 1000 km scales using aircraft (0.25-100 km) and AIRS H_2O/AMSU-B temp. (> 50 km) (overpass flights would be helpful)
   - Identify if regions near deep convective entrainment/detrainment show higher variability than regions far from convection (e.g. Jim Bresch WRF)
   - chemical ITCZ measurements? (short-lived tracers, not local sources)

NSF Gulfstream-V VCSEL hygrometer

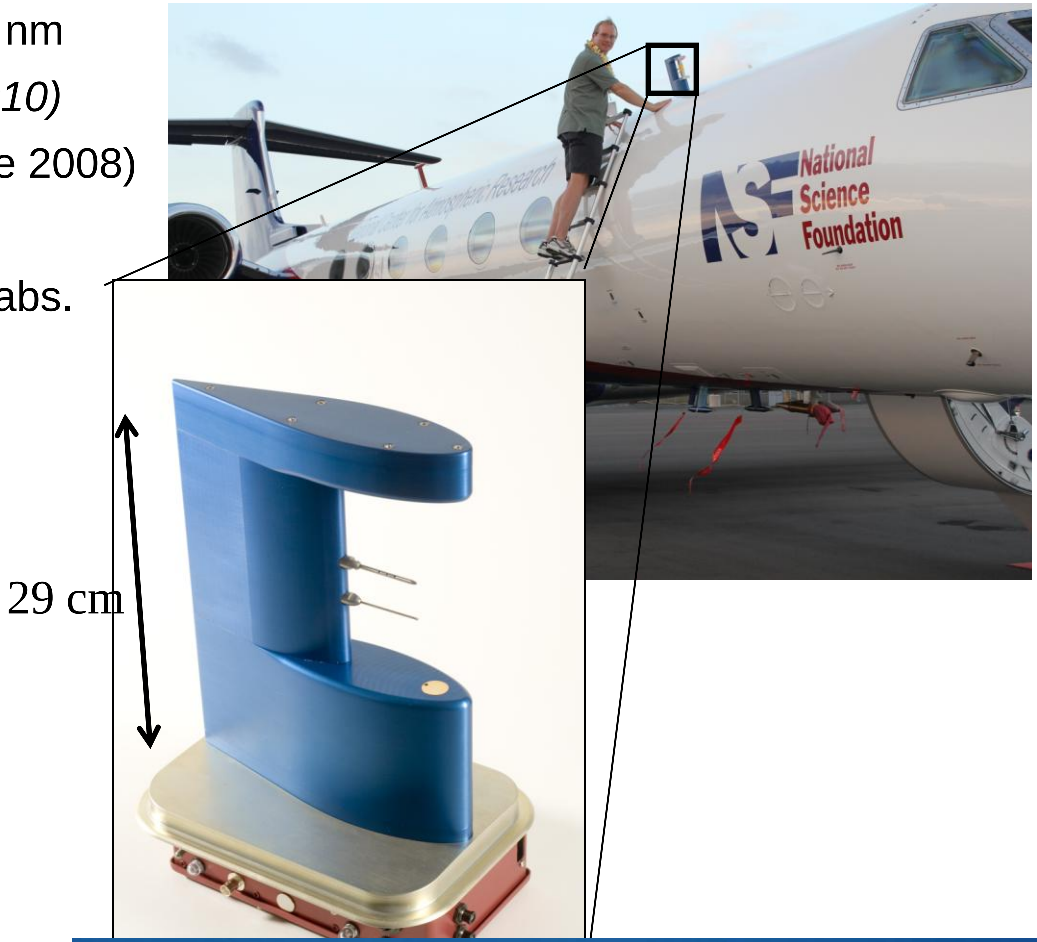
Vertical Cavity Surface Emitting Laser, 1854 nm

(Zondlo et al., JGR, 2010)

~ 600 flight hours, routine on NSF G-V (since 2008)

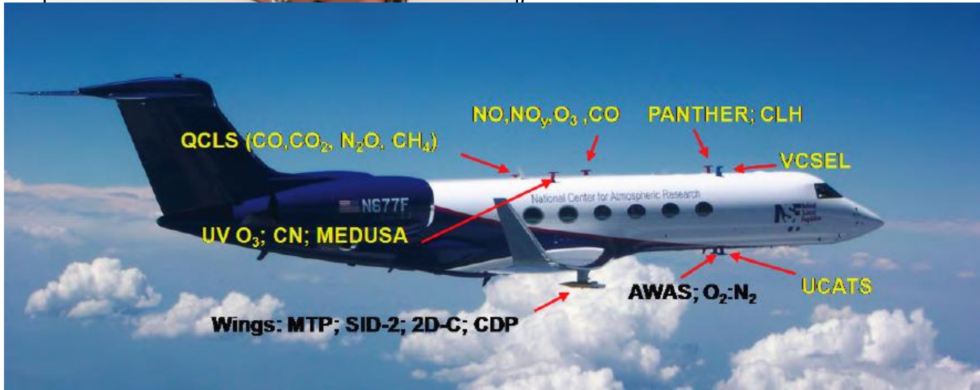
1854 nm fiberized VCSEL, WMS and direct abs.

Parameter	Specifications
Dew point range	-110°C to +30°C
Sensitivity (1 Hz)	0.05 ppmv
Frequency	25 Hz
Accuracy	2-10%
Precision	≤ 1%
Power	8 W
Weight	6 kg
Size	25 cm × 16 cm × 5 cm
Operation	unattended
Design	open-path



- VCSEL hygrometer is open-path
  25 pass Herriott cell: 3.74 m path; mirror radius=0.95 cm; 14.95 cm mirror separation)

