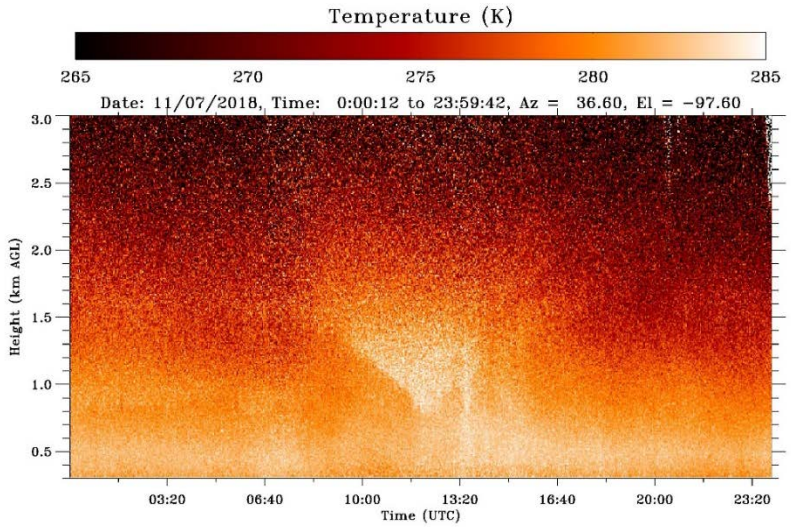
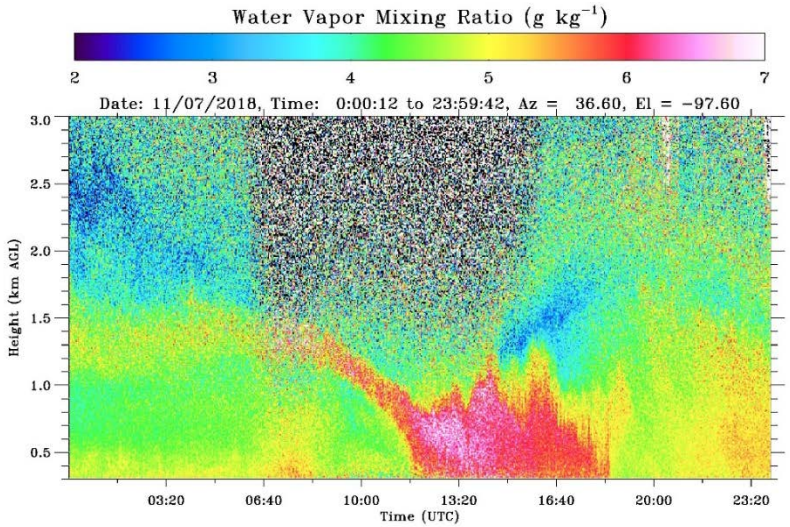
Compact Automatic Rotational Raman Lidar for Day-and Nighttime Temperature and Humidity Profiling up to the Turbulence Scale

Diego Lange, Andreas Behrendt, Volker Wulfmeyer
Institute of Physics and Meteorology (IPM)
University of Hohenheim (UHOH)
Stuttgart, Germany

Modular Observation Solutions for Earth Systems

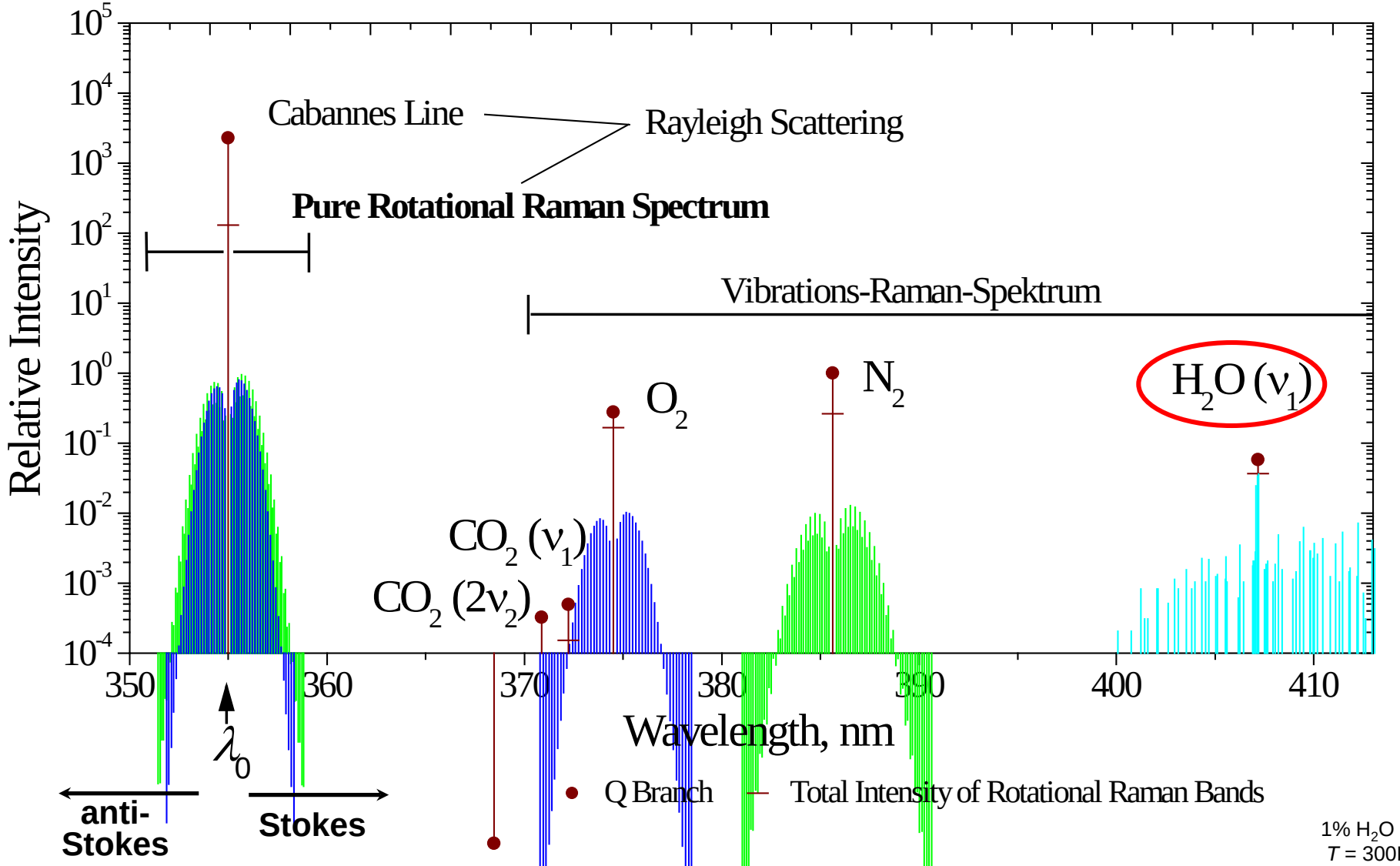




Downsized to < 10 %

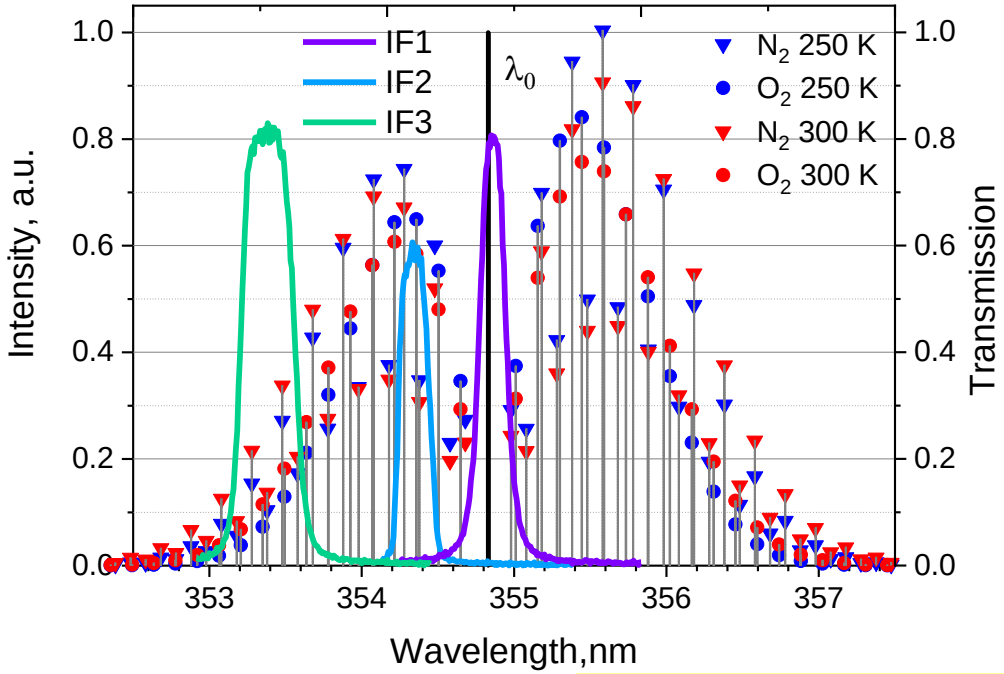
ARTHUS (Atmospheric Raman Temperature and Humidity Sounder)

