Aiming for the stratosphere:

Comparison of **RS41** and **CFH** RH measurements

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18.11.2025 | yann.poltera@unibe.ch | GRUAN ICM-16, 17-21 November 2025, Tenerife

Afterglow
ISS – NASA (30-Oct-2014)

UNIVERSITÄT BERN

Acknowledgments
UniBe/OCCR
ETH
Mylab
MeteoSwiss
EMPA
DWD/GRUAN-LC
AWI
FZJ
FMI
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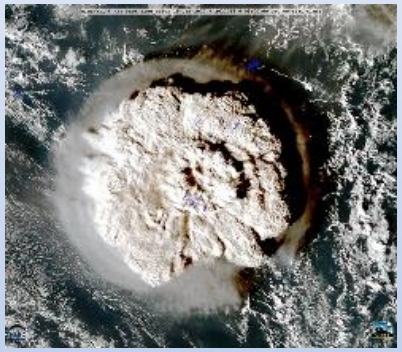
Motivation

- UTLS H2O impacts the **radiative balance,** high **clouds,** the **ozone layer** and **large-scale** dynamics(1).
- 2020's decade is experiencing
  - **major perturbations in SWV**(2)
    - Australian Pyrocumulonimbus 2019/2020
    - Hunga Tunga 2022
    - Build-up of rocket launches
  - **desertification** of observational capabilities(3)
    - Phase-down of HFCs
    - Aura/MLS end-of-life mid-2026
- **significant improvements** in radiosonde **technology** and **re-usability**
  - Easily access the stratosphere, heated sensors for all-weather robustness and emergence of new solutions for sonde recovery
- **RS41 record** (GRUAN/NDACC/SHADOZ/Campaigns/GTS)
  - High-resolution measurements over all latitudes
  - Timeseries now reaching decadal time-scale (pre- and post Hunga Tonga) on various sites



Hunga Tonga plume injecting ~140 Tg H_2O ↔ 10% global SWV increase (Himawari-8 15-Jan-2022)

Fine structures affecting radiative balance: cirrus and contrails (Schumann et al., 2017)

Cloud in the middle atmosphere from Soyuz reentry (ISS – NASA 11-Dec-2015)

(1) e.g., Salomon et al., 2010; Dessler et al., 2013; Charlesworth et al., 2023
(2) e.g., Millán et al., 2022; Khaykin et al., 2020; 2022; Vömel et al., 2022; Brown et al., 2024
(3) Salawitch et al., 2025; UNEP, 2016

RS41: thin-film hygrometry

Working principle:

i) Ad/de-sorption and diffusion of water molecules in sub-micron polymer film induces measurable changes (~ proportional to RH) in electrical capacitance(1)

ii) A sensor model converts capacitance to RH and corrects for slow kinetics at low temperatures

Vaisala Ojy, Finland

The humidity sensor of the **RS41** radiosonde(2) implements some of the best practices for upper-air applications(3)

- ❑ **Heated** (*Tair+5 K*) thin-film polymer with **integrated T-sensor**(4) → no need for solar radiation correction, shorter response time, efficient de-icing and responsiveness in clouds
- ❑ Sensor model accounting for changes in sorption equilibrium with temperature and possibly trace-gas interference(5)
- ❑ **Time-lag correction** accounting for the slow ad/de-sorption kinetics at low temperatures(6)
- ❑ **Reconditioning** & **Recalibration** accounting for changes in sorption capacity during transport & storage(6)

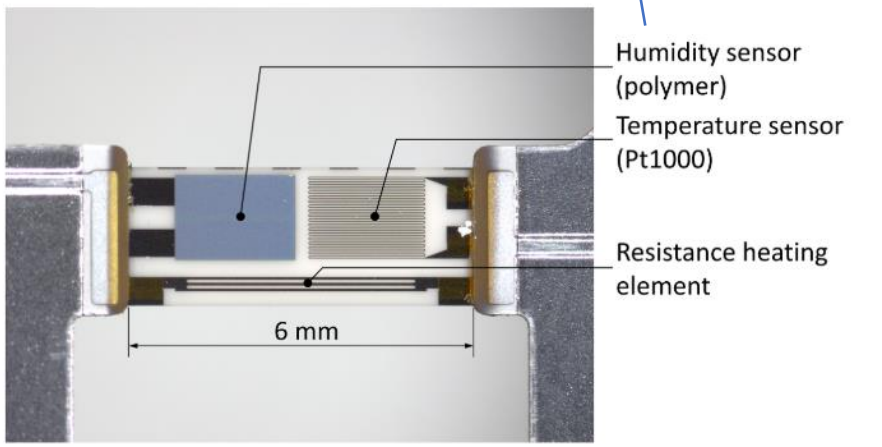


Figure 2.4: Humidity sensor chip (Humicap®) of the RS41 radiosonde.

GRUAN-TD-8

Combined uncertainty in sounding(6)

4 %RH (k=2), uncertainty given for Tair > -60 °C only

(1) Antikainen and Paukunnen, 1994; Wildmann et al. 2014
(2) WMO IOM-143 (Dirksen et al., 2024)
(3) WMO-8, 2023
(4) GRUAN-TD-8 Rev.1 (Sommer et al., 2023)
(5) Hiltunen et al., 2016 [FI127193B]
(6) Vaisala WP-B211317EN-A (2013); Jauhiainen et al., 2014; Survo et al., 2014

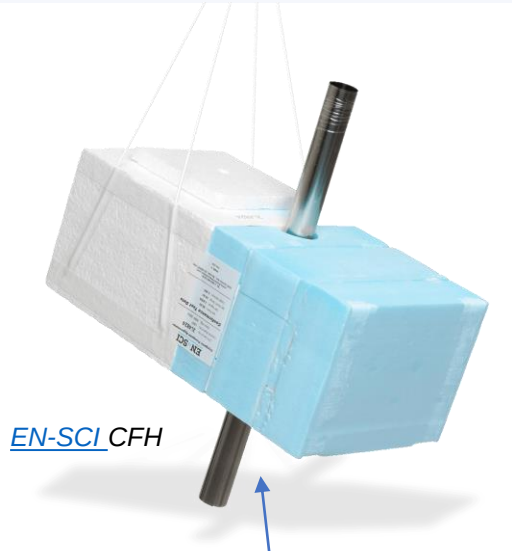
CFH: chilled mirror hygrometry

Working principle:

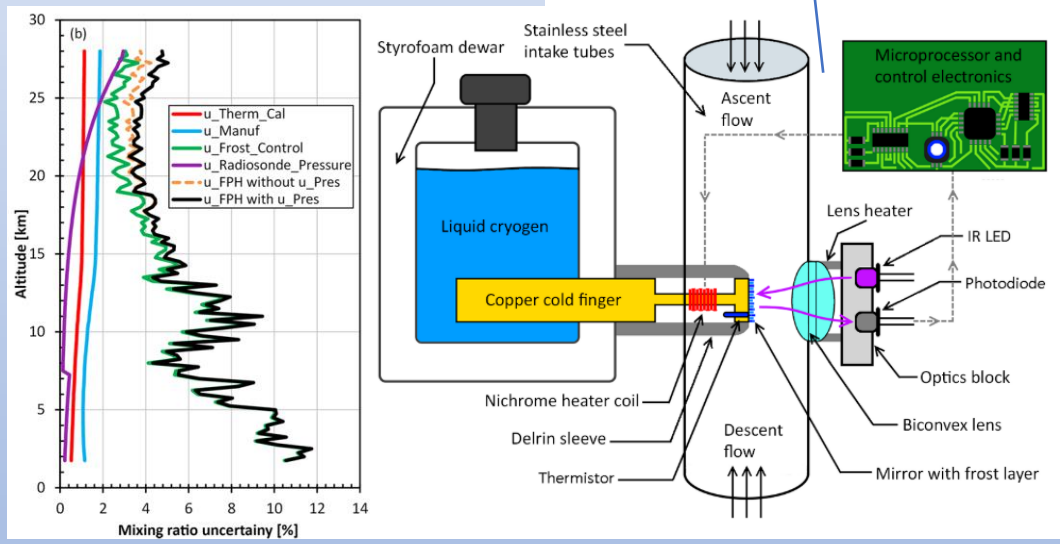
i) a mirror is cooled until a dew or frost layer forms onto the mirror.

ii) a feedback controller manipulates the temperature of the mirror such that the condensate *neither grows nor shrinks*.

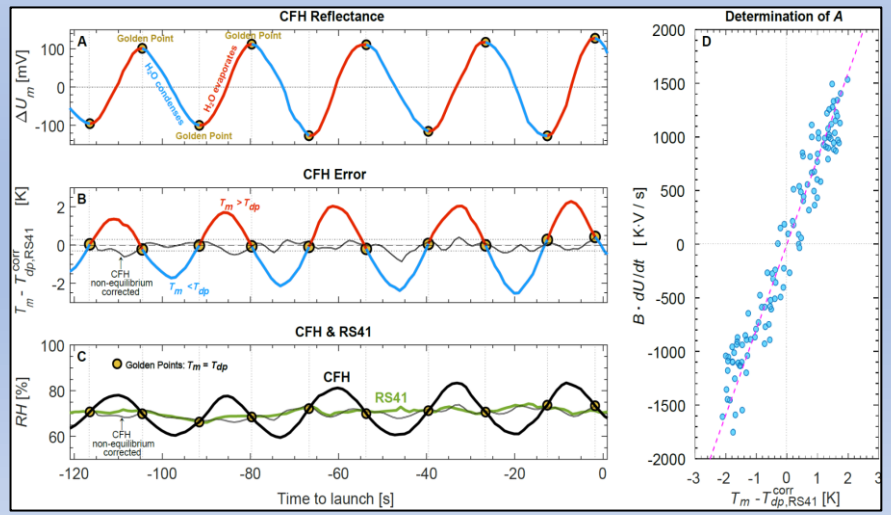
iii) the (averaged) mirror temperature gives an estimate of the dew/frost point



- **SI-traceable**, **high DR**, **low drift** chilled mirror technology(1)
- **State-of-the art** detector and field **reference instrument** for H_2O measurements in the UTLS(2)
- **Uncertainty** @ 250 m vertical resolution
  < 10 % from ground up to 28 km(3)
  < 4 % under stable frost control(3) or at '***Golden Points***' (4)



Hall et al., 2016 (NOAA FPH)



Golden Points and nonequilibrium 'textbook' example: Lindenberg, 13 March 2017, pre-launch data

(1) Vömel et al; 2007a; Hurst et al., 2016
(2) e.g. WMO IOM-107 (Nash et al., 2011); Fahey et al., 2014; Davis et al., 2016
(3) Hall et al., 2016; Vömel et al; 2016
(4) Poltera et al., 2021; 2025

Can the RS41 measure in the stratosphere?

YES, if: *(SNR>3)*

low temperatures and/or
high mixing ratios (w.r.t. ~ 3-6 ppmv background)
Related to **loss of sensitivity at ~< 2 %RH**

Tropics: Layers ~> 15 ppmv measurable@ 25 km
Tropics: Layers ~> 50 ppmv measurable@ 28 km
Tropics: Layers ~> 100 ppmv measurable@ 30 km

~< 3 ppmv measured 2 km above the tropical tropopause by RS41 and CFH

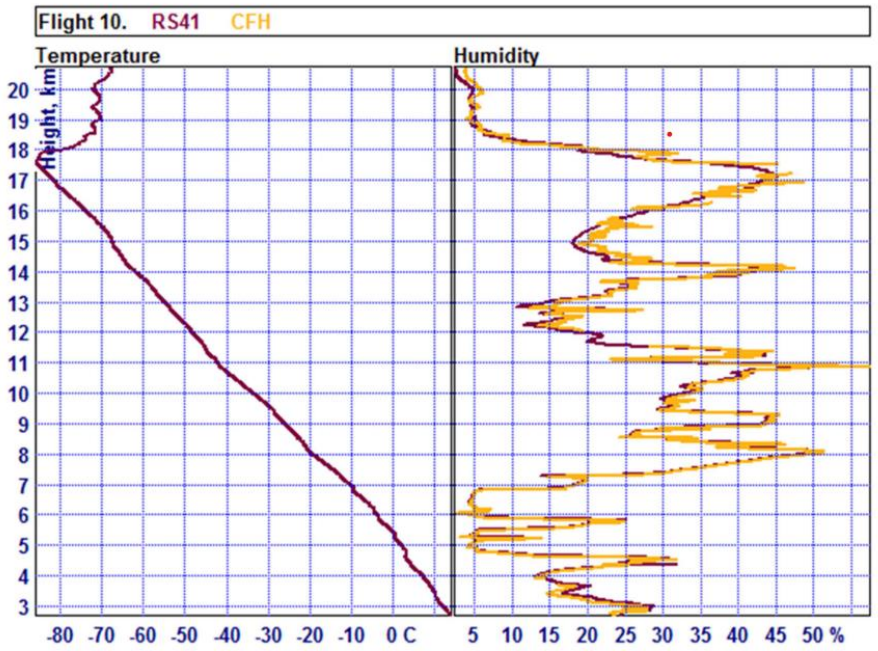


Figure 18. An example of a sounding carried out in Penang, Malaysia in 2013, compred against a CFH reference measurement. The figure shows relative humidity as measured by CFH (yellow) and the RS41 (brown).