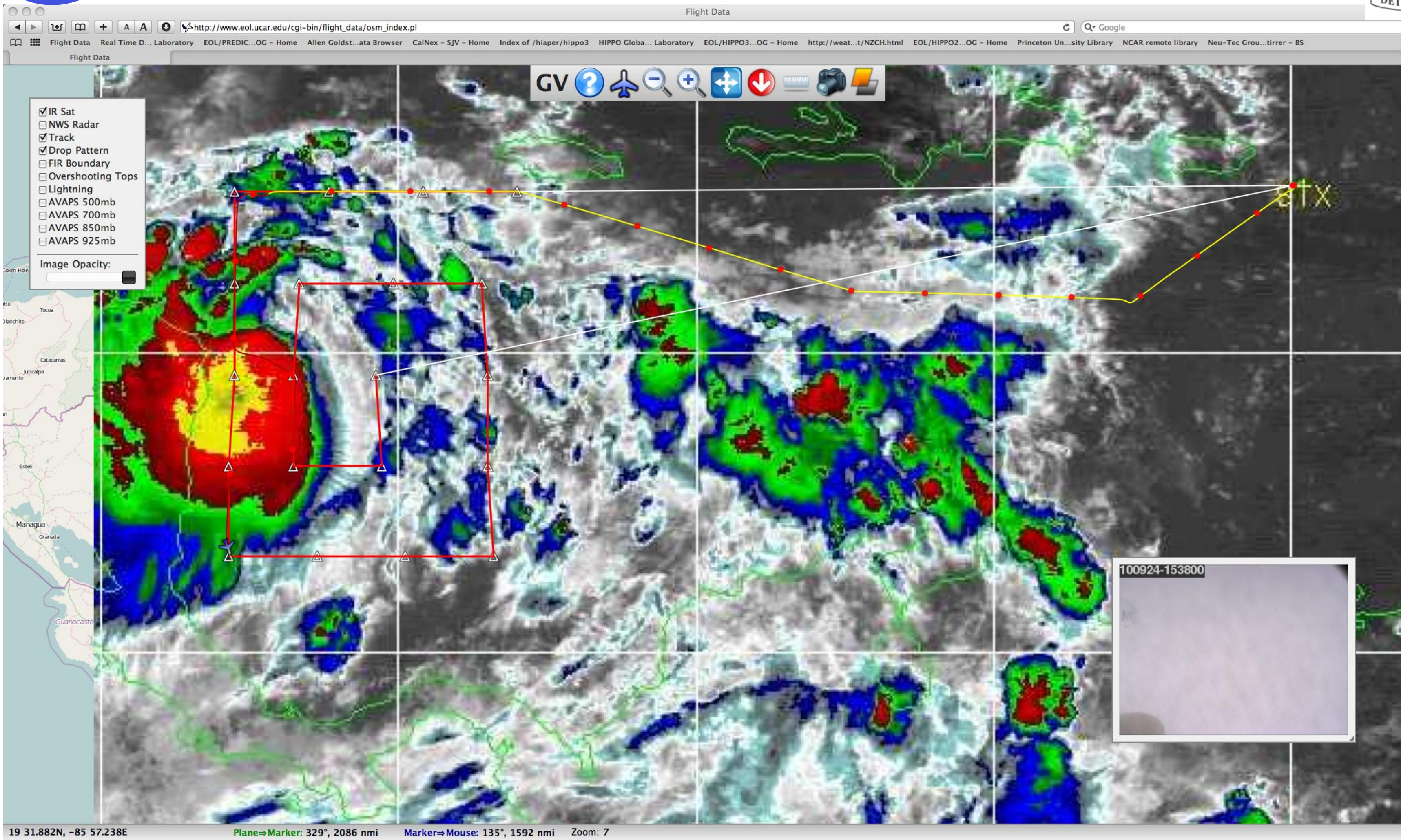
- HIPPO 4/5: 99.3% data coverage



NSF Pre-Depression Investigation of Cloud Systems in the Tro (PREDICT)

2010, St. Croix, U.S. Virgin Islands

G do some disturbances become hurricanes and others fall apart?

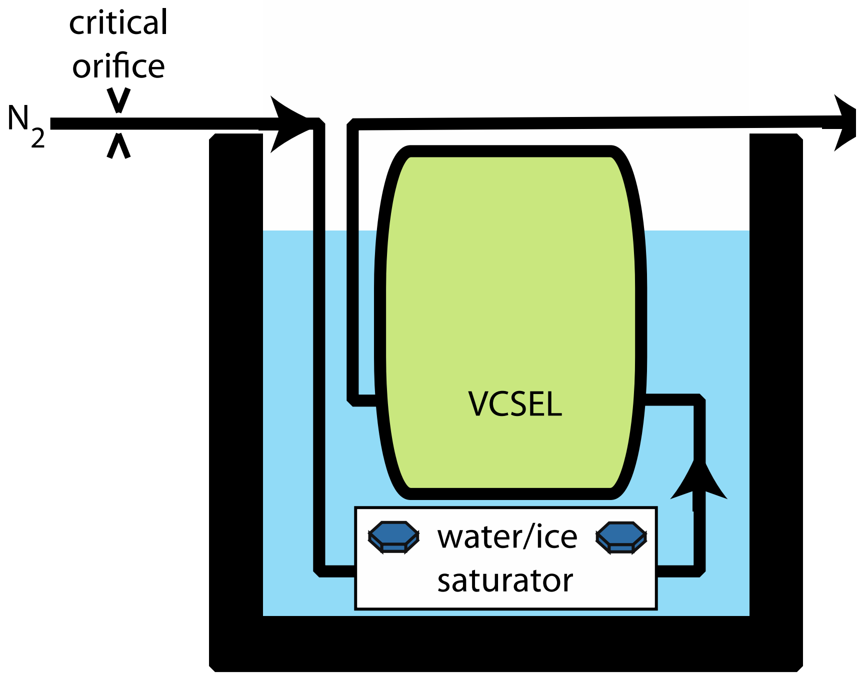


93 hrs. of flight data at T < -40ºC; N=5550 ice supersaturated regions (ISSRs)

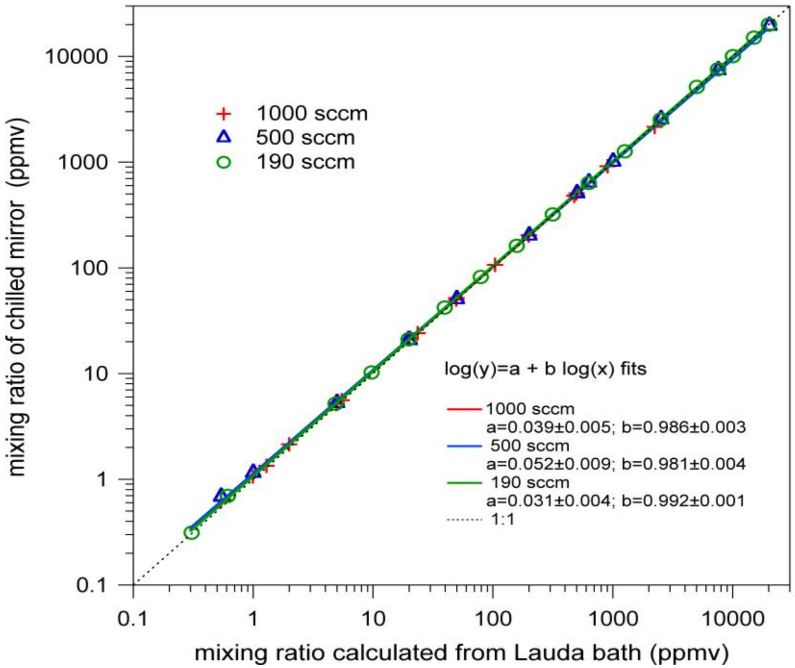
Challenges

Calibrations (small enough to enclose for UT/LS conditions in temp. baths)