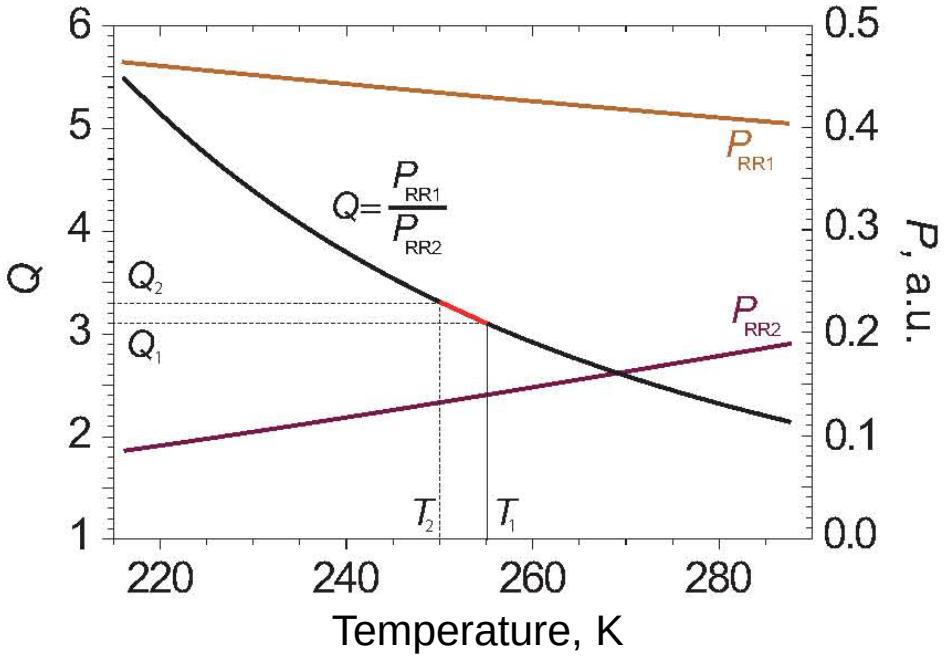
Water Vapor Raman Lidar



A. Behrendt, T. Nakamura, M. Onishi, R. Baumgart, and T. Tsuda, ***"Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient,"*** Appl. Opt. 41, 7657-7666, https://doi.org/10.1364/AO.41.007657, 2002

Temperature Rotational Raman Lidar: Principle and Statistical Error Analysis





$$T(R) = -\frac{2a^2}{b \pm \sqrt{b^2 - 4a\left[c - \ln Q(R)\right]}}$$

$$\sigma_T = \frac{\partial T}{\partial Q} Q \sqrt{\left(\frac{\sigma_{RR1}}{I_{RR1}}\right)^2 + \left(\frac{\sigma_{RR2}}{I_{RR2}}\right)^2} = \frac{\partial T}{\partial Q} Q \sqrt{\frac{1}{N_{RR1}} + \frac{1}{N_{RR2}}}$$

calibration is performed by signal theory or comparisons with in-situ or active remote sensors.

The statistical error σ_T scales according to:

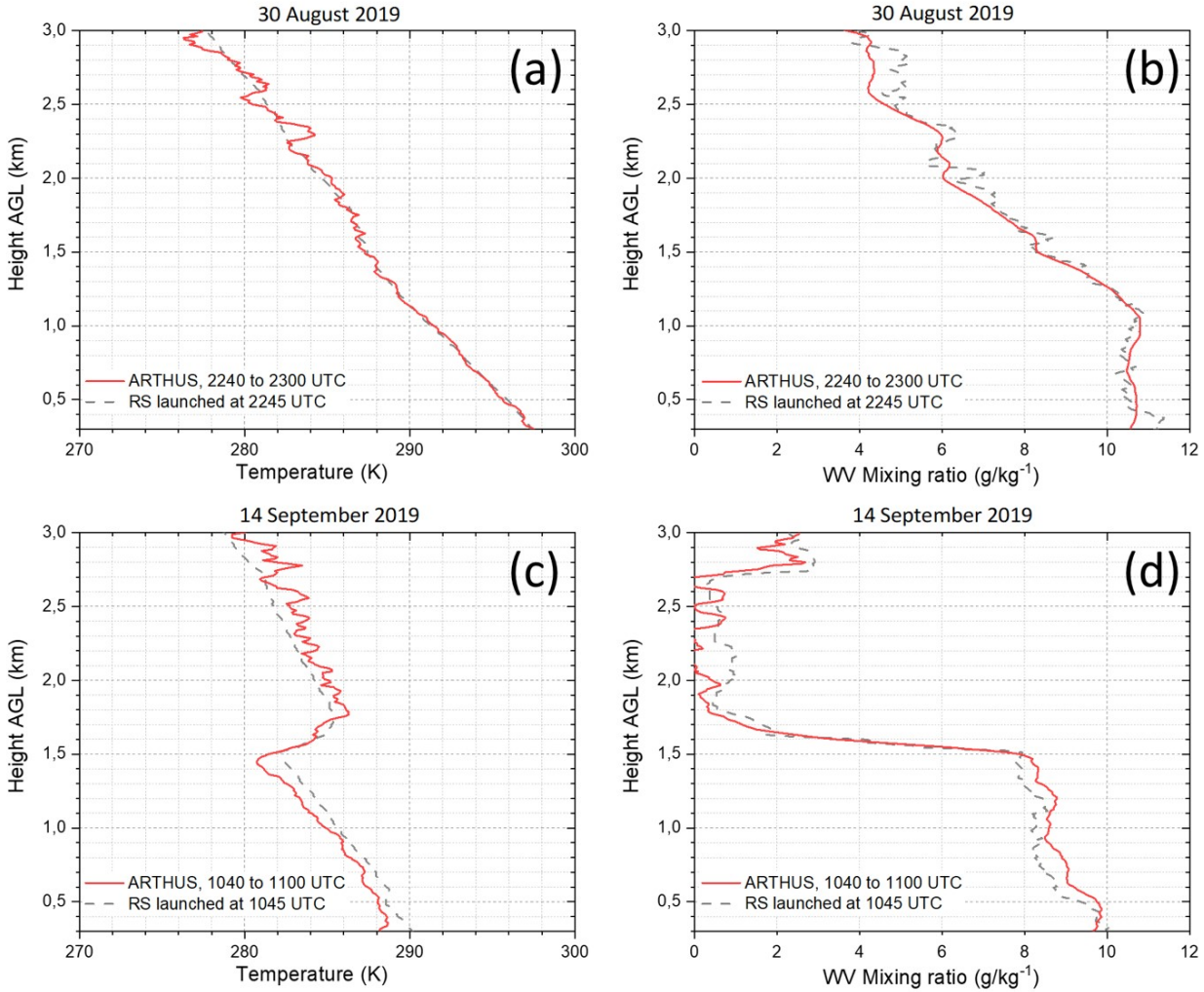
$$\sigma_T \propto \sqrt{\frac{1}{\Delta R}} \sqrt{\frac{1}{\Delta t}}$$

The vertical error correlation corresponds to ΔR.

Hammann, E., Behrendt, A., Le Mounier, F., and Wulfmeyer, V.: **Temperature profiling of the atmospheric boundary layer with rotational Raman lidar during the HD(CP)² Observational Prototype Experiment**, Atmos. Chem. Phys., 15, 2867–2881, https://doi.org/10.5194/acp-15-2867-2015, 2015.

Accuracy 2019

ARTHUS vs. local radiosonde, DWD Stuttgart Schnarrenberg



(a and b) Night measurements on 30 August 2019.