Survo et al., 2014; 2015

~ 5 ppmv measured 12 km above the wintertime polar tropopause by RS41 and CFH

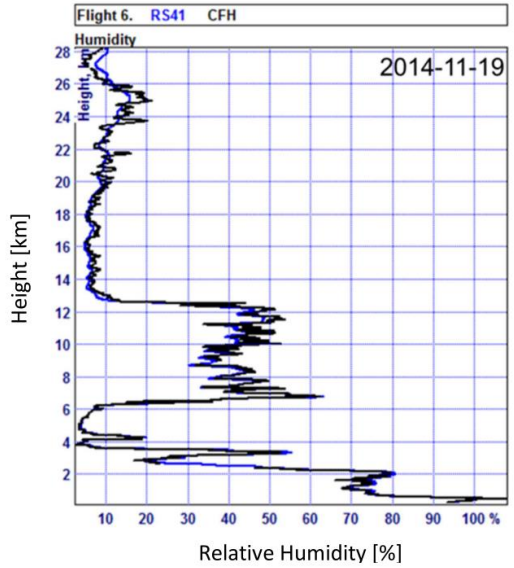


Figure 9. A winter-time relative humidity profile from Sodankylä measured with Vaisala Radiosonde RS41 (blue) and CFH (black).

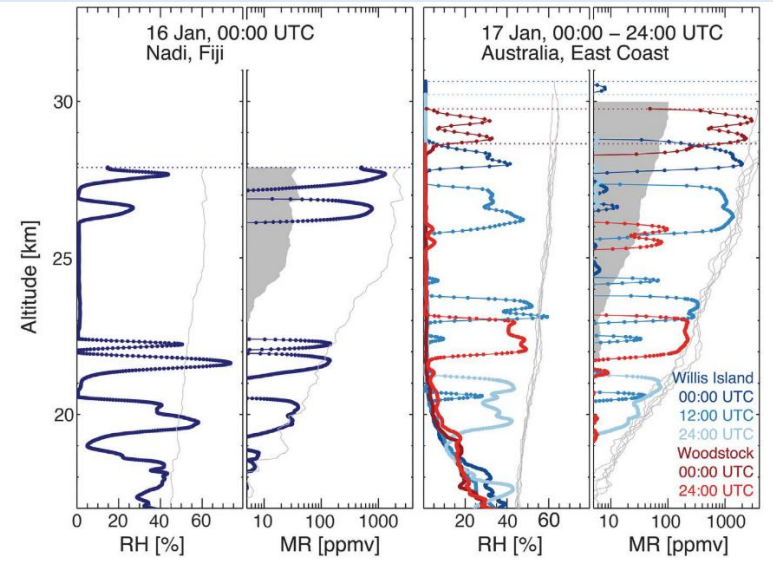


Fig. 1. First soundings within 48 hours after eruption. Left panels: Sounding at Nadi, Fiji, 16 January, 00:00 UTC, 19 hours after the eruption started. Right panels: Five soundings at two Australian east coast stations on 17 January. Ice saturation is shown as thin gray line. Balloon burst altitudes are indicated by dotted horizontal lines. The mixing ratio was calculated by first subtracting a 1% relative humidity baseline. The gray shaded area indicates the estimated detection limit.

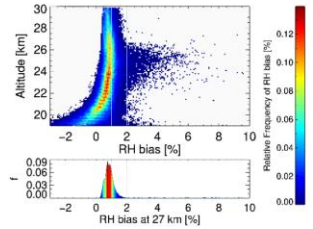
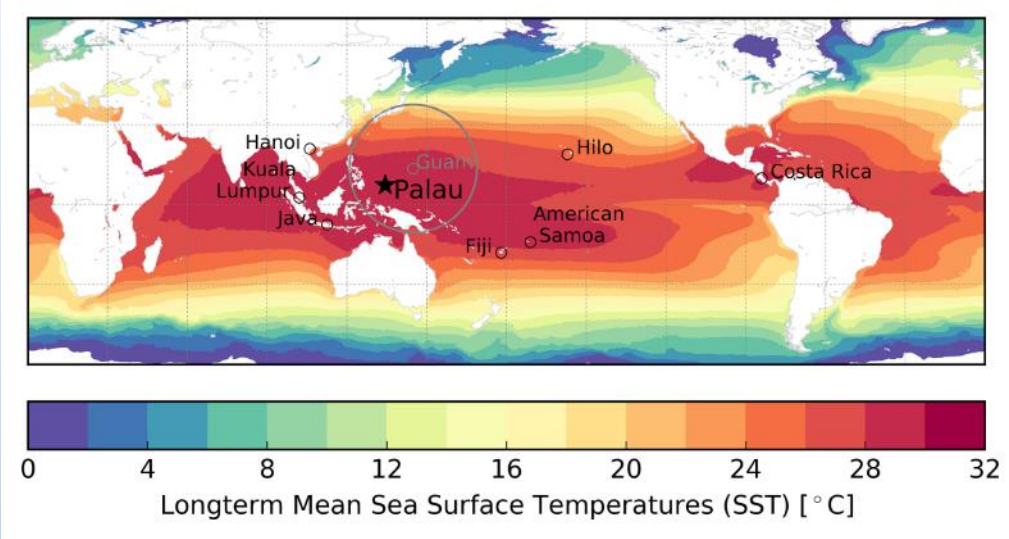


Fig. S1. Bias in 3161 relative humidity Vaisala RS41 radiosondes in the stratosphere used in this study. The volcanic layer is identified as larger bias in the 23 to 27 km region. At 27 km, the mean bias is 0.9 % with a standard deviation of 0.3%. For simplicity, we chose a bias correction of 1% and assumed a 3-sigma uncertainty of 1% to define the lower detection limit at which the signal is equal to the uncertainty.