Artifacts / biases in calibration play critical roles in accuracy

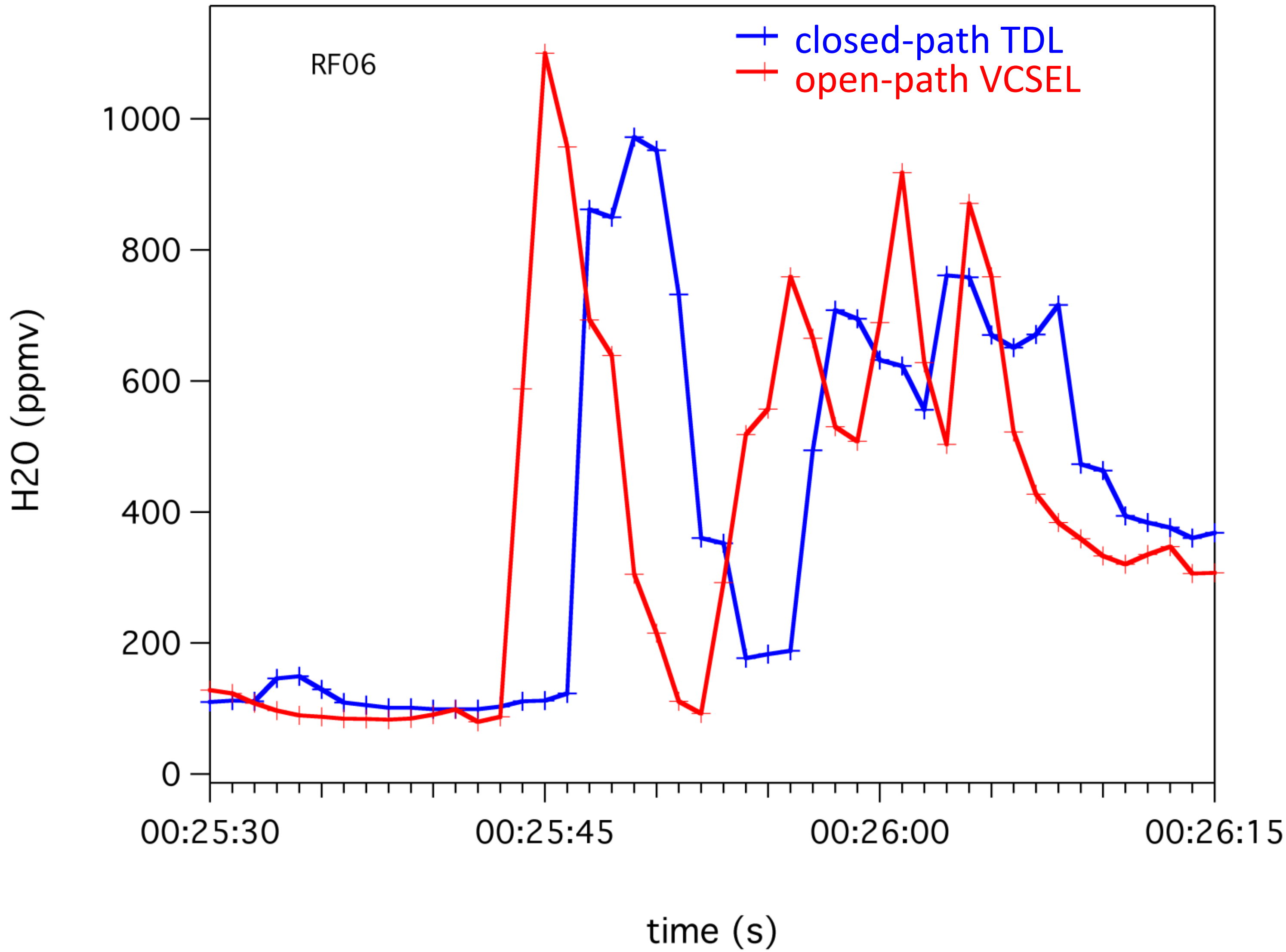


temperature-controlled bath



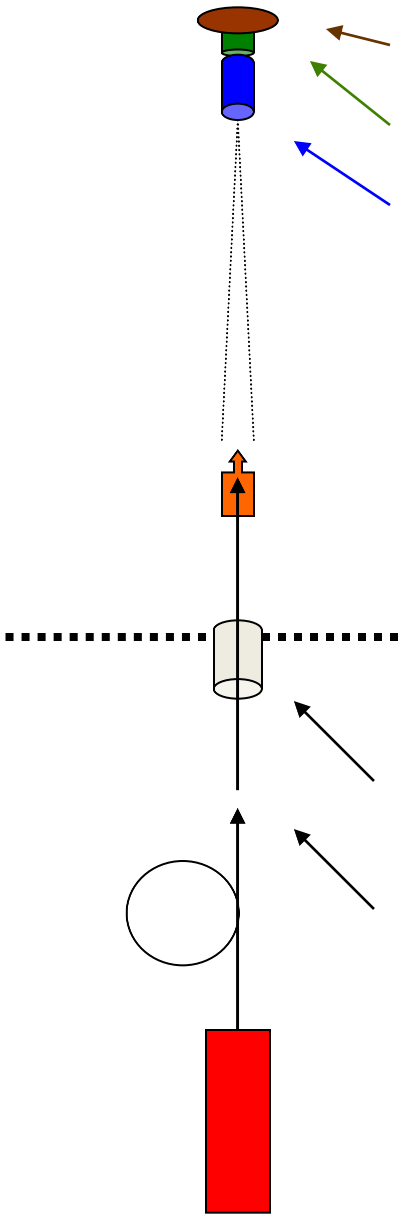
Example: Open vs. close-path sampling

HIPPO-3: 525 hPa, 255 K



Closed-path TDL sensor shows damped response, variable time lags

Optomechanical design



ex-InGaAs detector (downward facing)

1850 ± 50 nm filter: minimizes other λ

AR focusing lens: only light ±7º onto detector

(Herriott cell: 25 passes, 14.95 cm base = 3.74 m),
1.9 cm dia. mirrors)

AR-coated GRIN lens: collimates light into cell

outside fuselage

inside fuselage

fiber optic feedthrough: > 78 K, high vacuum

FC/APC connector (10 fiber cm before; 50 cm after)

