Combining the RS41 with CFH's Golden Points for Reference Quality Humidity Retrievals

Poltera et al., in preparation for AMT
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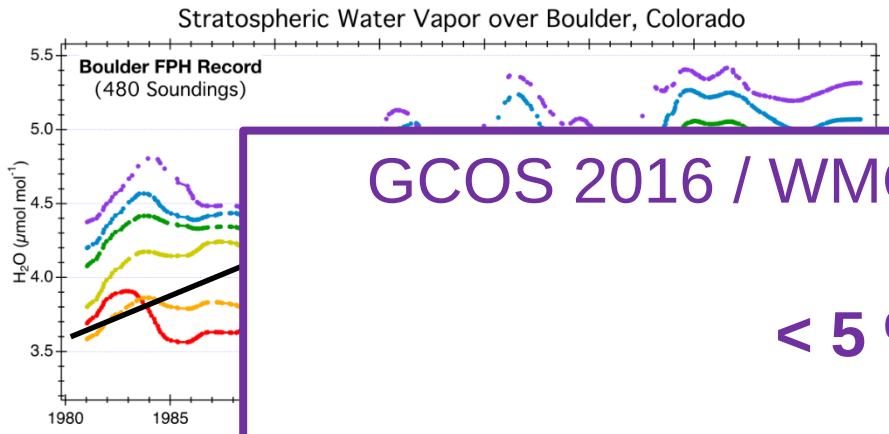
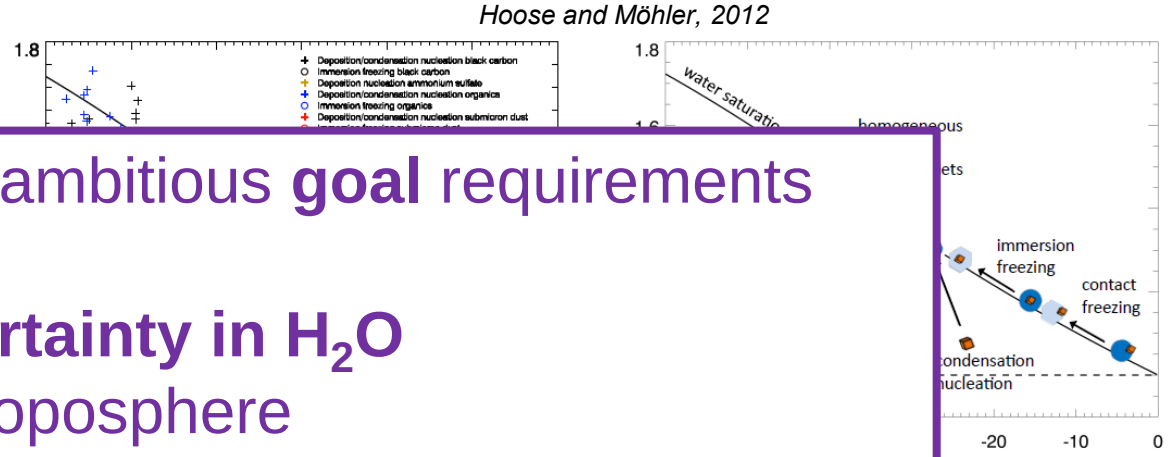
Motivation: need for accurate balloon-borne measurements of H_2O

Accurate measurements of atmospheric H_2O are important, e.g.:





GCOS 2016 / WMO 2021 ambitious **goal** requirements

< 5 % uncertainty in H_2O
in the troposphere

< 4 % uncertainty in H_2O
in the stratosphere

➢ **Chilled Mirror Hygrometers**

Monitorin ***sphere***

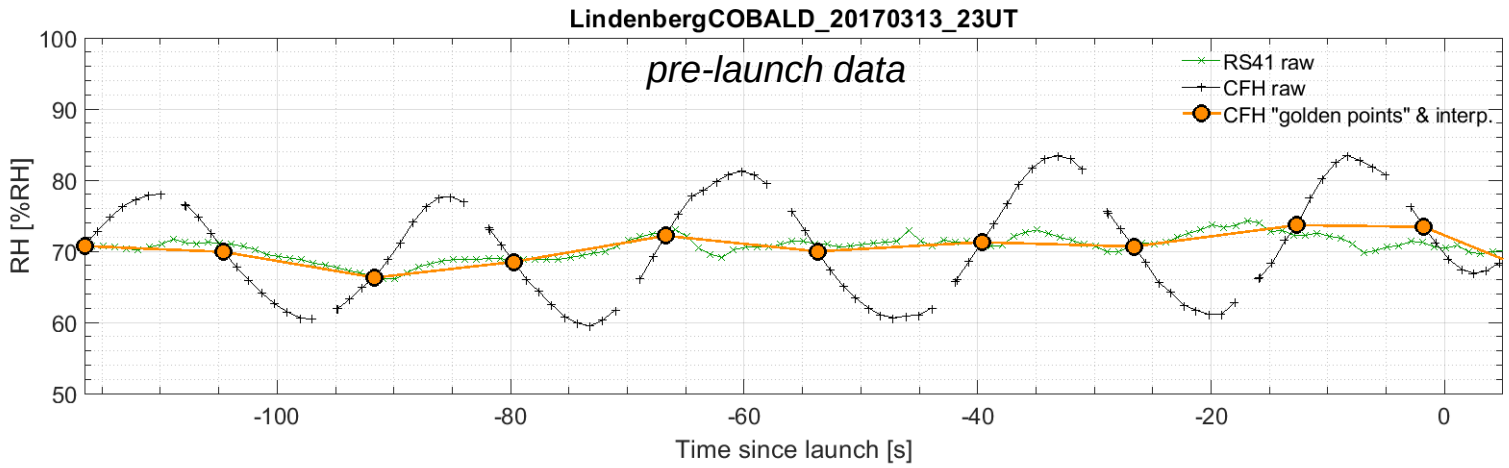
- H_2O: mo chanisms main pos an 10%

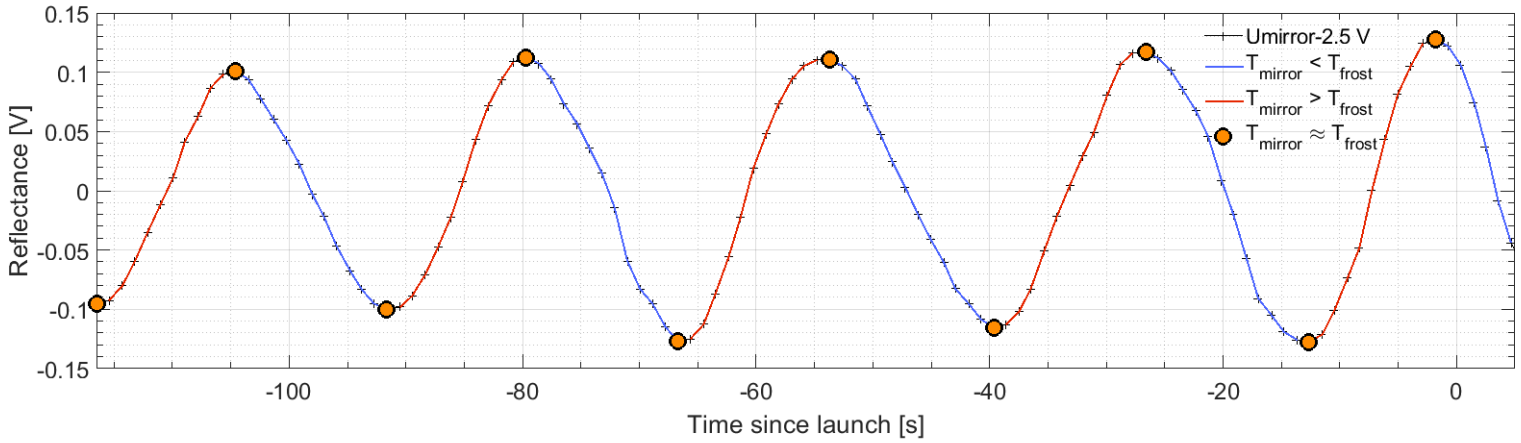
- Small tre (few hun significant impact on our climate (Forster and Shine, 2002; Solomon et al., 2010).

  - ***Numerical Weather Prediction***
  - ***Satellite validation and drift-detection***

Mirror Temperature, Mirror Reflectivity and “Golden Points” I

Chilled mirror instruments measure the **mirror temperature**.
However…
what we want is the **frost point temperature**.





Chilled mirror instruments measure also the **mirror reflectivity**.

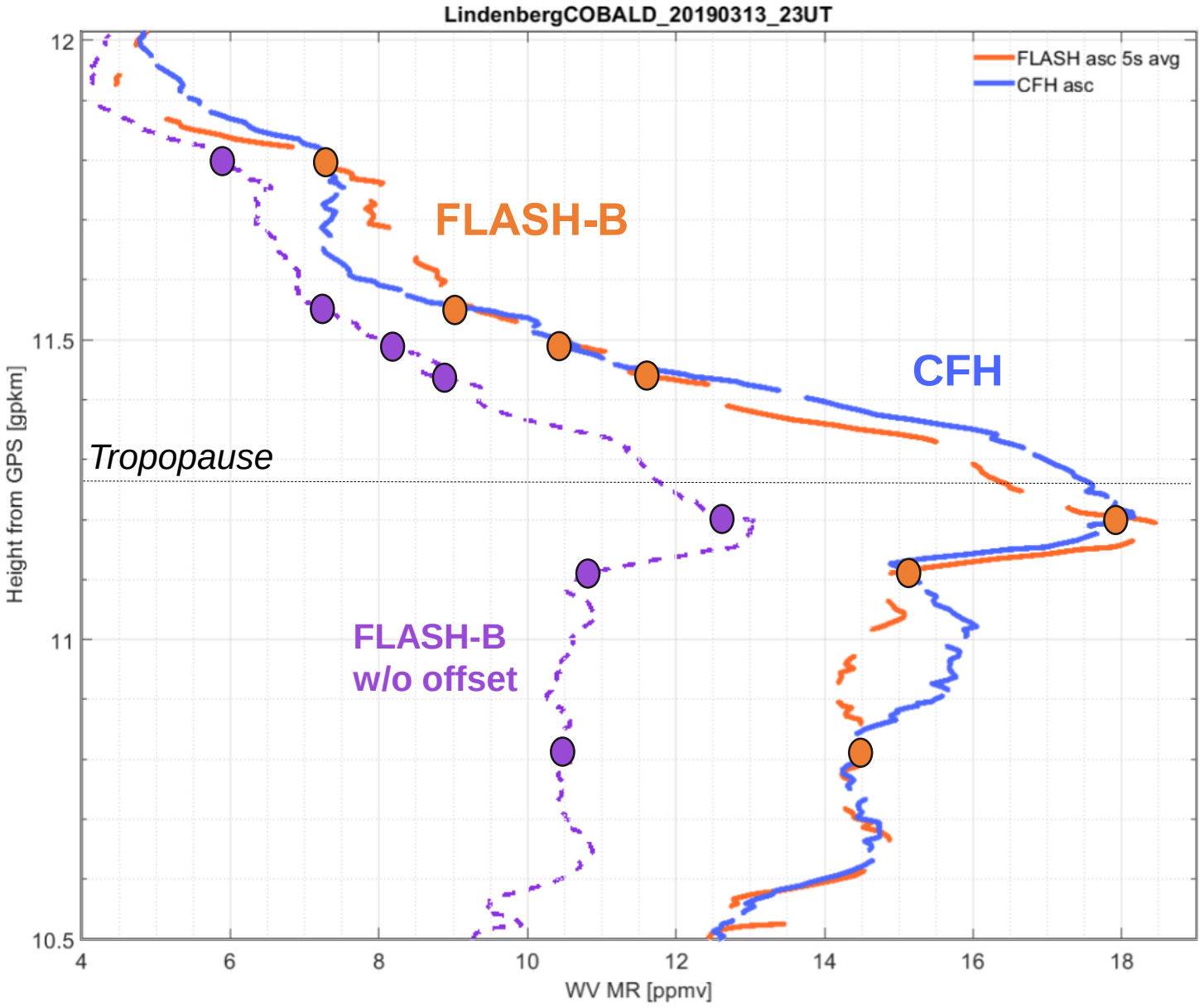
mirror reflectivity increases
-> mirror coverage decreases
-> condensate evaporates
-> **mirror too warm**