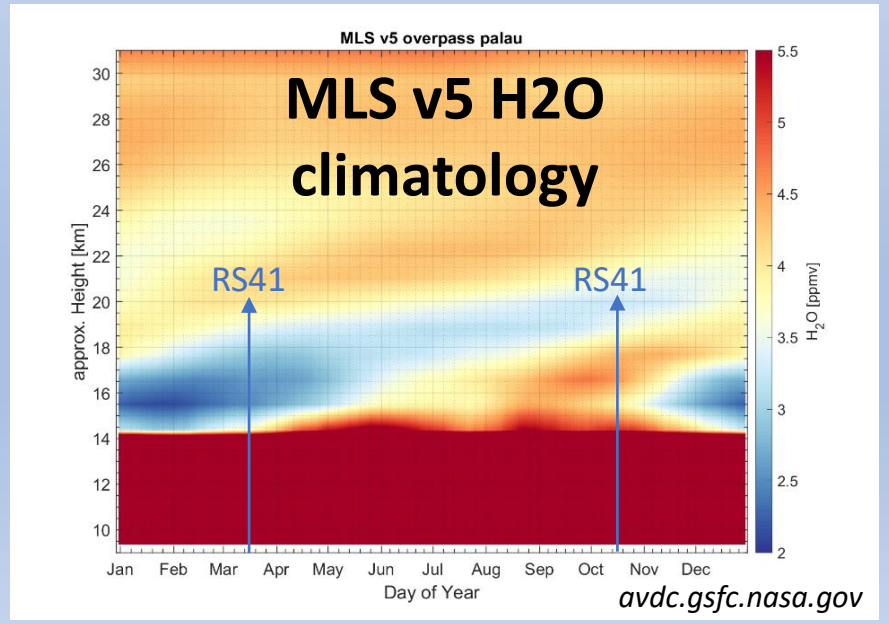
Vömel et al., 2022

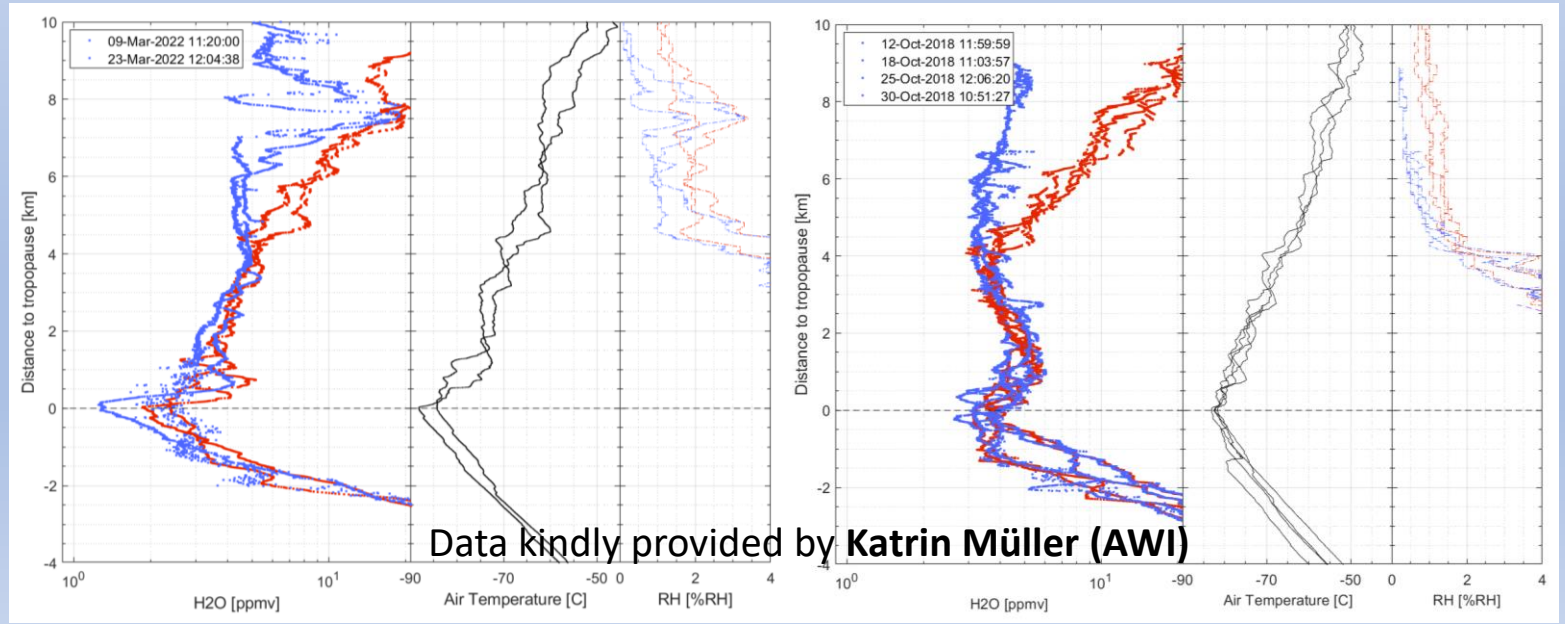
Palau: Tape-Recorder & Hunga Tonga Signal



AWI site **Palau** (7.3 N, 134.5 E) in remote tropical western Pacific warm pool area. Year-round convective activity, main source region of stratospheric air in boreal winter, and global minimum in tropospheric O3 column with ITCZ-modulated seasonality (Müller et al., 2024).
Part of **SHADOZ** network, future plans for **NDACC** and **GRUAN**.

RS41 can measure the lower part of the **tropical tape recorder** and ~20 ppmv Hunga signal. Loses sensitivity @RH ~< 2 %RH.



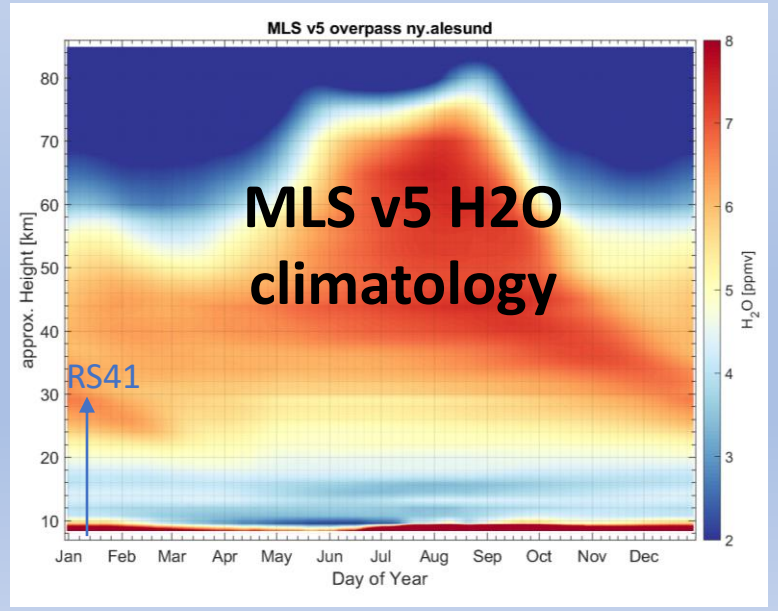


Polar Winter and Polar Stratospheric Clouds

Janek Uin (CC BY 4.0)