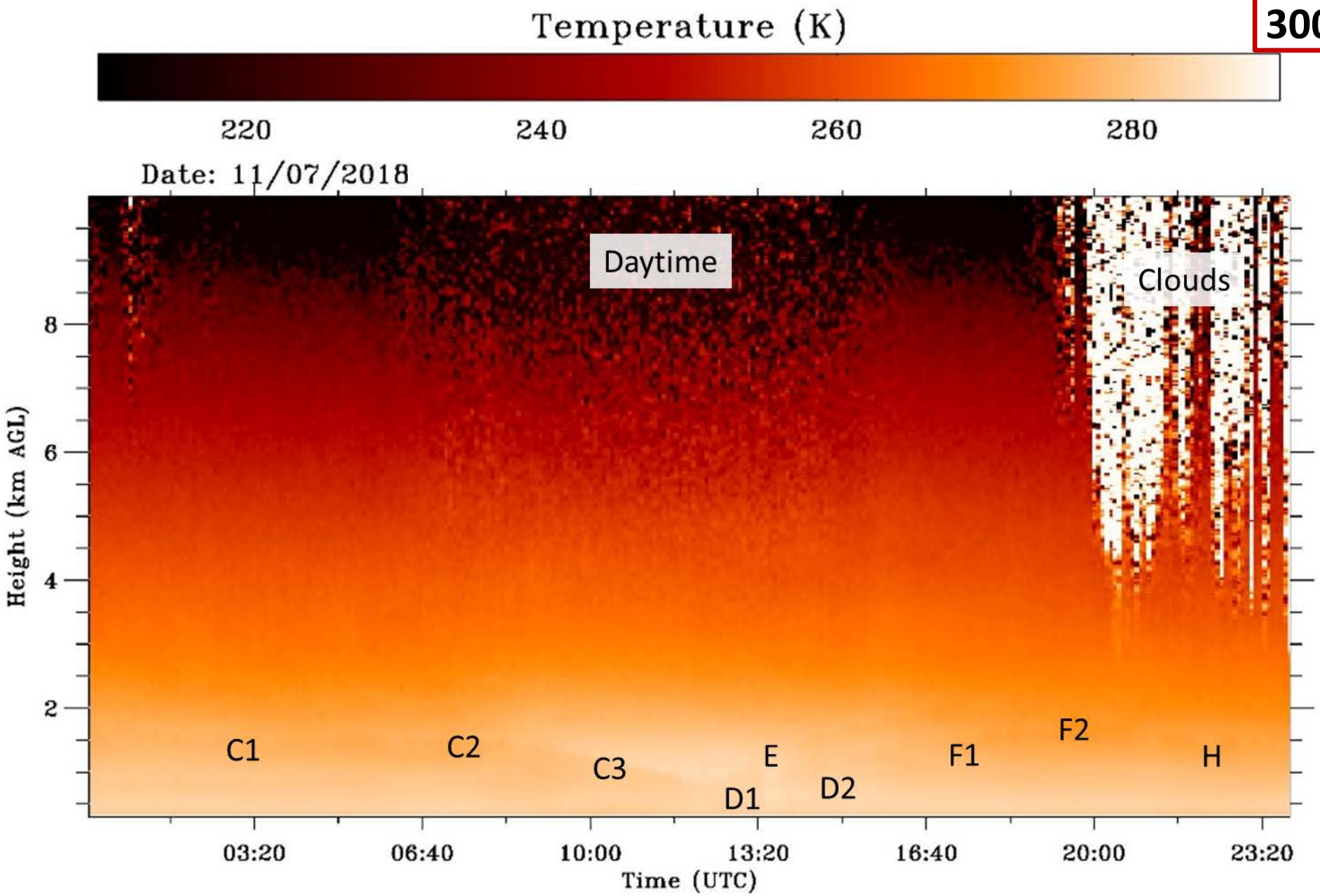
(c and d) Noon measurements on 14 September 2019. Same calibrations as in (a) and (b).

Lange, D., Behrendt, A., & Wulfmeyer, V. (2019). ***Compact operational tropospheric water vapor and temperature Raman lidar with turbulence resolution.*** *Geophysical Research Letters, 46, 14,844–14,853.* https://doi.org/10.1029/2019GL085774

07.11.2018

300 s, 97.5 m

A to J: Several layers observed during this day



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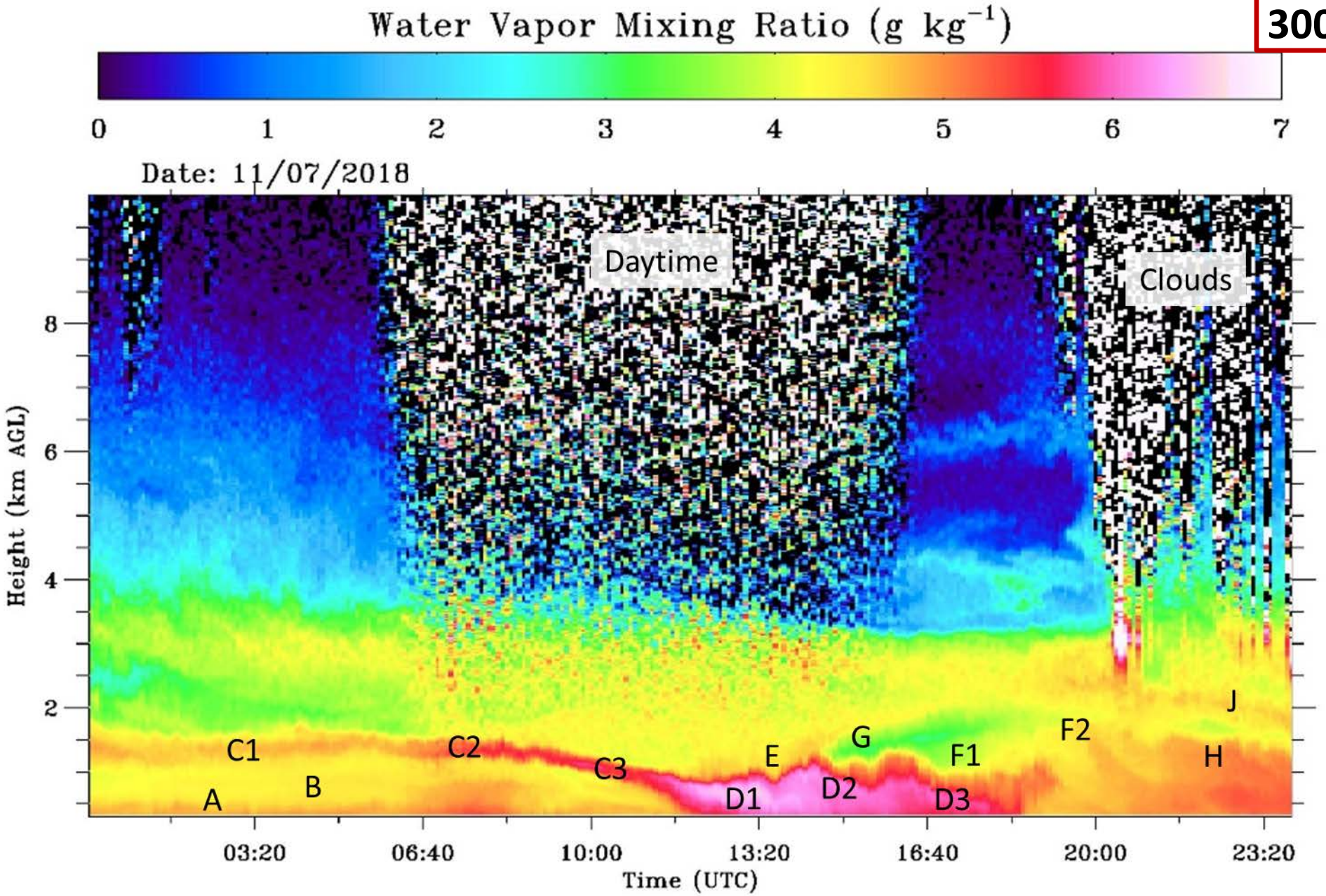
07.11.2018