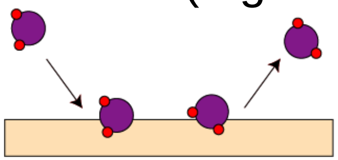
VCSEL: end coupled fiber to laser, <20 µm

Open-path detection: advantages and challenges

Open-path detection: gas sampled at ambient conditions, no sample handling

<u>Advantages</u>
sampling minimized
no gas handling
fast response
no inlet delay issues
no pumps (lower power)
no phase re-partitioning

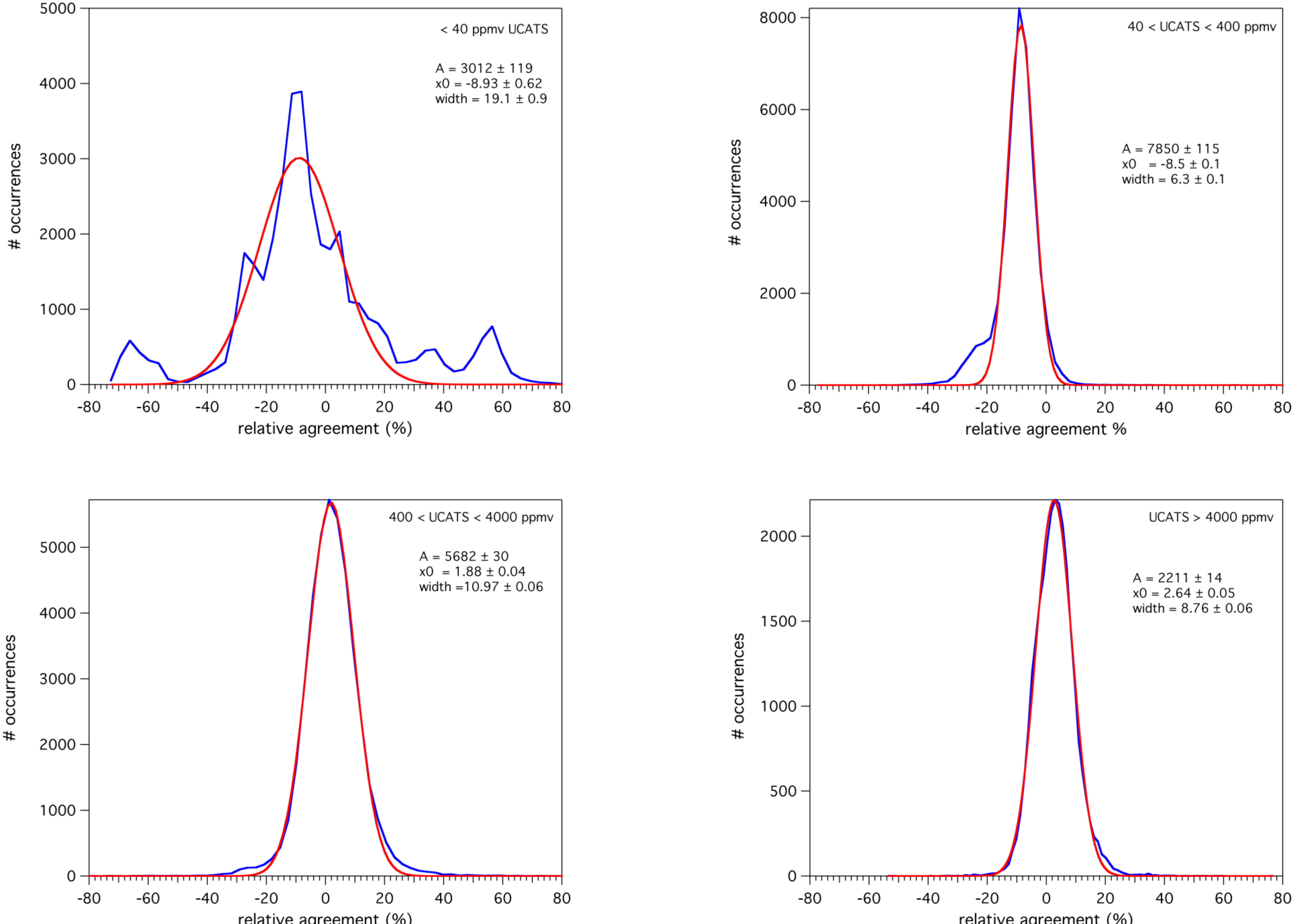
<u>Challenges</u>
spectroscopy over range of temp., pressure
need to know T, P in optical path
broad lineshapes, interferences from other gases
extreme, changing conditions
calibration
mirror/optics need to be relatively clean
(e.g. sea salt, dew/frost, bugs, mold)



Open-path is the best choice for "sticky" species, fast measurements (H_2O, NH_3, HNO_3…)

Essential for airborne-based platforms and in rapidly changing environments, especially at low mixing ratios where adsorption effects become a large unknown

histograms (VXL-UCATS)/UCATS*100



Stratosphere-troposphere analyses of regional transport (START08)