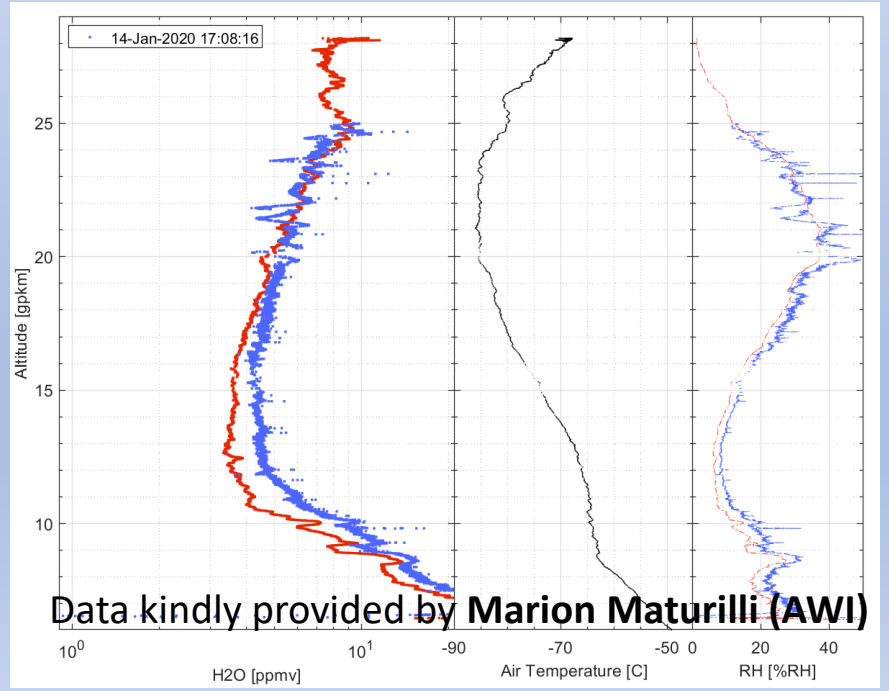
MOSAIC Expedition RS41+CFH+ECC+COBALD Sounding (87.4 N, 104.7E) through PSC in January 2020. Unusually cold and stable conditions in the Arctic stratosphere led to severe ozone loss (Wohltmann et al., 2020).

RS41 maintains sensitive (but dry biased) nearly all the way up to 28 km. CFH contamination at 25 km after passage through PSC, RS41 heated sensor not contaminated.

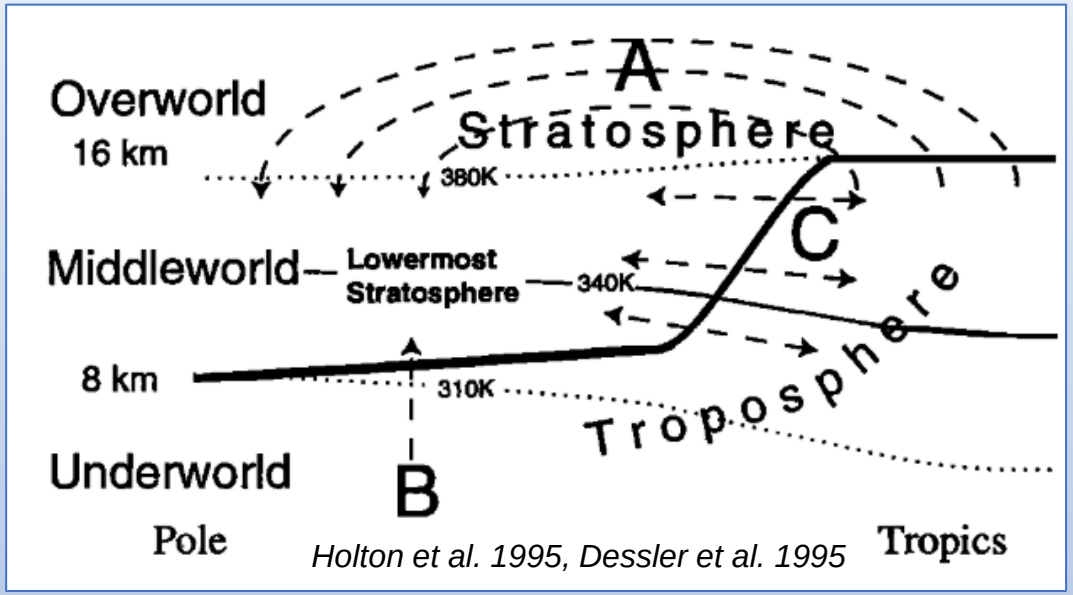


avdc.gsfc.nasa.gov

In winter polar regions, RS41 can measure the lower part of the downward-shift of middle atmospheric H_2O maximum



RS41 and lower stratospheric H_2O: valuable asset, does not replace reference measurements



Holton et al. 1995, Dessler et al. 1995

- ❑ A: aged, freeze-dried tropical air + CH_4 & H_2 oxidation (BD-Circulation)
- ❑ B: Direct Injections (Summer Monsoons, Convection, Volcanoes)
- ❑ C: transport through extra-tropical tropopause (synoptic scale eddies)

- ❖ With H_2O measurement ability in the lower stratosphere all-year around in the tropics and during polar winter, RS41 can **help understand middle atmospheric dynamics**.
- ❖ When combined with O_3 and backscatter sondes, it can **help detecting PSC-depletion patterns**, albeit with large uncertainties in microphysical interpretation due to biases in the radiosonde measurement.

- ❖ In case of **substantial H_2O injections** (e.g. from explosive volcano), RS41 can **help detect the moist (~> 2 %RH) layers** (Vömel et al. 2022; Khaykin et al., 2022).
- ❖ Extra-tropical UTLS (mid-latitudes) is the main region of stratospheric H_2O radiative feedback, and **trend detection requires high-accuracy measurements in the lower stratosphere** (Dessler et al., 2013; Banerjee et al., 2019), which is beyond the RS41 capabilities.