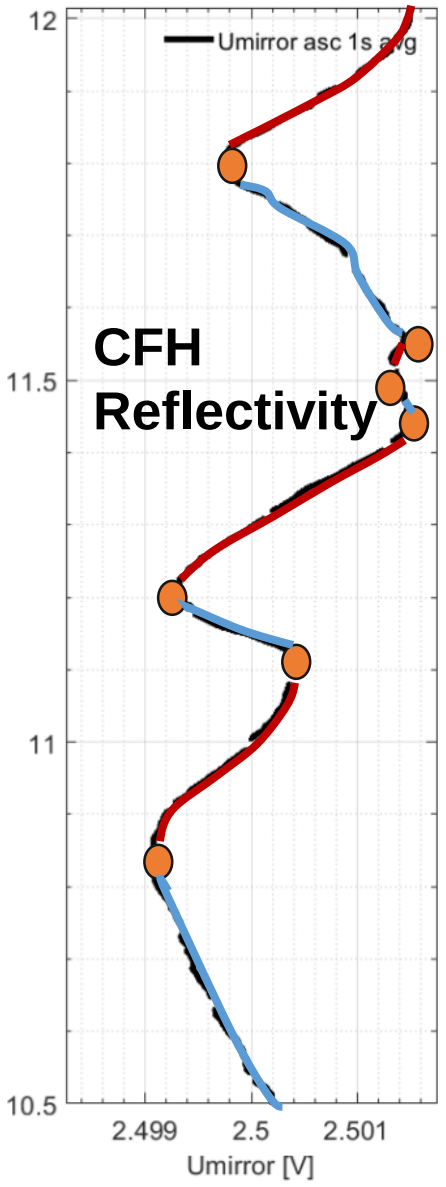
mirror reflectivity decreases
-> mirror coverage increases
-> condensate grows
-> **mirror too cold**

mirror reflectivity has a min/max
-> condensate transitions from growing-to-evaporating or evaporating-to-growing.
-> thermodynamic equilibrium
-> **Tmirror = Tfrost**

At those transition points, a.k.a.
“Golden Points”
we obtain an *accurate estimate* of the true atmospheric frost point.

Mirror Temperature, Mirror Reflectivity and “Golden Points” II





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In this example, the **Golden Points** allowed to:

- perform in-flight calibration of FLASH-B (see also Krämer et al. 2009) and discover the existence of a **fluorescence counting offset** in this particular FLASH-B instrument.

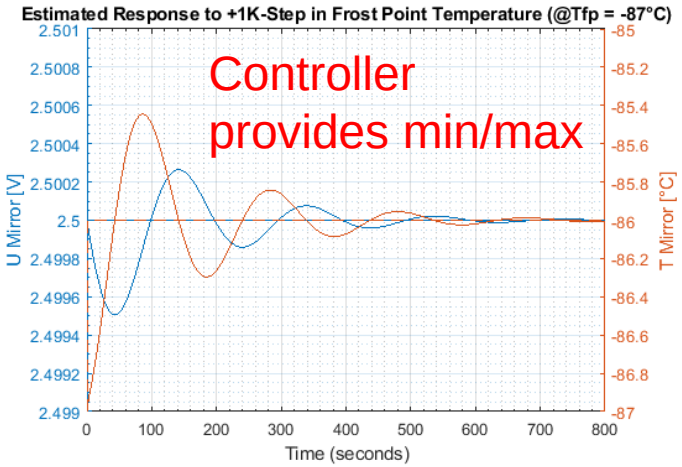
Golden Points: summary

In principle, **any chilled mirror hygrometer** with an *accurately calibrated mirror temperature* provides several **accurate frost point temperature measurements ("Golden Points")** per balloon sounding.

- ➢ Accuracy in **frost point of 0.2 K (k=2)** (assuming ~5 s smoothing to eliminate noise).
- ➢ Reference for **calibrating other instruments** (e.g. offset, bias and time-lag correction).
- ➢ **Outside** the Golden Points, we have **non-equilibrium**→ warm/cold **excursions (few mK to few K)**

The **number of Golden Points typically decreases with altitude, and depends on**:

- ❖ the performance of the feedback controller (fast-responding vs. slow-responding)



PID controller with 3 overshoots.