300 s, 97.5 m

A to J: Several layers observed during this day



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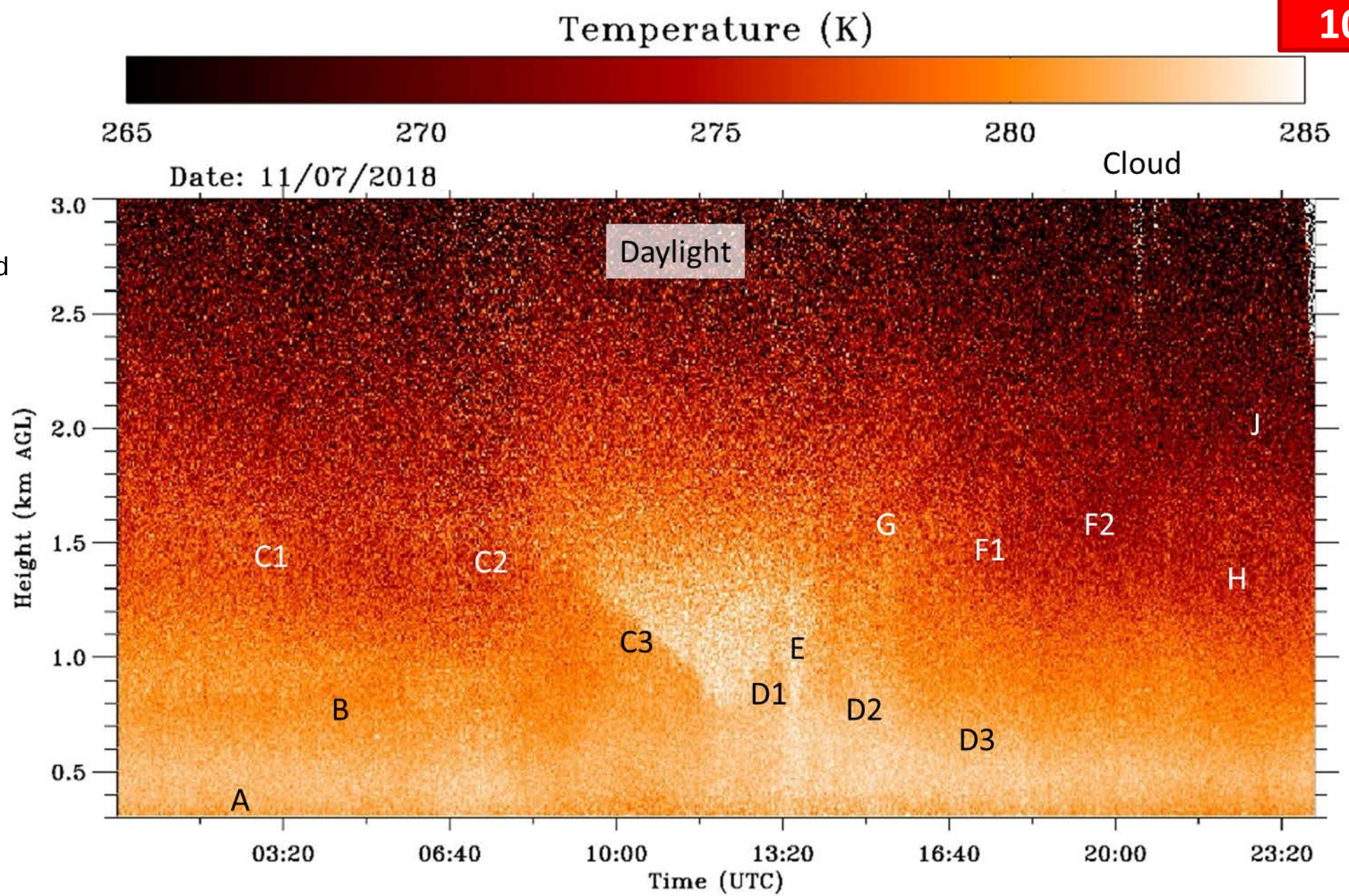
07.11.2018

10 s, 7.5 m

A to J: Several layers observed during this day



Lange, D., Behrendt, A., & Wulfmeyer, V. (2019). ***Compact operational tropospheric water vapor and temperature Raman lidar with turbulence resolution.*** *Geophysical Research Letters, 46, 14,844–14,853. https://doi.org/10.1029/2019GL085774*

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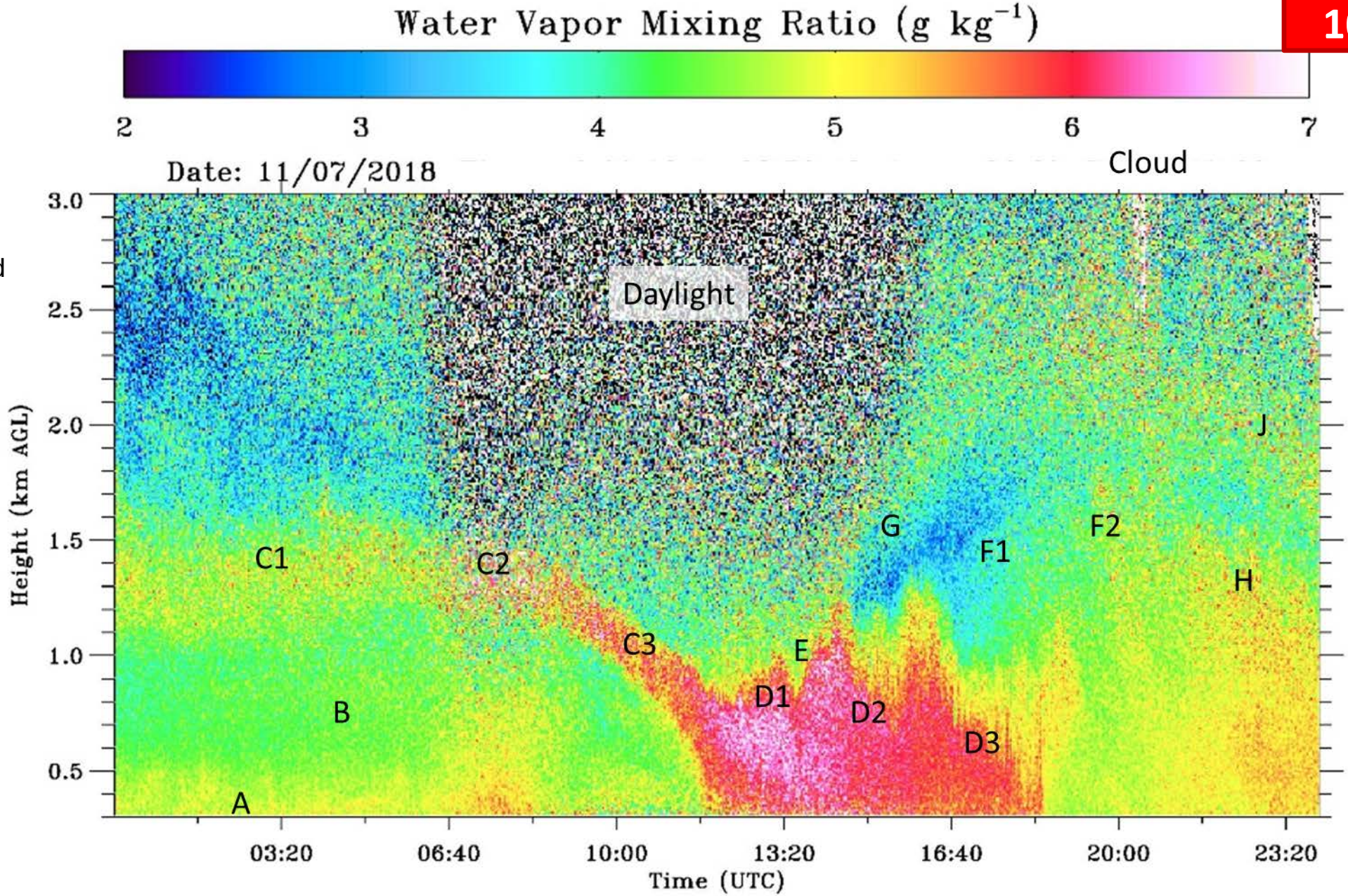

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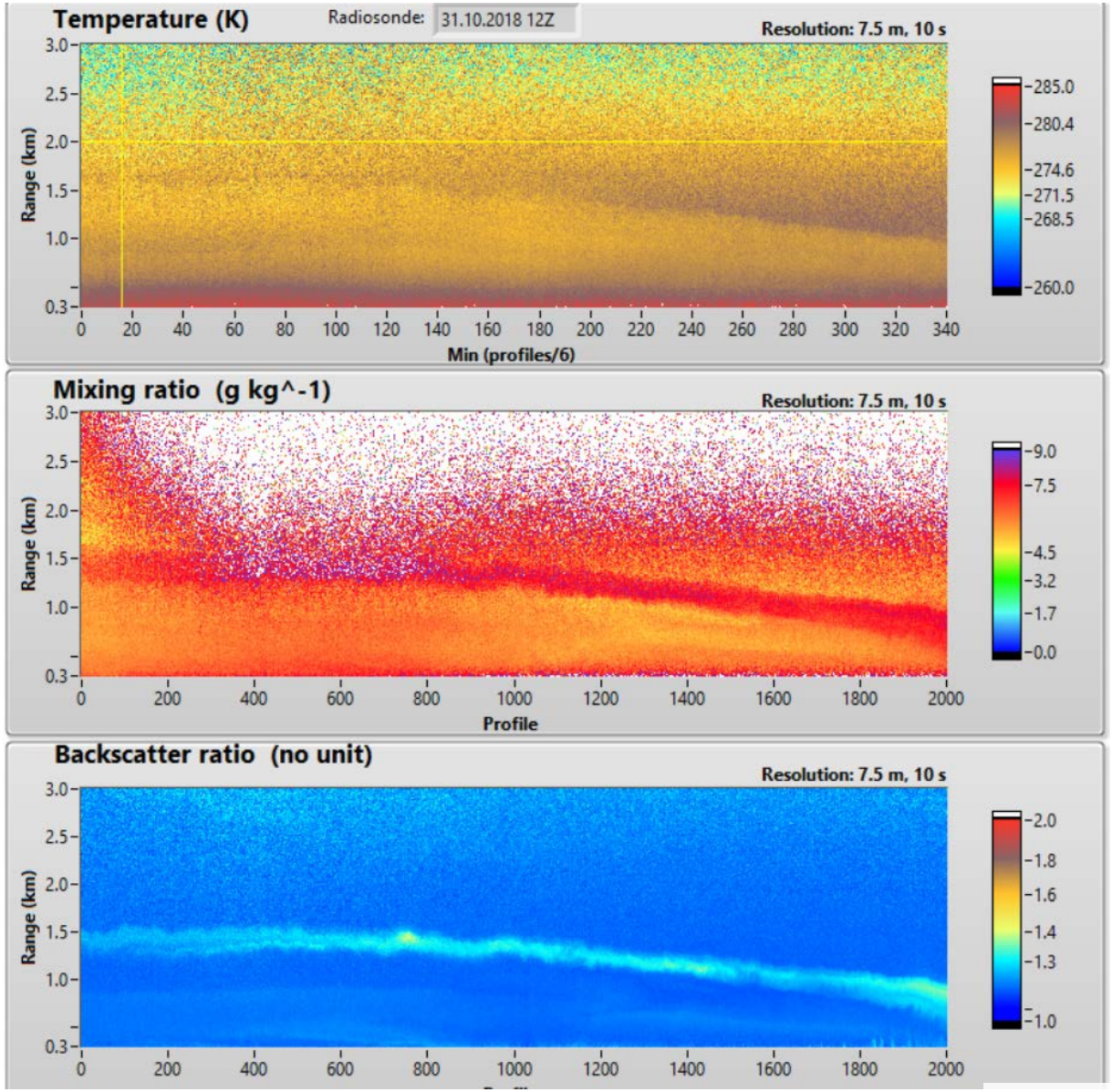
Real-Time Control: LabView Panel