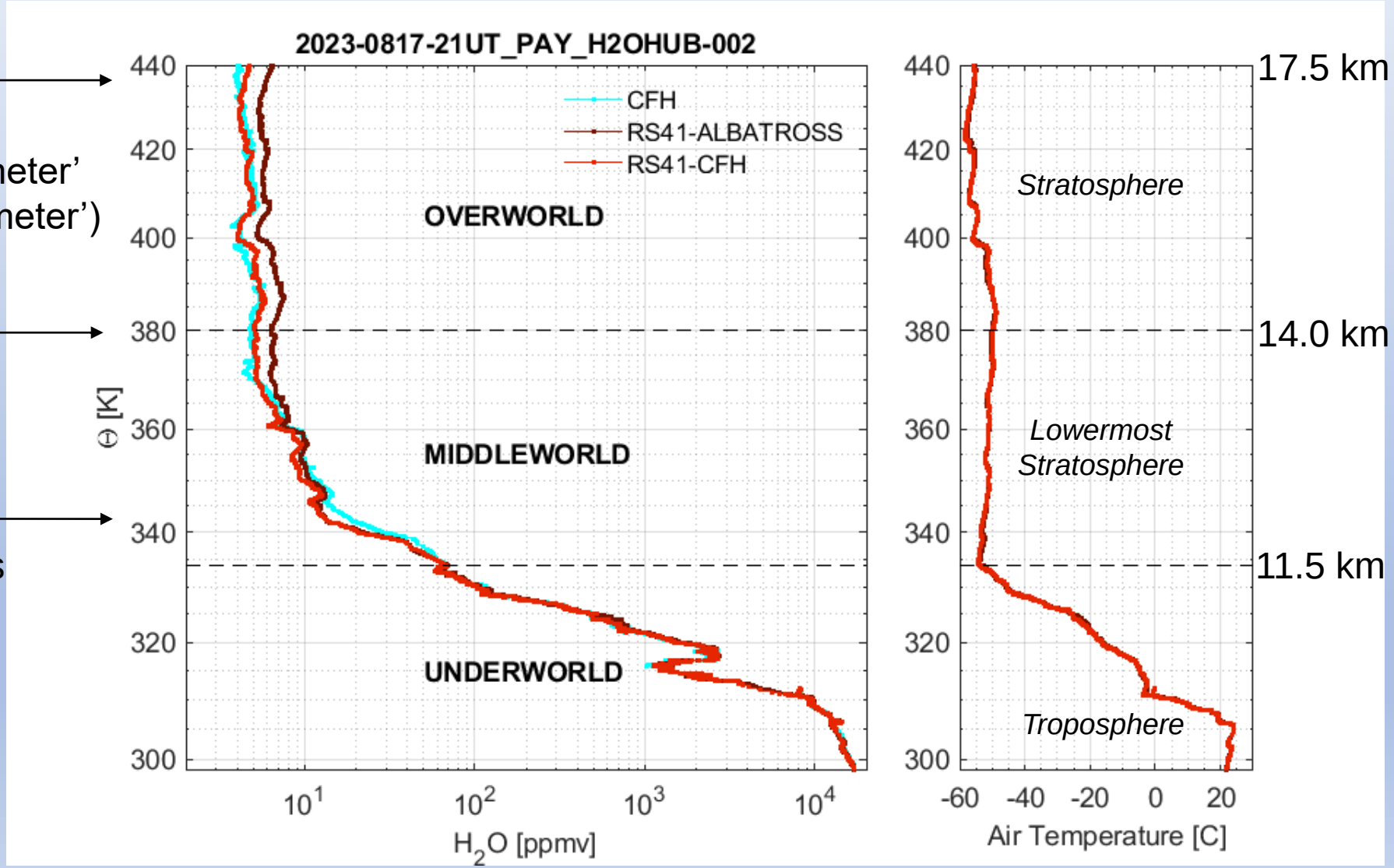
Main challenges for stratospheric RS41 measurements: residual time-lag and sensor model errors, sonde-to-sonde variability, loss of sensitivity

Two balloons launched within < 2 minutes

RS41 Sensitivity loss (acts as ‘thermometer’ instead of ‘hygrometer’)

RS41 Sonde-to-Sonde Variability

RS41 Systematic Errors (**time-lag** *residual* error and **bias**)



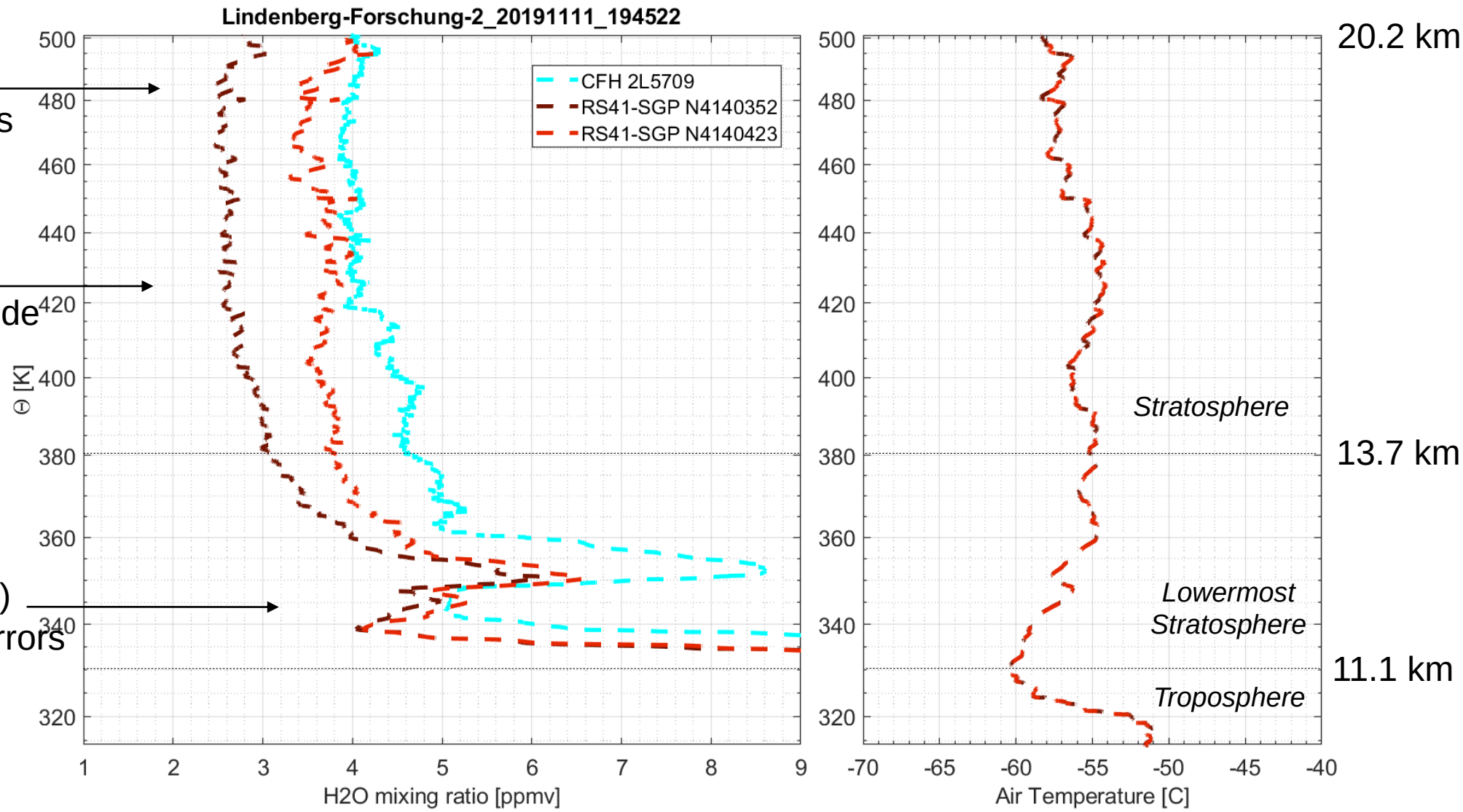
Sonde-to-sonde variability (on radiative forcing relevant linear scale)