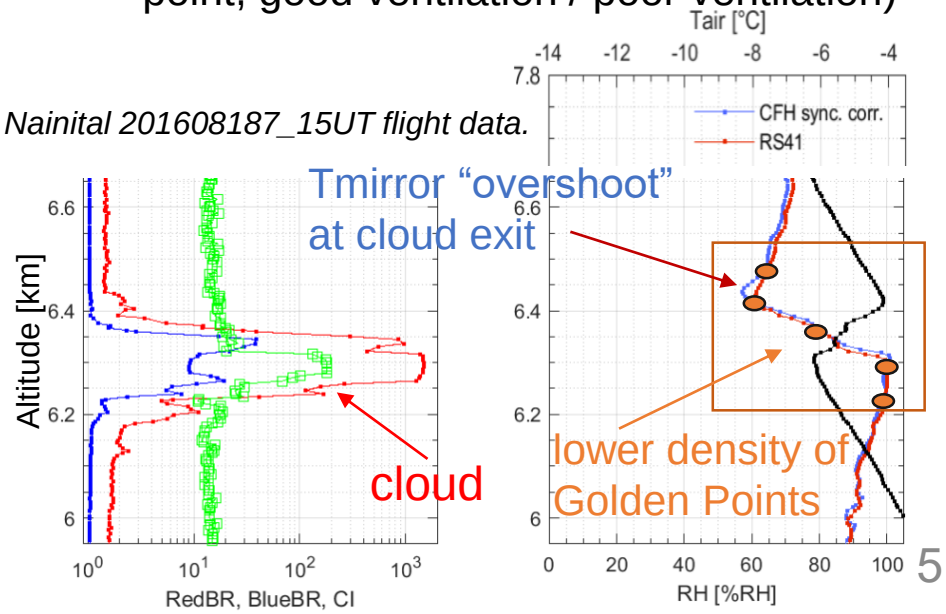
- ❖ the nature of the condensate (fine frost vs. coarse frost)

low nb of G.P. *high nb of G.P.*

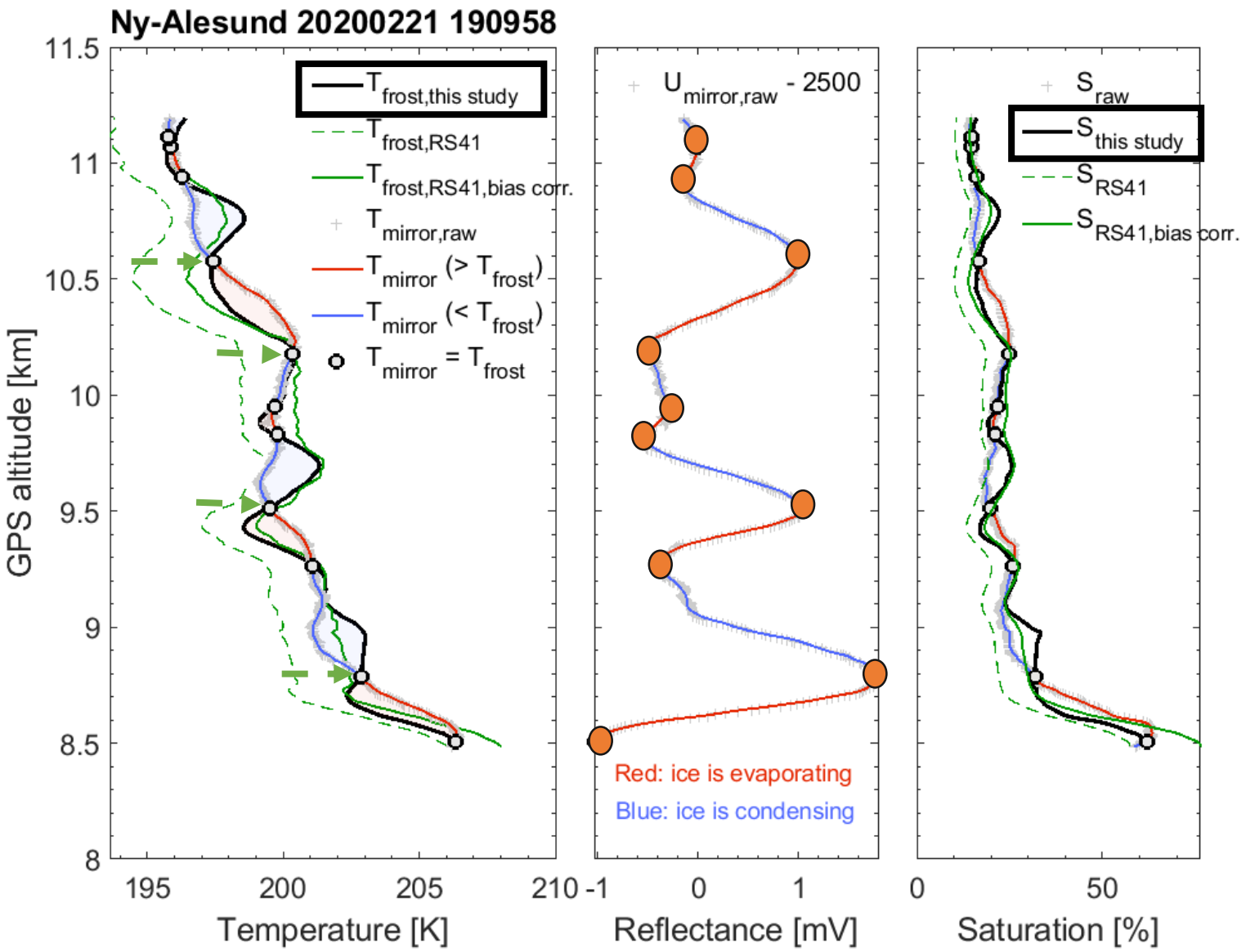
Polycrystalline frost layer on CFH. From Vömel et al. 2016.