May/June 2008

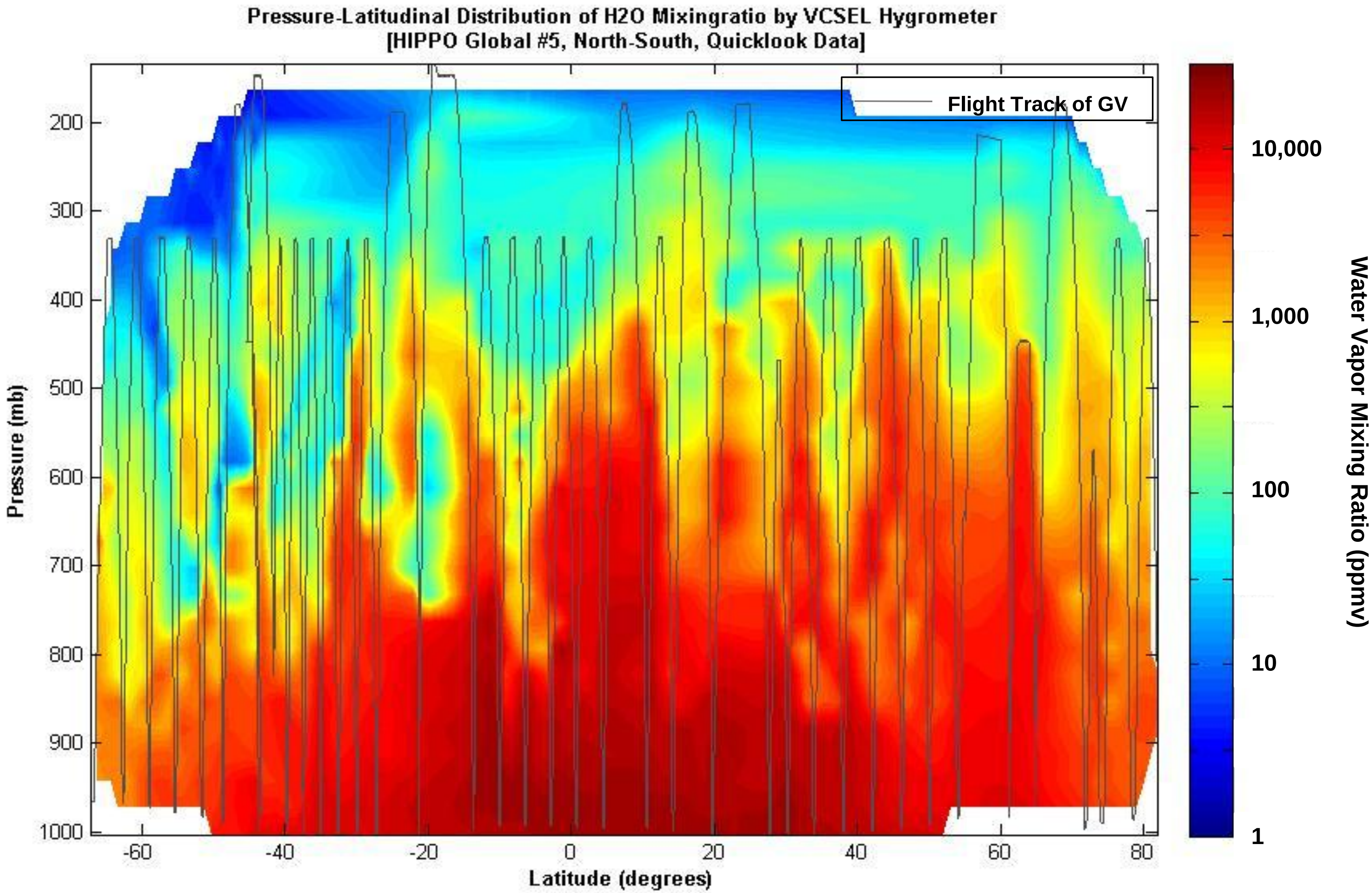
central N. America

extratropical tropopause

62 hrs. of T<-40ºC; N=531 ice supersaturated regions

Dataset: NSF HIAPER Pole-to-Pole Observations (HIPPO)

Slices of the atmosphere at global scales with *extremely* fine-grained resolution:



145 flight hours at T≤-40ºC; N=1406 ice supersaturated regions

Analyses for AIRS / VCSEL intercomparisons

AIRS data: Level 2 standard product, v5

VCSEL: 5 s data; final data START08, preliminary data HIPPO Global #1

Criteria:

Distance: coincident, 22.5, 50, 100 ... 600 km

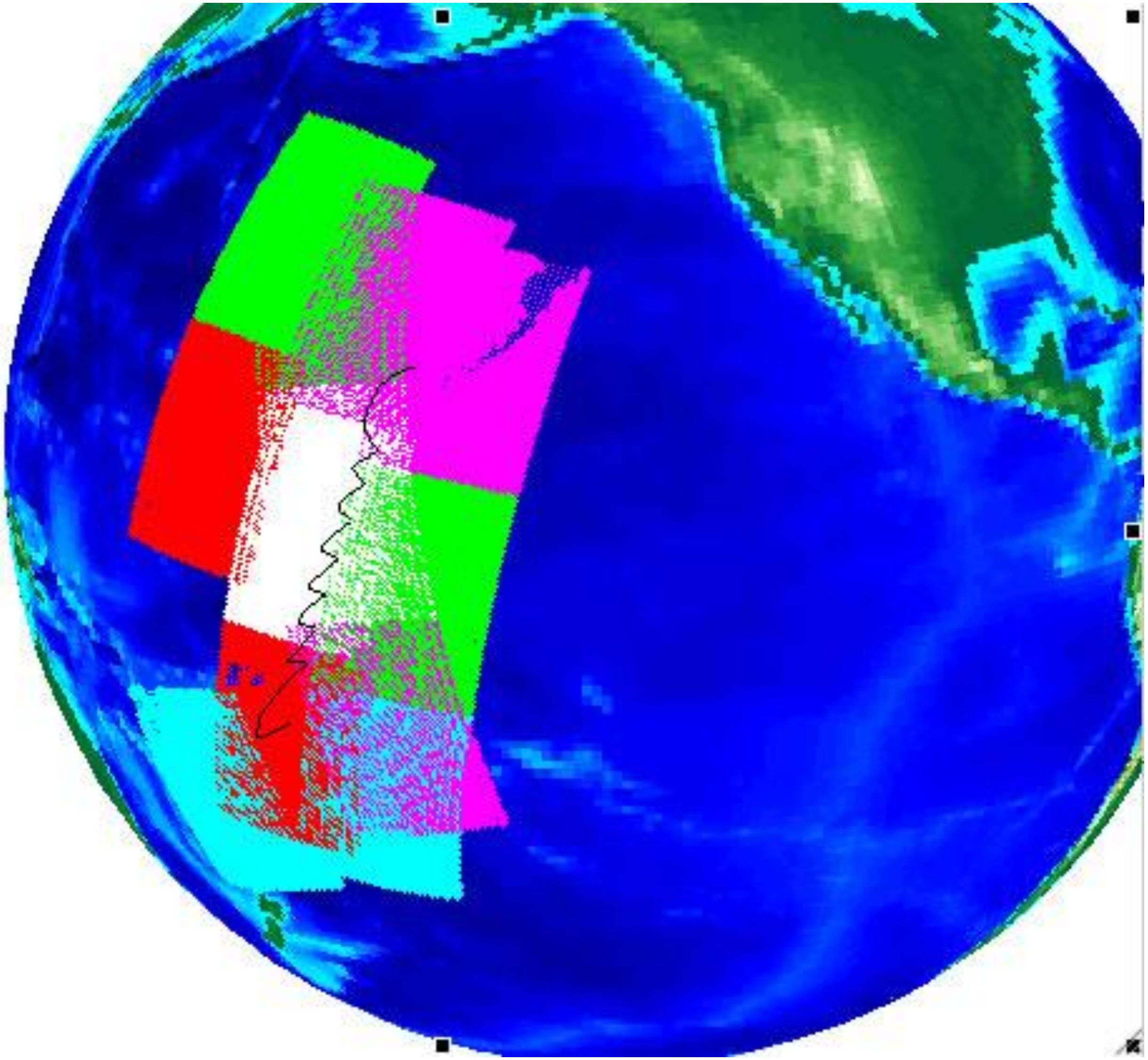
Time: coincident, 90, 120, 180 …1440

Constant pressure

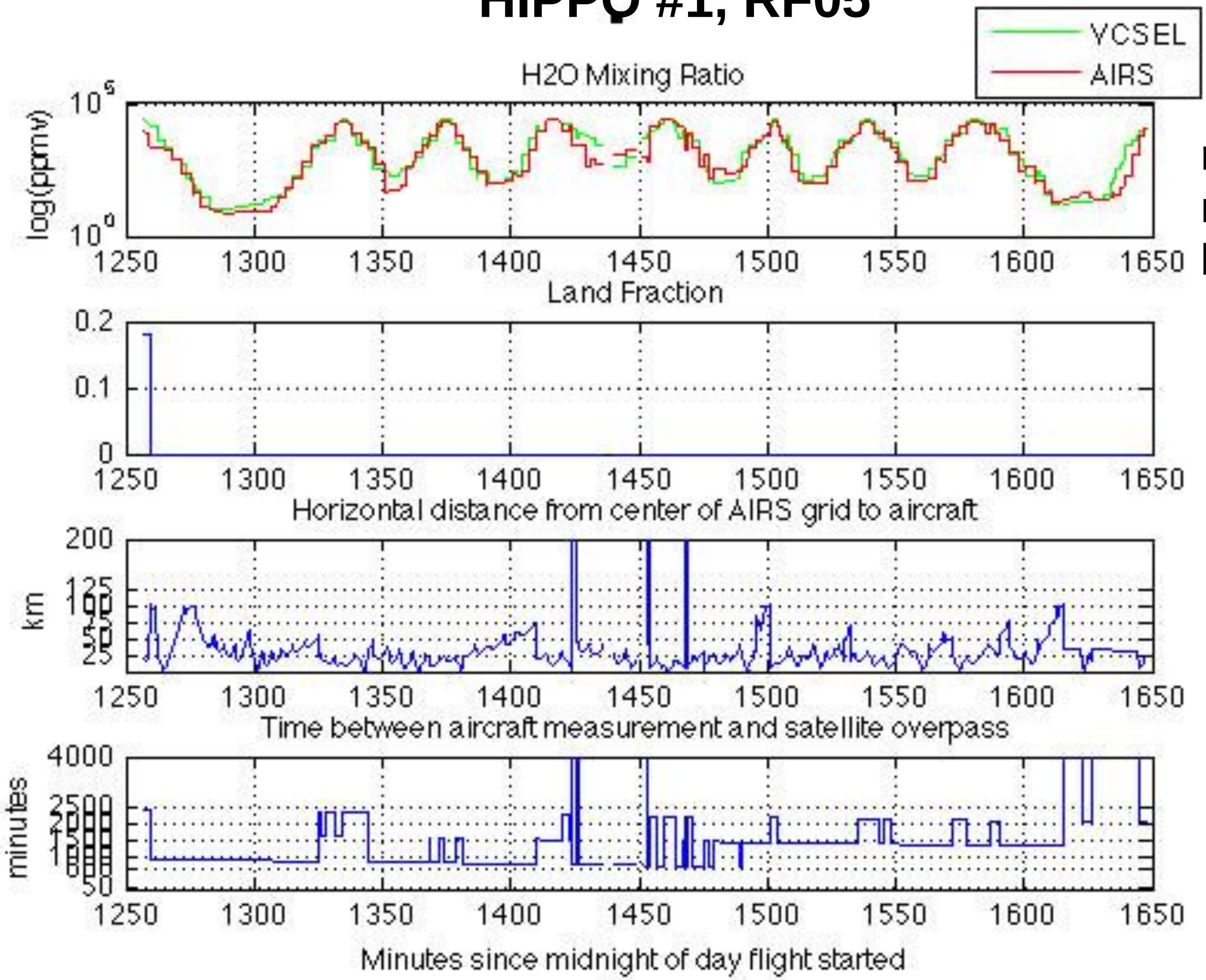
Analyzed flights 3-18 of START08 (N. America, mid-latitudes)
meridional transect of Pacific, HIPPO Global #1(RF3-7)

….

HIPPO #1: RF05, Hawaii to Samoa



HIPPO #1, RF05



$r^2 = 0.96$
m=1.03
b=518 ppmv

Variations in time / space

e.g. RF04 in START08 (100-150 km away from flight) (98% land)

Time (min.)	R^2	N
0-1	0.92	32
1-90	0.80	2600
90-180	0.76	1640

With greater ΔT, less correlation between AIRS and VCSEL

Distance (km)	R^2	N
0-22.5	0.96	478
100-150	0.76	1640

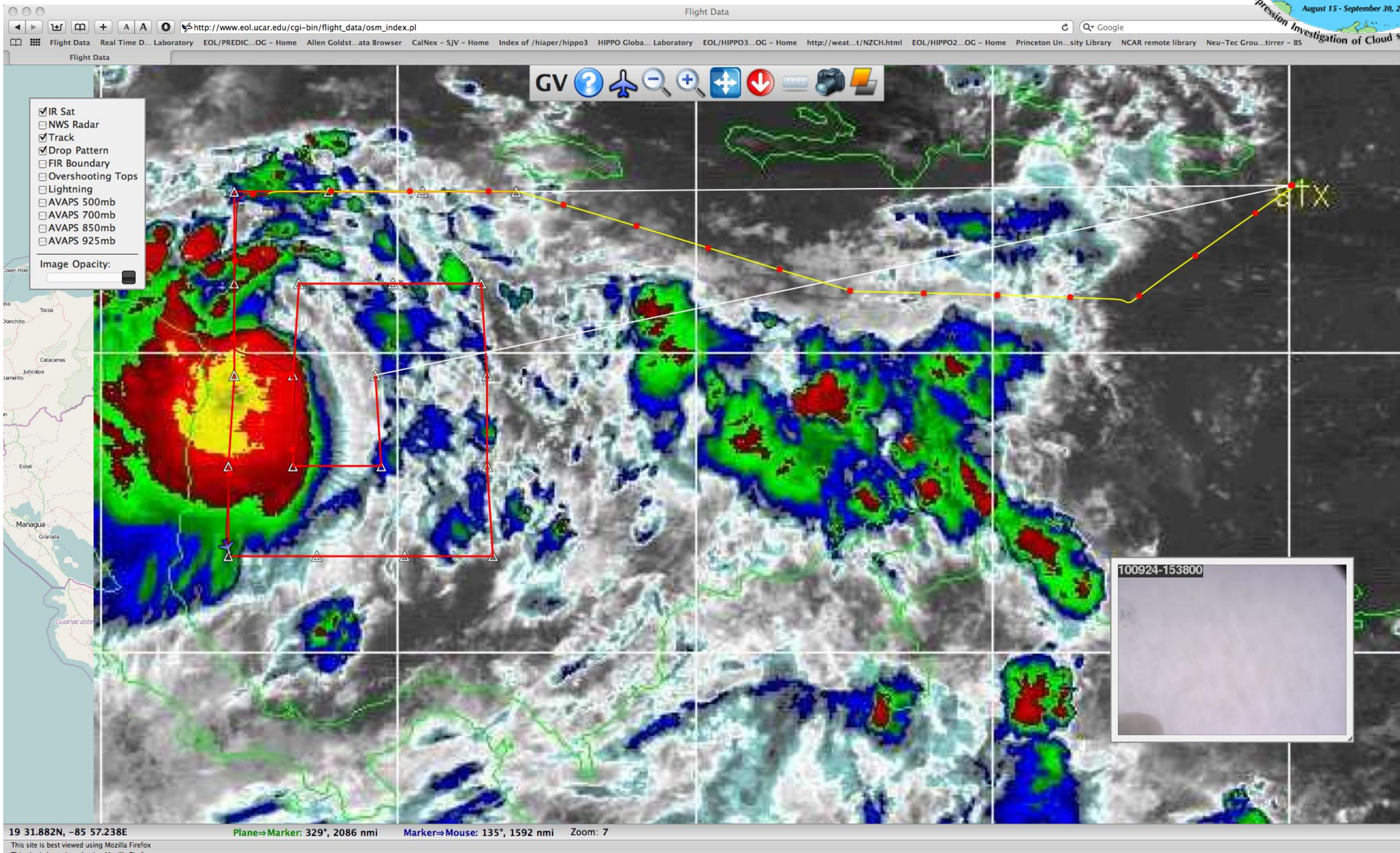
With greater Δt and Δd, less correlation between AIRS and VCSEL