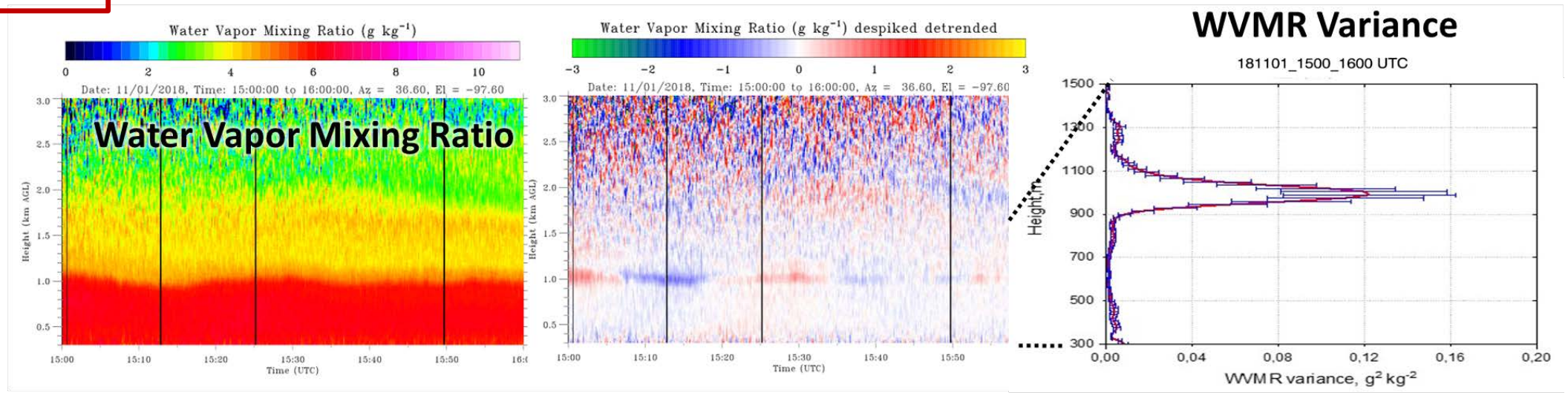
07.11.2018,
06:10 - 11:40 UTC

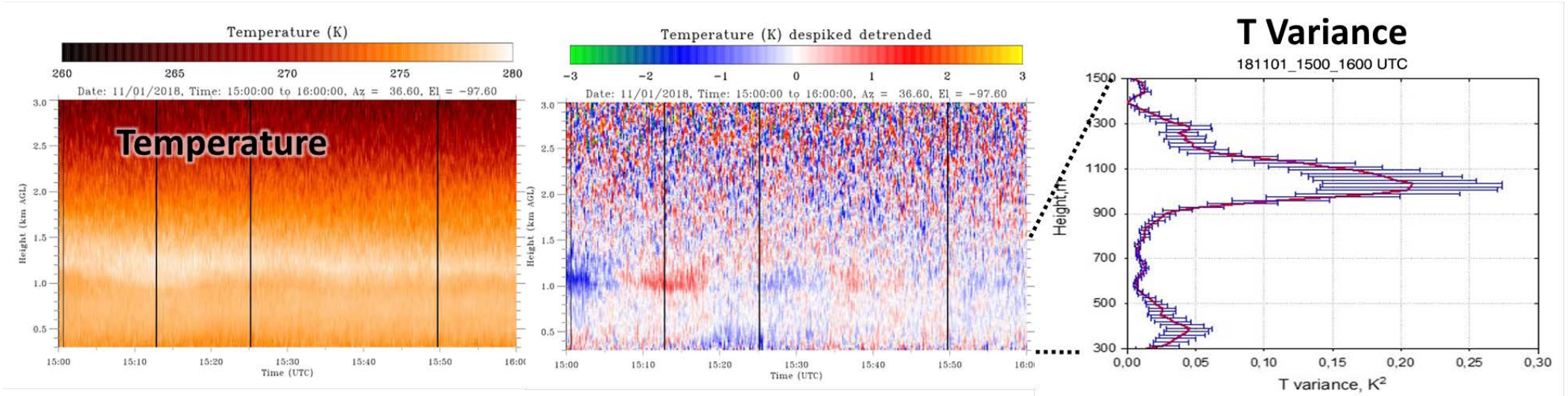
10 s, 7.5 m



T and WV MR measurements between 15:00 and 16:00 UTC on 1 November 2018

10 s, 100 m





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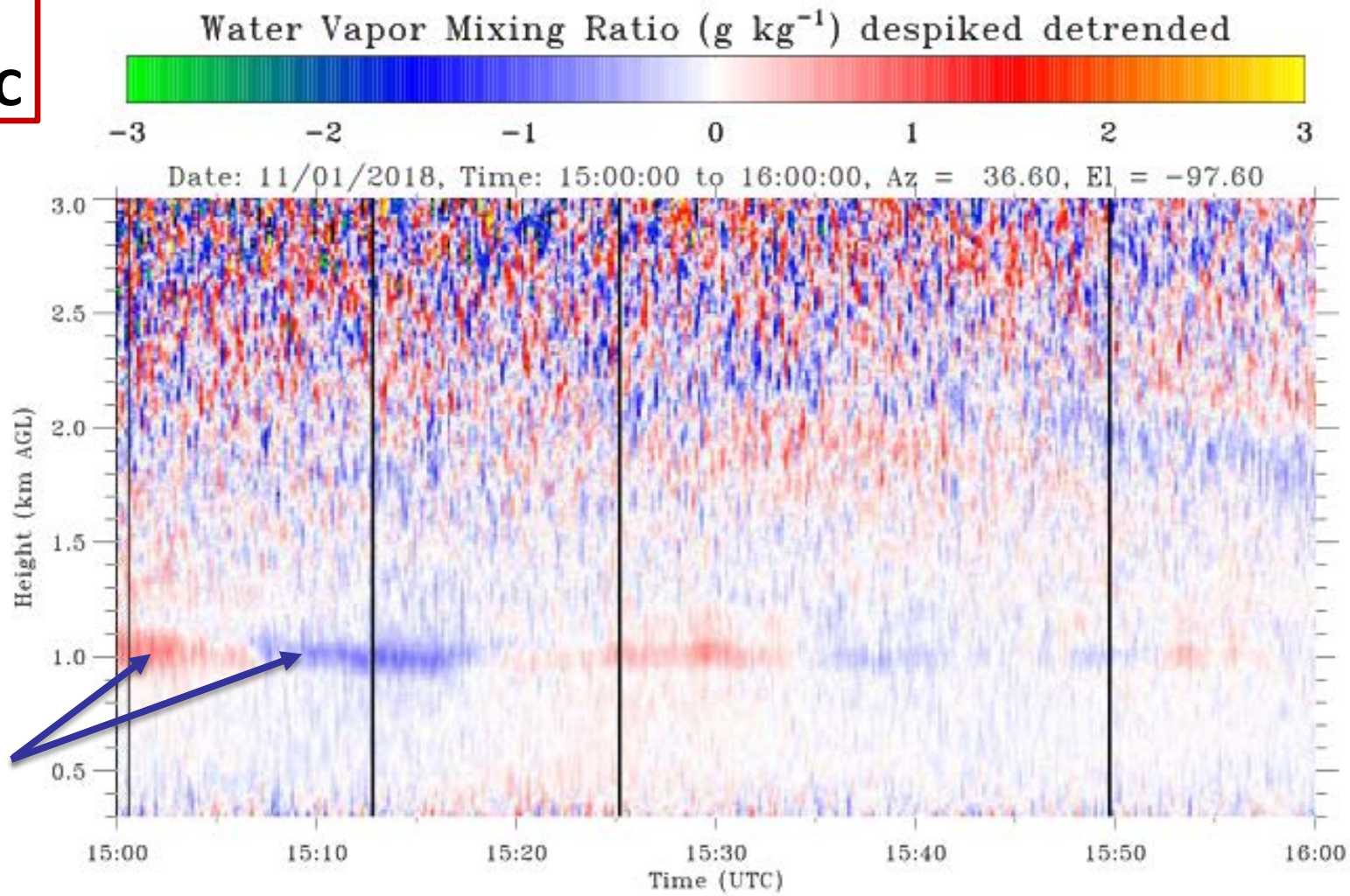
Water Vapor Mixing Ratio Fluctuations