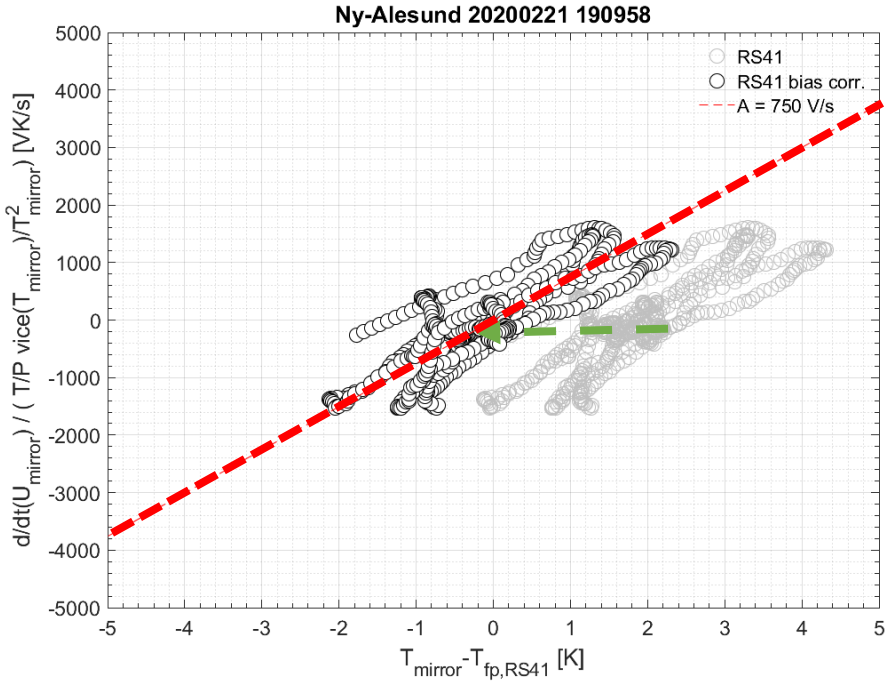
- ❖ the state of the atmosphere (slowly-varying frost point / fast-varying frost point, good ventilation / poor ventilation)

Nainital 201608187_15UT flight data.



Non-Equilibrium Correction: CFH and RS41





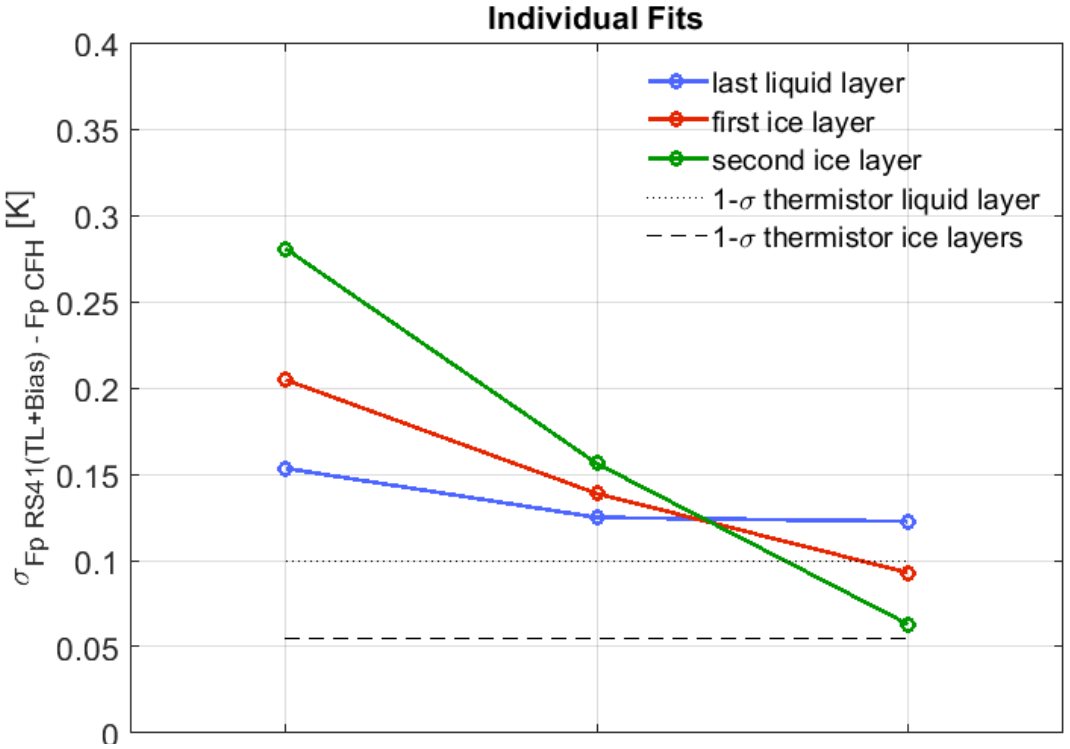
i) Find the Golden Points
ii) Find time-lag and bias parameters to fit RS41 @ Golden Points
iii) Calculate the mirror sensitivity (slope) A
iv) Correct CFH:

$$T_{frost}(t) = T_{mirror}(t) - \frac{B(t)}{A} \cdot \frac{dU_{mirror}}{dt}$$

see also Poltera et al., ICM-13

CFH-RS41 comparison (70 nighttime flights): CFH non-equilibrium error

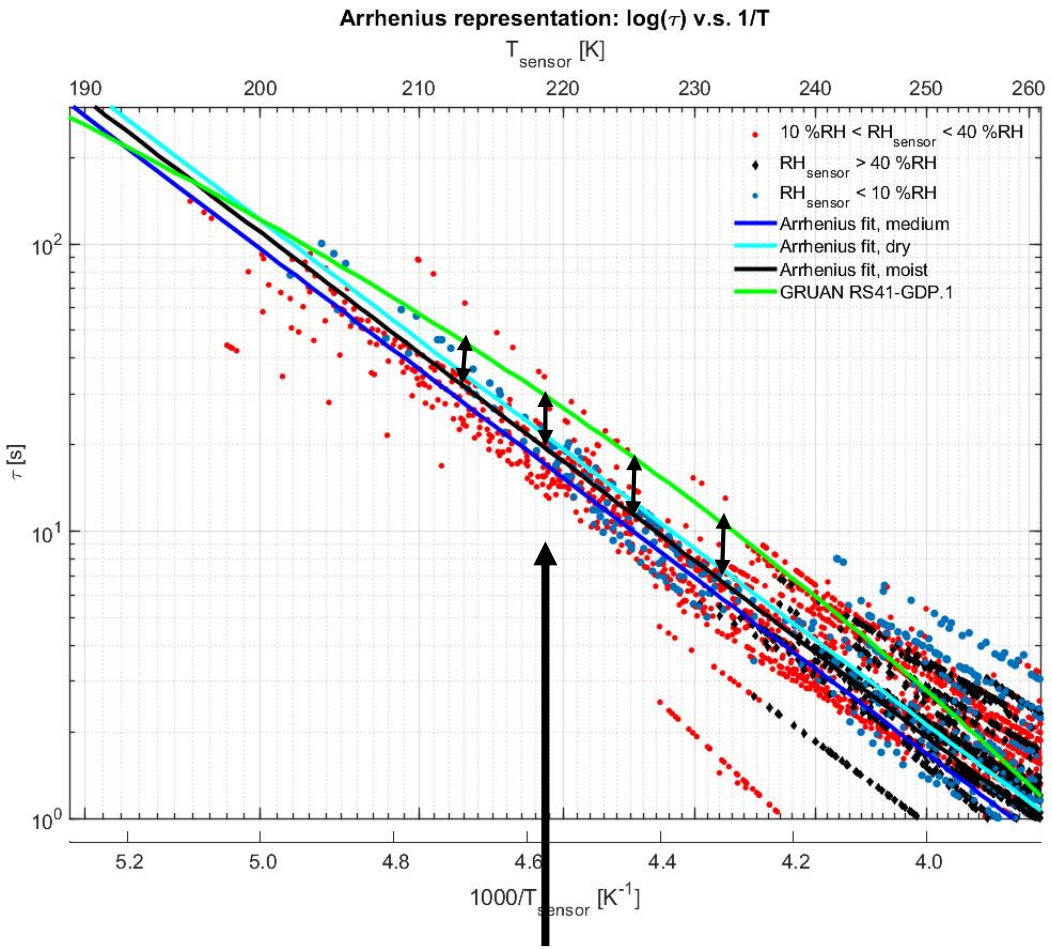
RMS error [K]
CFH vs.
RS41 corrected.



"CFH raw" "CFH corrected" "CFH Golden Points"

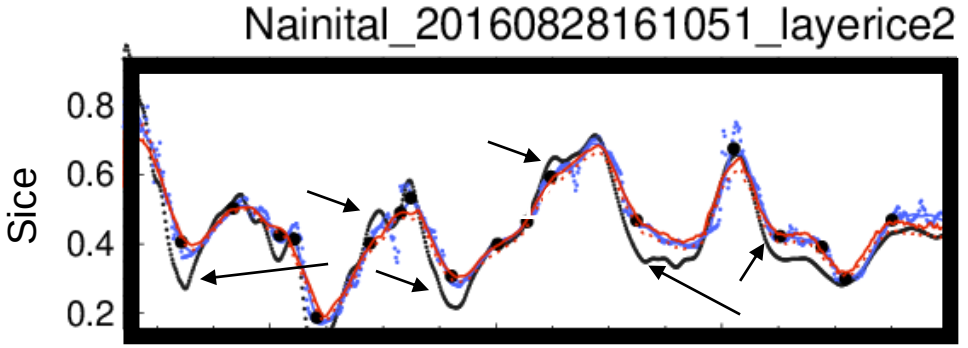
- **UT/LS (second ice layer) benefits the most out of the non-equilibrium correction:**
  ~45% reduction of the residual error between raw and corrected (up to 80%-90% in some cases)
- **Mid-troposphere (first ice layer):** ~30% error reduction
- **Lower-troposphere (last liquid layer):** ~20% error reduction
- **Mean CFH error < 0.021 K:** on average, negligible non-equilibrium error 'asymmetry'

CFH-RS41 comparison (70 nighttime flights): Time constant of RS41



Time-lag correction of RS41

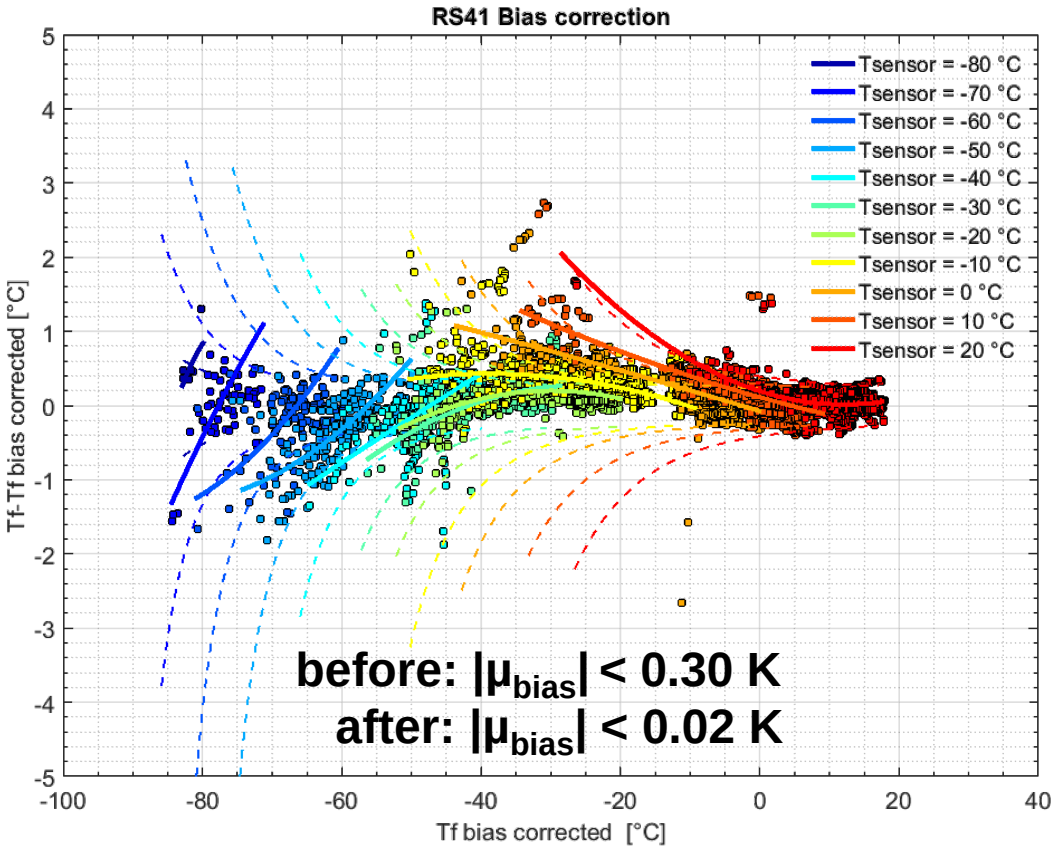
- **Arrhenius** relationship with temperature (physically more reasonable than exponential)
- Empirical **RH-dependence**
- **Smaller τ** than GDP.1 measurements (≈ Vaisala) performed between -68°C and -5°C (205K to 268K)