(need aggregate data over all flights)

NSF Pre-Depression Investigation of Cloud Systems in the Tropics

Aug./Sept. 2010, St. Croix, U.S. Virgin Islands

Goal: why do some disturbances become hurricanes and others fall apart?

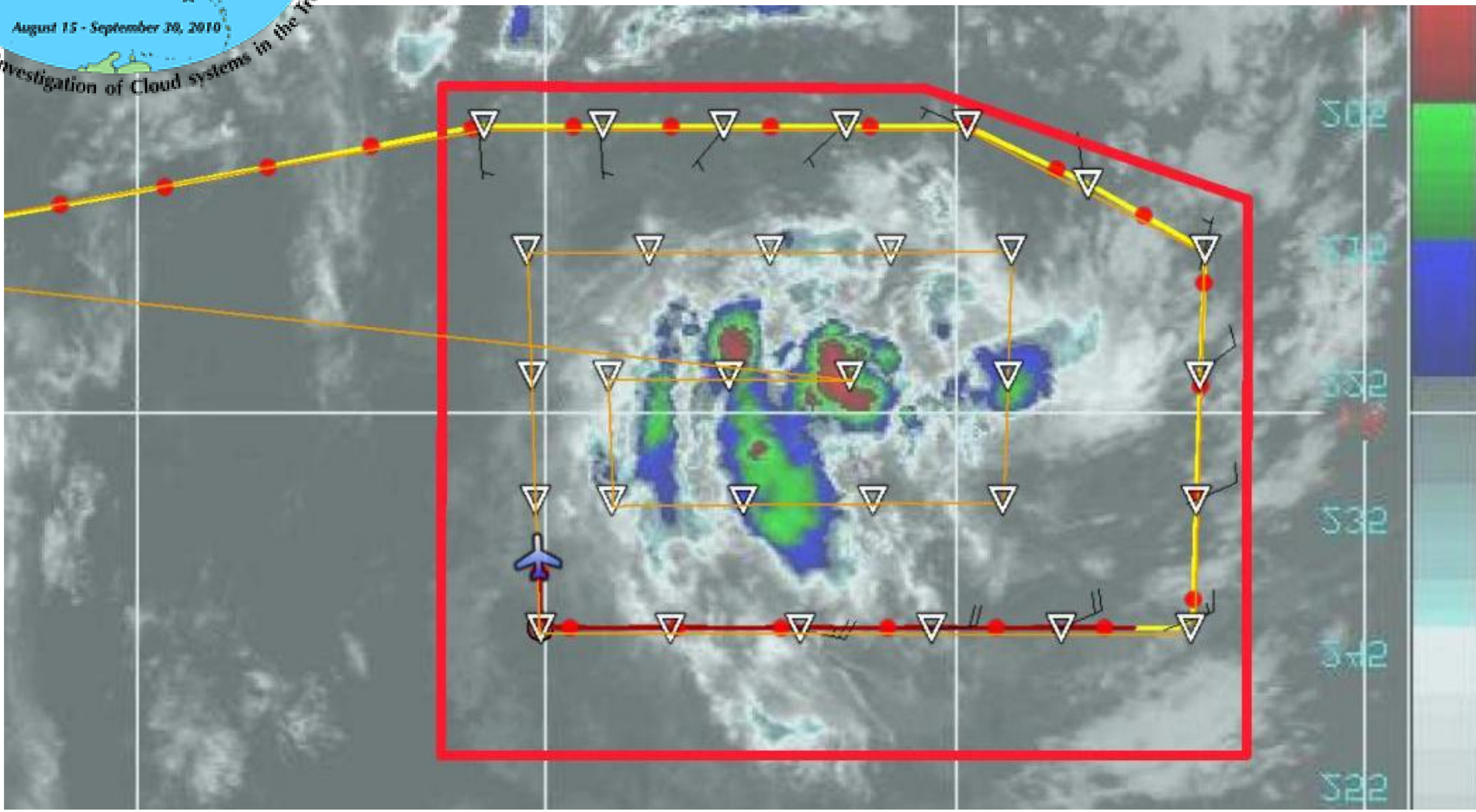


- tropical, upper tropospheric dataset exclusively (130-200 hPa)
- 93 hrs at T≤-40ºC; N=5550 ice supersaturated regions

e-Depression Investigation of Cloud Systems in the Tropics (PREDICT)

St. Croix, U.S. Virgin Islands

e disturbances become hurricanes and others fall apart?



tropical, upper tropospheric dataset exclusively (130-200 hPa)