10 s, 100 m

01.11.2018
15:00 – 16:00 UTC



A gravity wave causes anti-correlated fluctuations in the temperature and WV mixing ratio

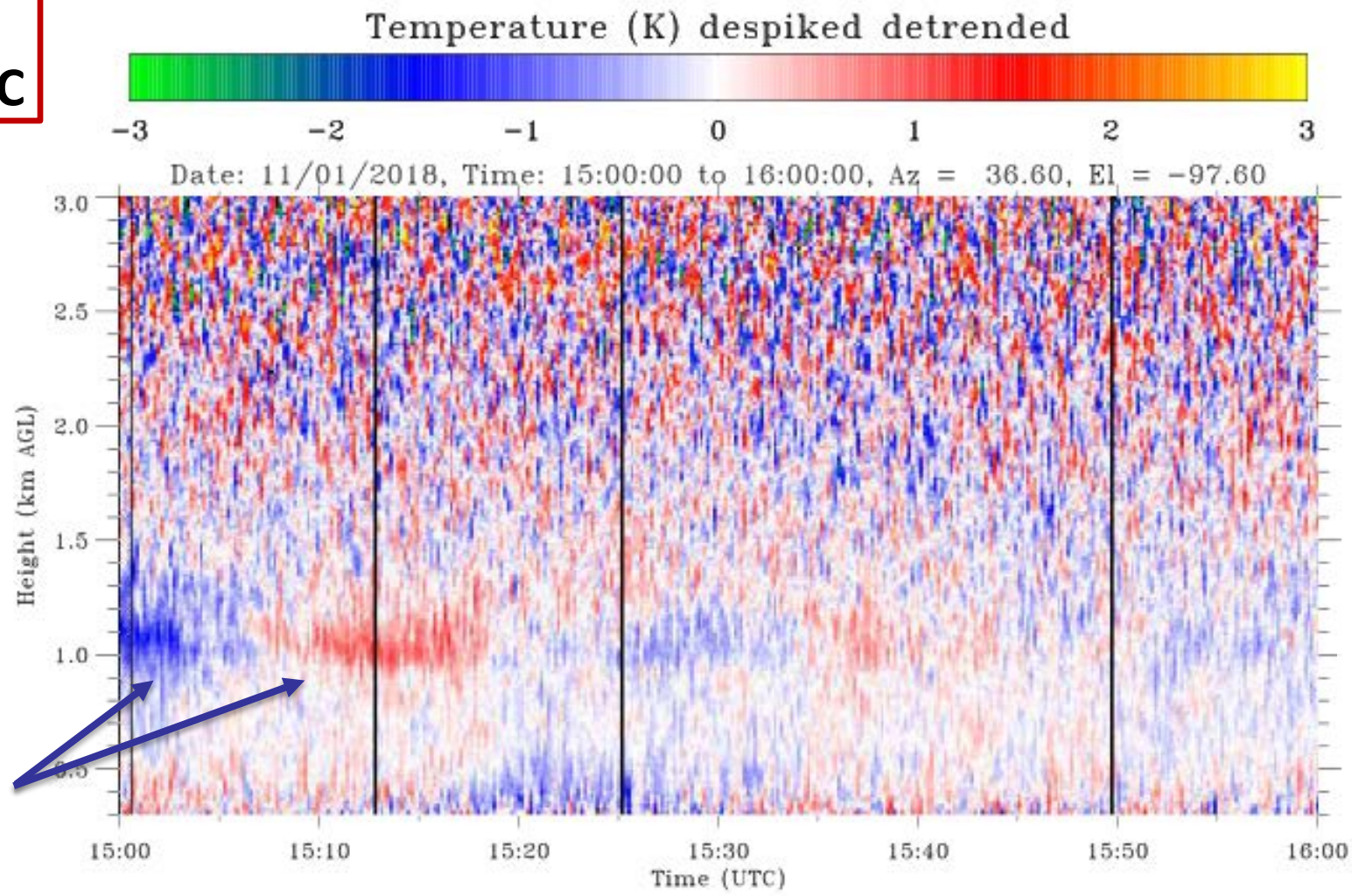
Boundary layer was not convective but stable

Lange, D., Behrendt, A., & Wulfmeyer, V. (2019). ***Compact operational tropospheric water vapor and temperature Raman lidar with turbulence resolution.*** *Geophysical Research Letters, 46, 14,844–14,853. https://doi.org/10.1029/2019GL085774*

Temperature Fluctuations

10 s, 100 m

01.11.2018
15:00 – 16:00 UTC



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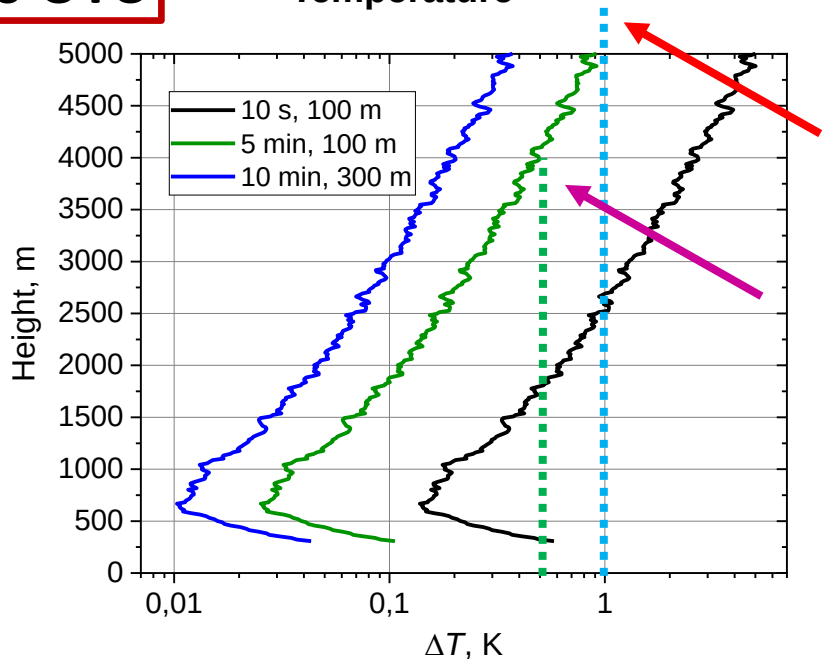
ARTHUS: Statistical Uncertainties

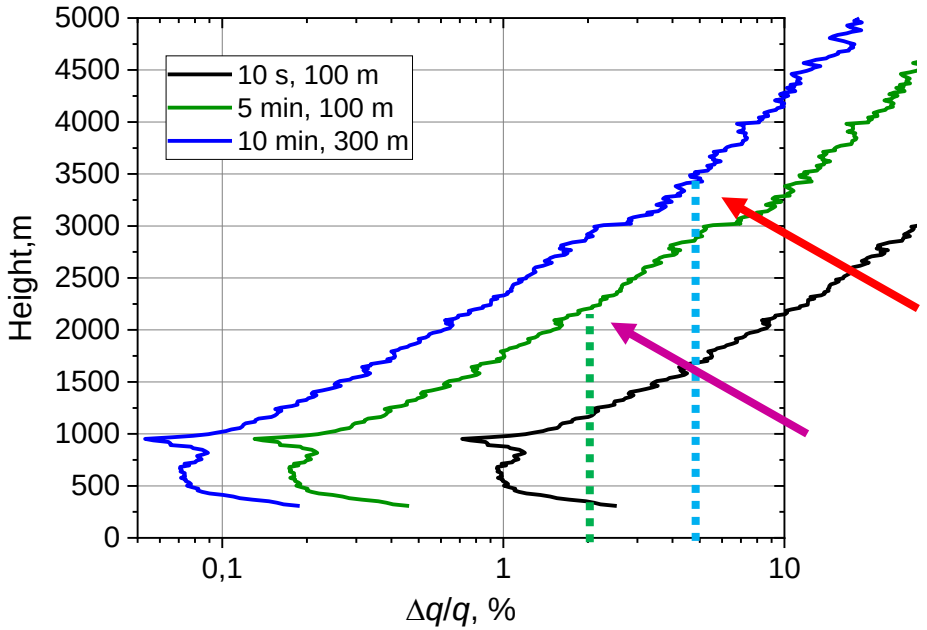
01.11.2018
15:00 – 16:00 UTC

Method of Wulfmeyer et al. 2016

Temperature



Water Vapor Mixing Ratio



WMO Requirements for Nowcasting/Very Short Range Forecasting in the Lower Troposphere:

"Breakthrough" requirement (10 min, 300 m):
1 K *Fulfilled >> 5 km!* ***5%*** *Fulfilled up to 3.5 km!*

"Goal" requirement (5 min, 100 m):
0.5 K *Fulfilled up to 4 km!* ***2%*** *Fulfilled up to 2.2 km!*

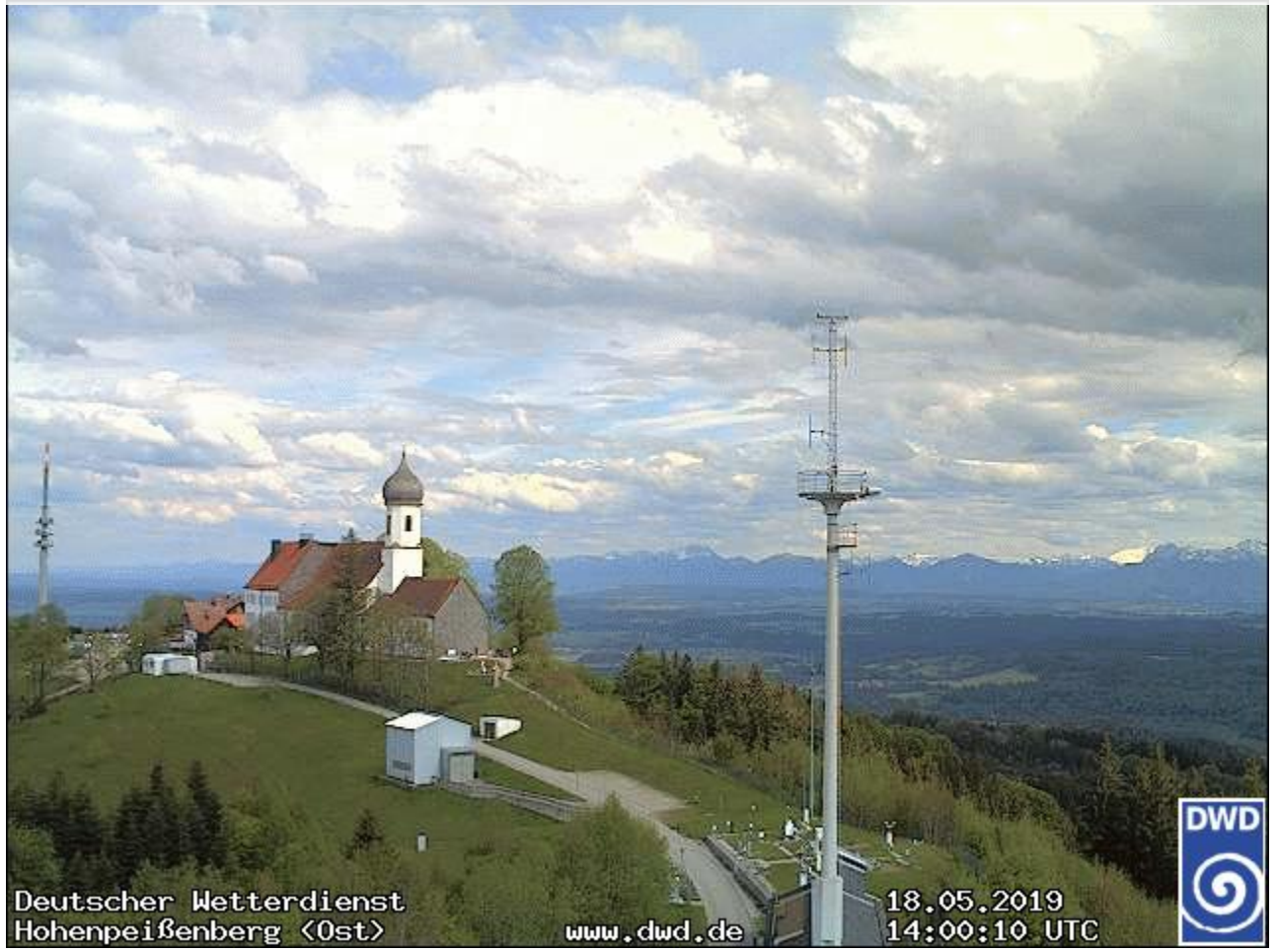
Lange, D., Behrendt, A., & Wulfmeyer, V. (2019). ***Compact operational tropospheric water vapor and temperature Raman lidar with turbulence resolution.*** *Geophysical Research Letters, 46, 14,844–14,853. https://doi.org/10.1029/2019GL085774*