2xRS41 & 1x CFH on *same* balloon

RS41
Sensitivity loss

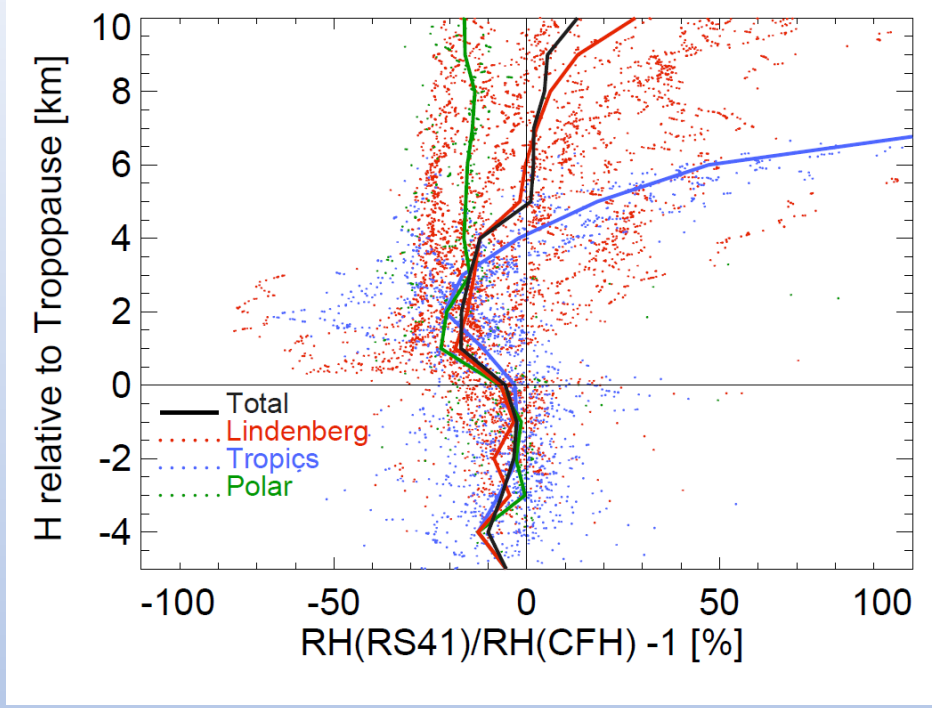
RS41
Sonde-to-Sonde
Variability

RS41 (MW41)
Systematic Errors



Present RS41 performance

**Compare all RS41 data with RH > 2 %
(Vaisala product) with CFH Golden Points**



RS41 performance

Mean values

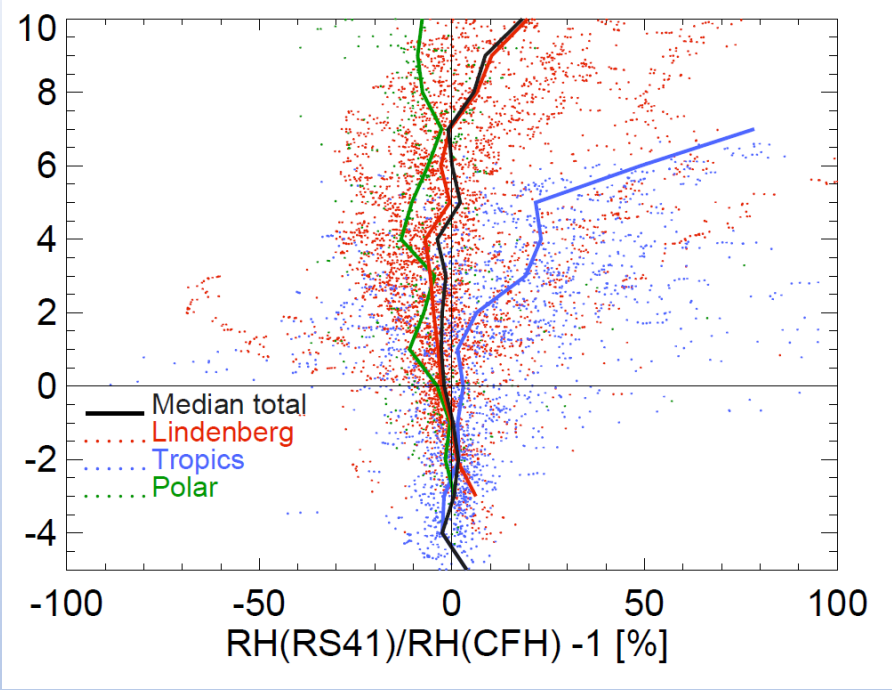
- Upper troposphere:
  - Slight mean dry bias (≤ 10%)
- Lower stratosphere:
  - Dry bias increases sharply above TP
  - Dry bias exceeds ~15% at TP + 1 km