93 hours at T<-40ºC; N=5550 ice supersaturated regions

Outline

1. Motivation for open-path systems

2. How do clouds form?

    A. NSF Gulfstream-V VCSEL hygrometer

    B. Fine-scale observations of cirrus clouds

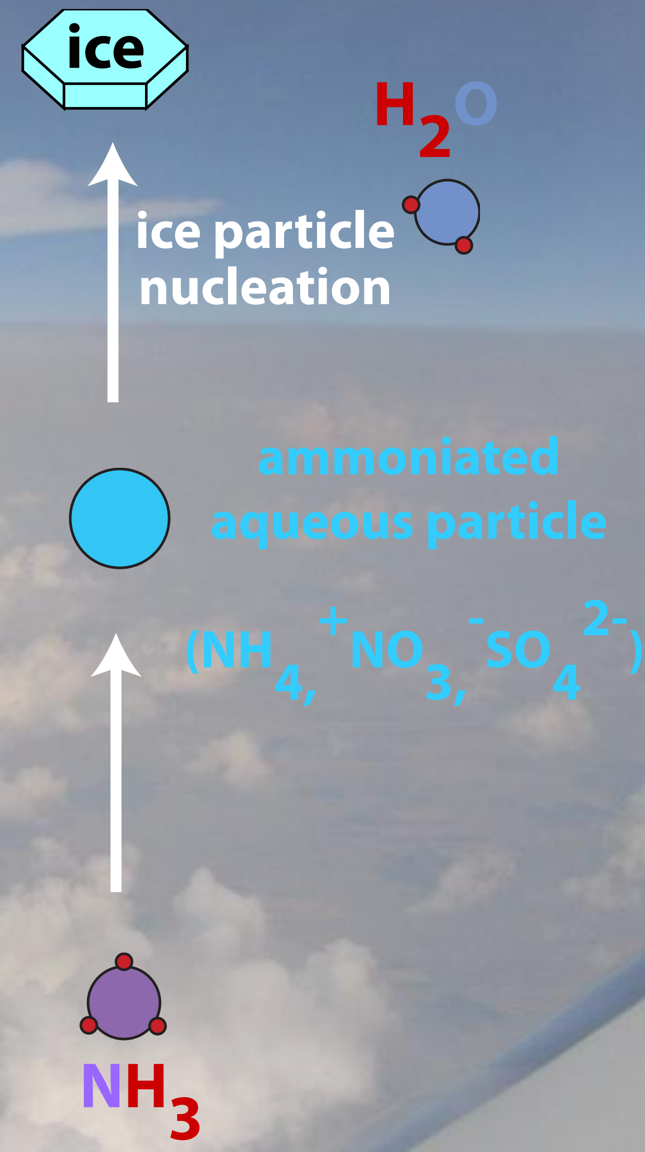
        (START08, HIPPO, PREDICT)

3. Open-path QCL ammonia sensor

    A. Experimental

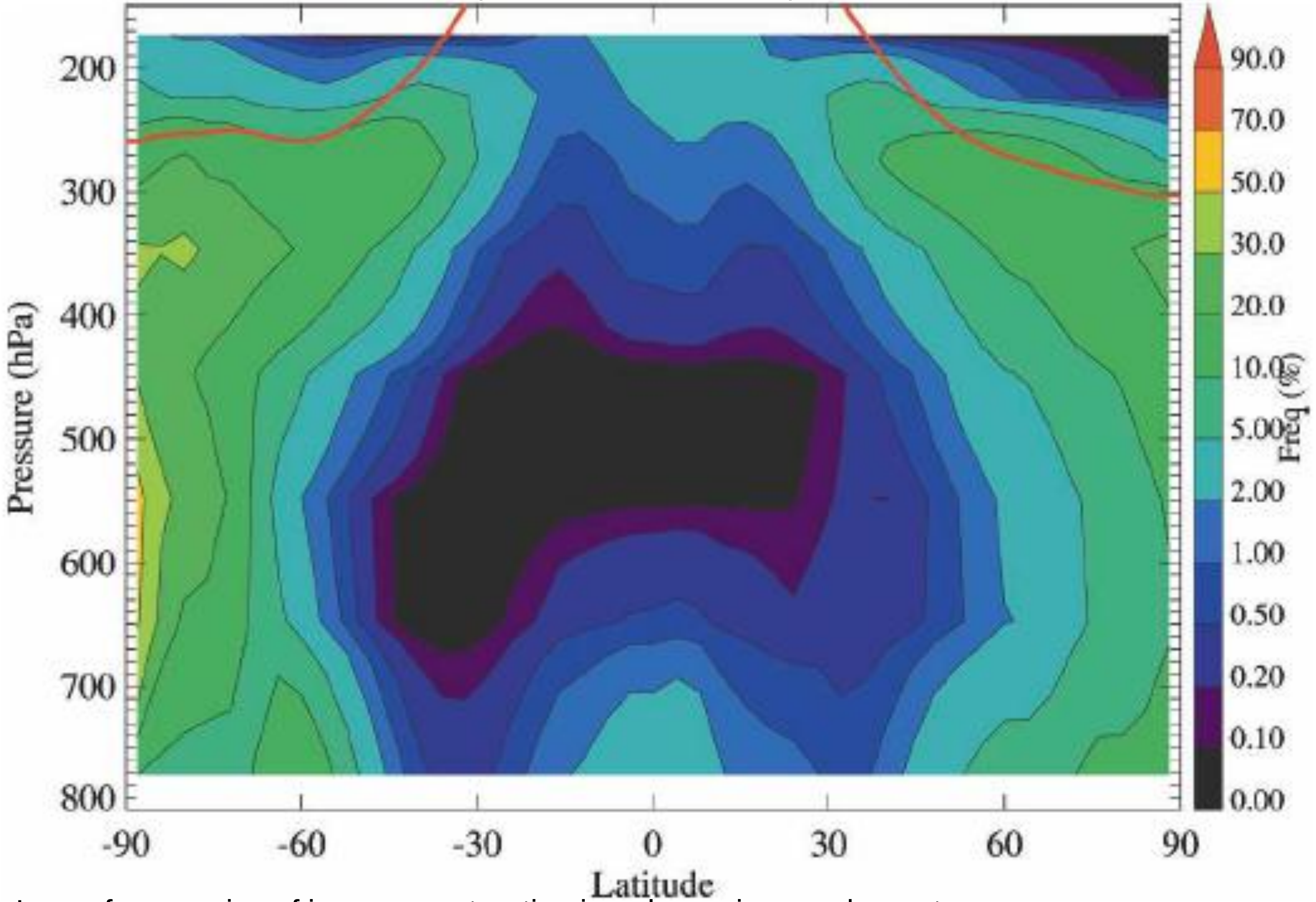
    B. CALNEX 2010

    C. Is there a significant urban source?



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?