Vendor's time-lag over-correction in T-sensor range of 205 K to 227 K

Mid-latitude lowermost stratosphere responsible for over 75% of SWV climate feedback (Banerjee et al., 2019). Time-lag overcorrection might introduce a systematic error in mid-latitude lowermost stratosphere.

CFH-RS41 comparison (70 nighttime flights): Bias of RS41



~ within Survo et al. (2014) 2-σ uncertainty after storage and ground-check procedure

Bias correction of RS41

- **Frost point** and **Temperature** dependent.
- **Sensor model of Vaisala** (= no bias correction) is **good, but has room for improvement**, especially at **low temperatures and/or very dry conditions**.
- **Dry bias** at -70 < T < -40°C and dry conditions might introduce a systematic error in mid-latitude lowermost stratosphere.

See also:
Sun et al. (2021) (satellite)
Lee et al. (2021) (lab)

CFH + (FLASH-B or RS41) Reference Humidity Retrieval

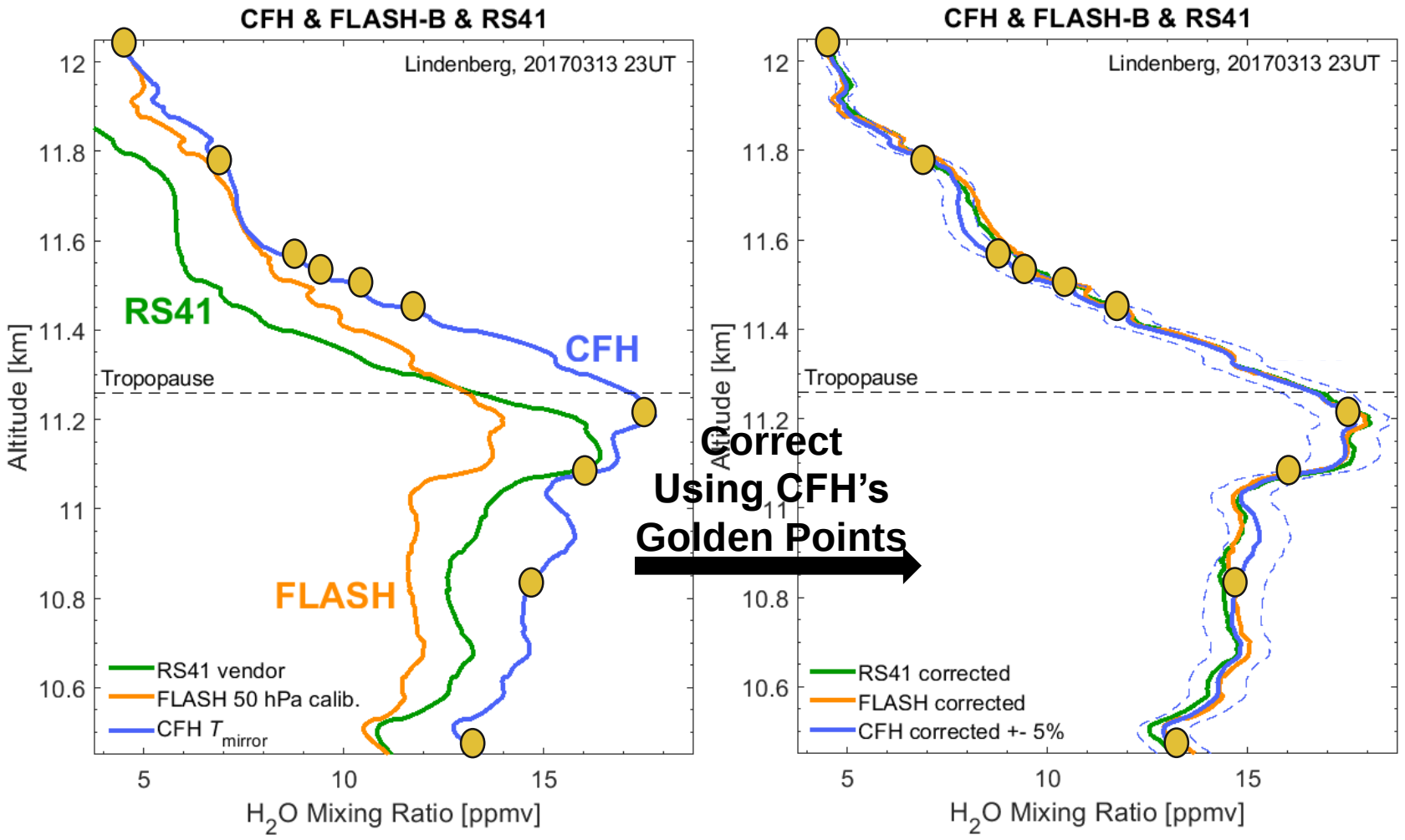
- **Up to 50% differences near the tropopause**
- **Determine the location of Golden Points**
- **Apply corrections**

Error sources:

RS41
- dry bias in sensor model
- τ assumed too high

FLASH
- offset (constant) in fluorescence counts

CFH
- non-equilibrium errors outside the Golden Points



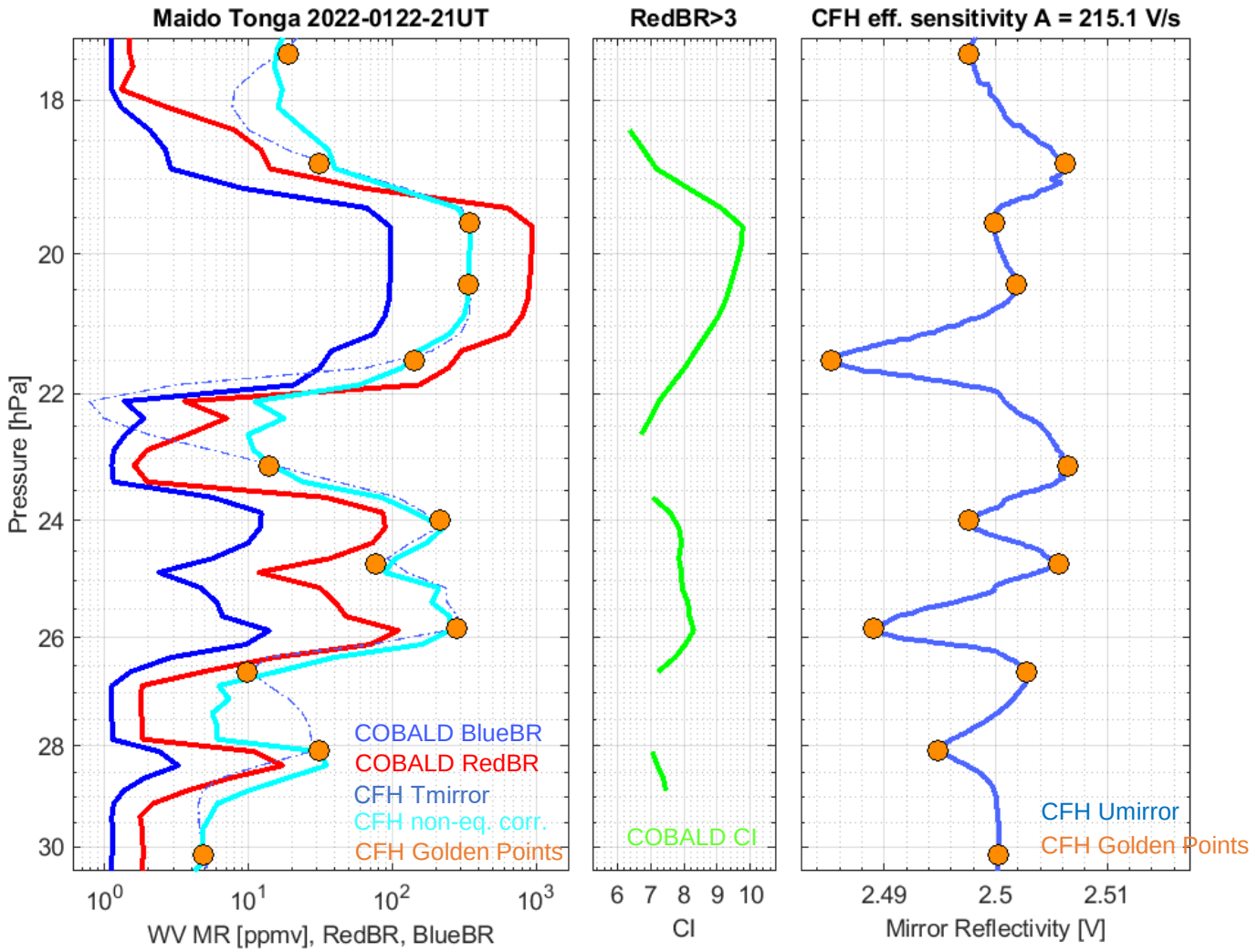
Differences within ~ 5 % after corrections

FLASH calibrated in the stratosphere @50 hPa w.r.t. CFH, taking quenching, H_2O and O_2 absorption into account (Lykov et al., ICM-9)

CFH correction in the Hunga Tunga - Hunga Ha'apai plume

2 Golden Points in peak of the plume @ ~ 350 ppmv (consistent with Vömel, Evan and Tully, 2022).

High vertical resolution evidence that aerosol and H_2O profiles are highly correlated



CFH's non-equilibrium correction allows to recover from the raw H_2O profile the 5 layers seen by the fast-responding COBALD sonde

Conclusions

CMH provide feedback of thermodynamic equilibrium through the reflectivity measurement. We found:

At the Golden Points (dU/dt=0):

- The mirror temperature is the frost point with an accuracy **better than 0.2 K** (assuming ~5 s smoothing to eliminate electronic noise). This corresponds to an uncertainty in H_2O partial pressure **better than 3-4% in the stratosphere and even less in the troposphere**.
- The golden points can be used to **calibrate other instruments** (e.g. offset, bias and time-lag correction).
- Based on the CFH golden points, we have derived an **improved time-lag and bias correction** for the **Vaisala RS41 radiosonde.**

Outside of the golden points (|dU/dt|>0):

- The mirror is in **non-equilibrium** with warm/cold temperature **excursions**. A **correction can be achieved using simultaneous measurements** from a second instrument.
- For **CFH**, in the **worst cases, deviations larger than 5 K** between mirror temperature and the estimated frost point are possible, but in general, they are **typically better than 0.5 K**.
- When the mirror temperature deviates significantly from the true atmospheric frost point, our **non-equilibrium correction may remove 80%-90% of the non-equilibrium error**, thereby **increasing significantly the vertical resolution and accuracy** of the measurement. This happens typically for cases with coarse ice films and/or large mixing ratio changes in the atmosphere.

Thank you!