Sonde-to-sonde variability

- Is very large
- Strat. measurements from a single sonde meaningless
- But for climatological studies, mean values from 1000s of sondes flown each year may be valuable

Best (?) possible performance

Improving the RS41 bias and time-lag corrections by means of the CFH Golden Points



Improved bias and time-lag (glocorrections

Mean values

- Upper troposphere:
  - Mean biases reduced to < 5%
- Lower stratosphere:
  - Midlatitudes better than 5% to TP + 8 km
  - Arctic winter slightly dry biased (< 12%)
  - Tropics good to TP + 2 km (< 7 %)
  - Tropics > TP + 2 km severely moist biased (outliers)

Sonde-to-sonde variability

Not improved, still very large

# of flights

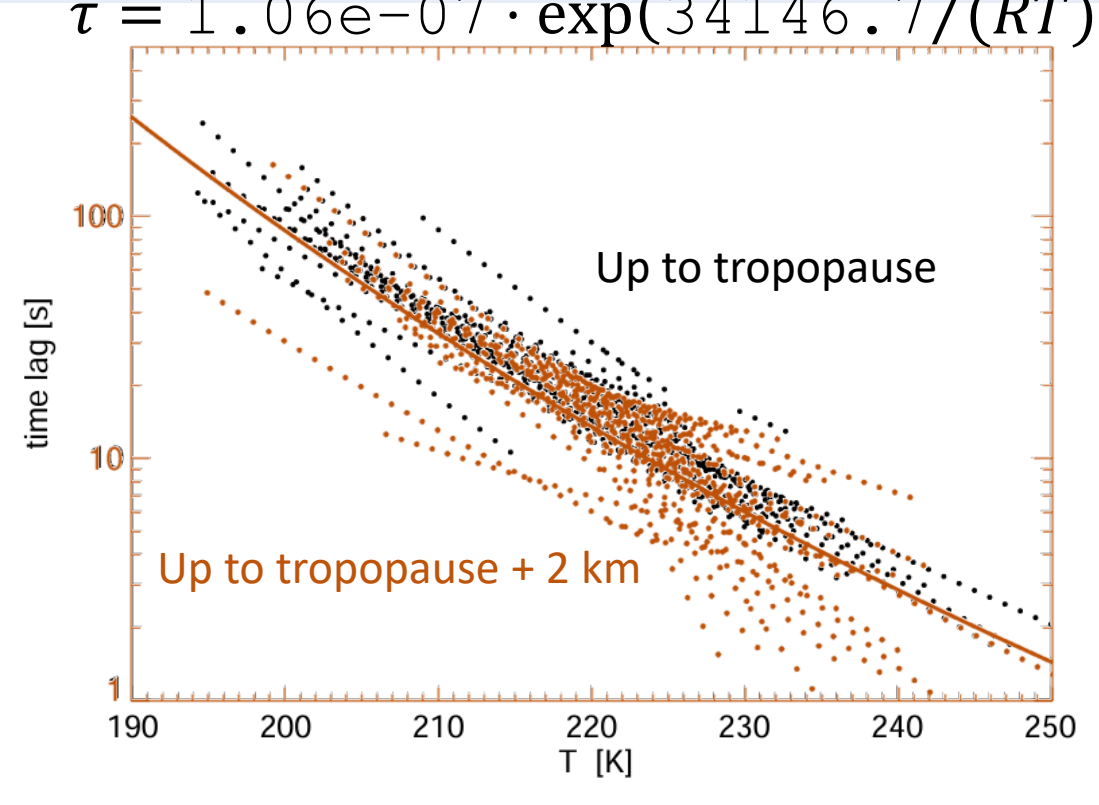
Lindenberg:	38
Tropics:	17
Polar Winter:	4

RS41+CFH Golden Points analysis in lower stratosphere (*prelim. work*)

Potential for an improved (global) time-lag and bias correction

Improved time-lag correction parameters (Arrhenius) by means of the CFH Golden Points

$$\tau = 1.06e{-}07 \cdot \exp(34146.7/(RT))$$



2022-08 | Improved U time lag correction | No data continuity effect

- The reported humidity values in DigiCORA software use improved algorithm for the humidity sensor time lag correction.
- The change decreases the overshooting of the humidity values, in the fast step-like humidity changes that may occur in the sounding, such as during the rapid drying around the tropopause.

https://www.vaisala.com/en/sounding-data-continuity (access: Nov. 2025)

Fitted RS41 time constants for the lowermost stratosphere (balloon ascent, prelim. work)

- Fits up to 2 km above tropopause give ~15% lower values than fits up to tropopause

→ **Desorption time constants are faster** than average time constant values (see also von Rohden et al., 2022; Kim et al., 2025)

- **In-situ fitted** time constants for RS41 (with CFH Golden Points reference) **are ~40% lower than** the **laboratory fits** (e.g. GRUAN GDP.1 in the -65 C to -40 C Tsensor range).

- **N.B.** Vaisala **changed the RS41 time-lag correction in MW51**, reducing over-correction at the tropopause. Likely to have an effect in the lowermost stratosphere for sites that change from MW41 to MW51. To be monitored.

Conclusions: RS41-CFH comparison

- The capacitive sensor of RS41 is robust against poor weather and has the capacity to measure a few kilometers beyond the tropopause, everywhere on Earth. In polar winter, it may measure up to balloon burst. The measurement capability is related to a sensitivity loss around 2 %RH.

- It faces however **3 main challenges to *accurately* measure in the lower stratosphere**
  - **Sensitivity Limit:** RS41 loses sensitivity to moisture below about 2 %RH (in ultra-dry conditions, the capacitance measurement becomes much more sensitive to changes in air temperature than changes in dew/frost point, making the RS41 act like a 'thermometer' instead of a 'hygrometer') **Can be improved** with no-heating of the sensor in stratosphere;; or stabilization of Tsensor temperature **(?)**
  - **General bias and sonde to sonde variability:** sensor model errors in dry conditions (~ too moist when warm, ~ too dry when cold)
    Can be improved with a better sensor model and average of 8 x RS41 with MW51 **(?)**
  - **Response Time in the UTLS:** the time constants associated with the sensor's ad/de-sorption kinetics are the largest (in the order of the minute), increasing the residual uncertainty of any time-lag correction procedure.
    Can be improved (to a certain extent) with better time-lag correction procedure **(?)**

- CFH requires more efforts in preparation and post-flight quality checking, but **remains sensitive and accurate** along the whole profile, with potential for high-resolution using Golden Points analysis.

Thank you! Questions?