ScaleX Campaign – MOSES – May/June 2019

https://blogs.helmholtz.de/moses/de/

https://scalex.imk-ifu.kit.edu/#campaigns

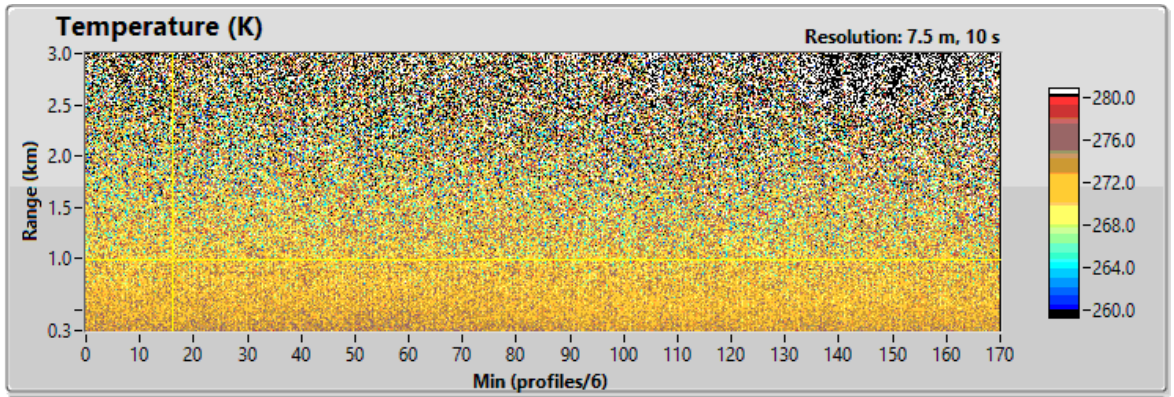
Hohenpeißenberg – Bavaria, Germany

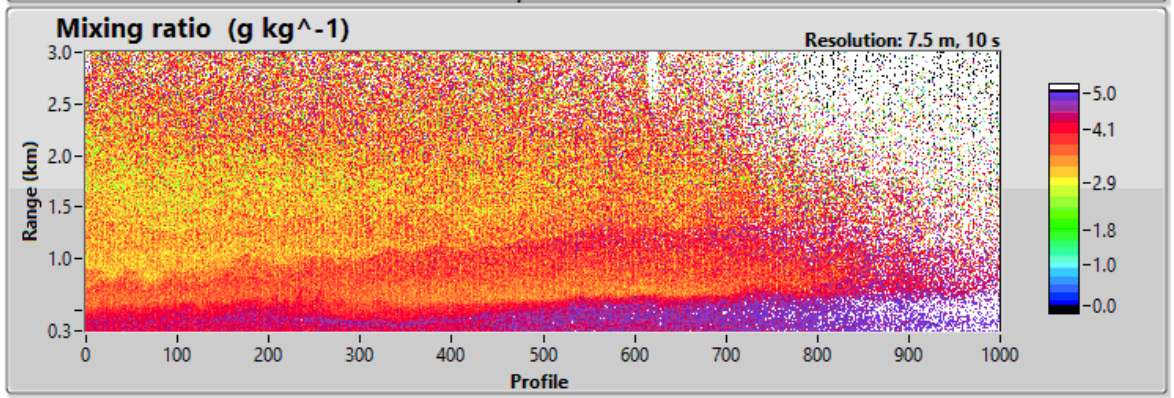


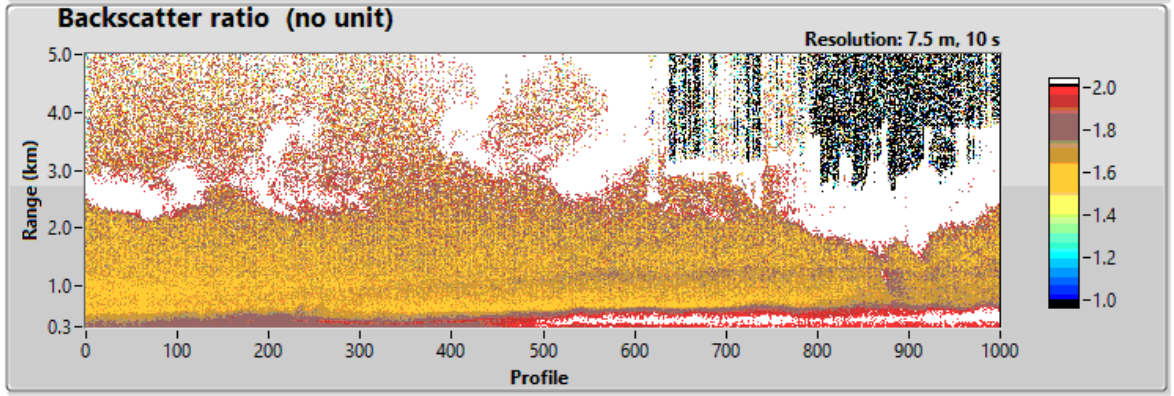
Real-Time Control

19.05.2019,
01:18 - 04:07 UTC

10 s, 7.5 m



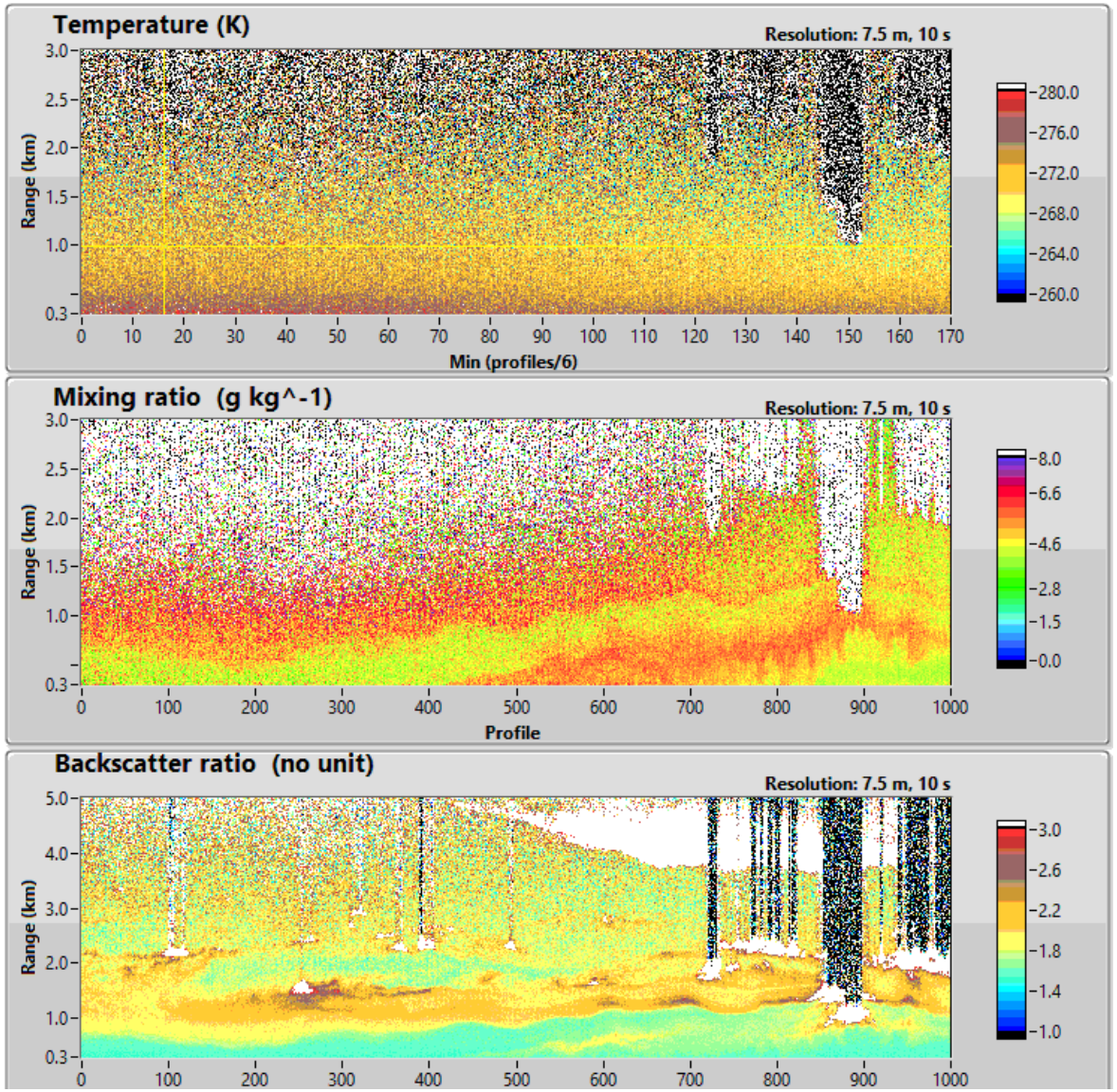




Real-Time Control

19.05.2019,
16:41 - 19:30 UTC

10 s, 7.5 m



Intercomparison Campaign at DWD
21 Aug – 25 Sept 2019

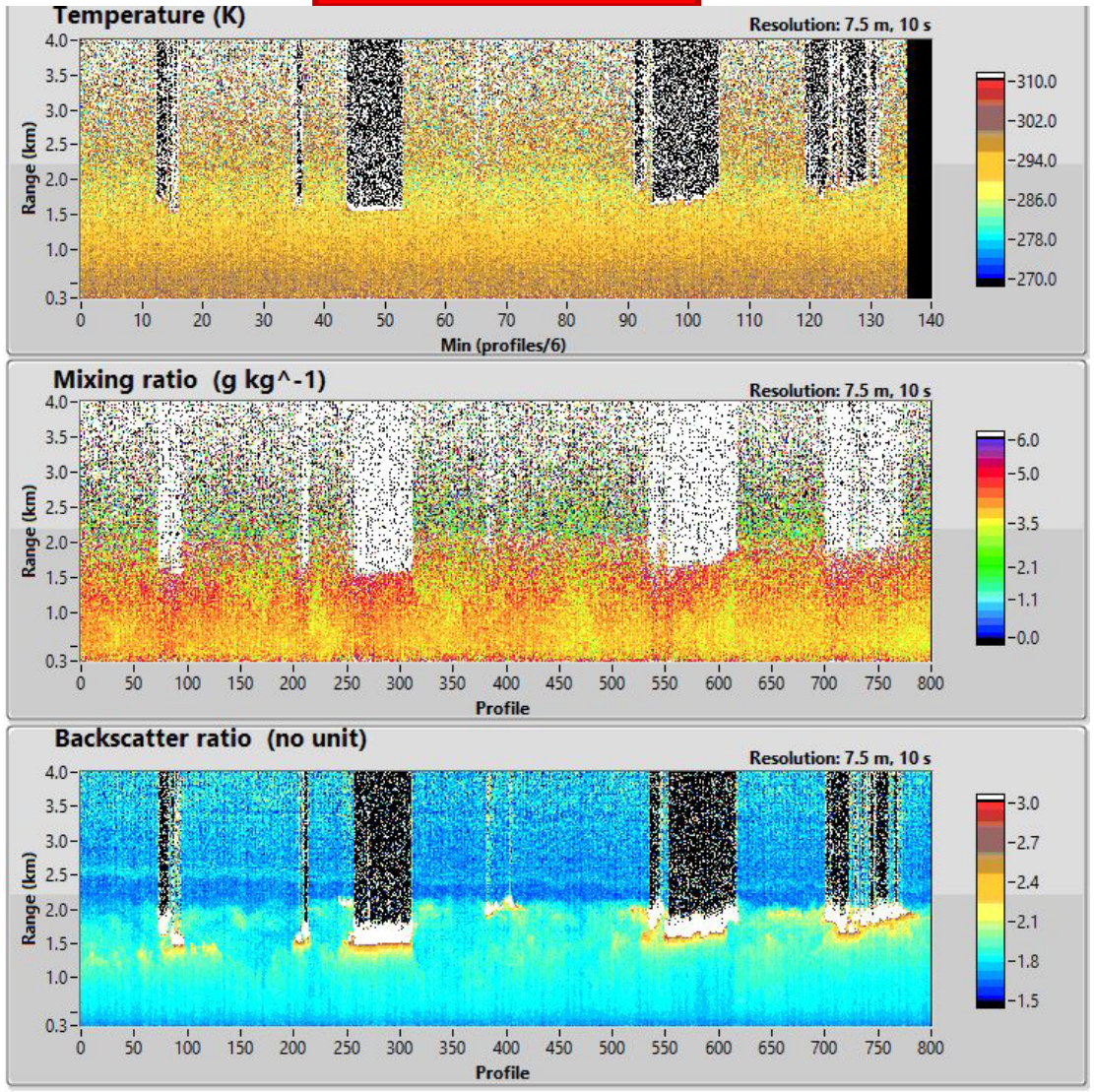
Radiosondes launch pad

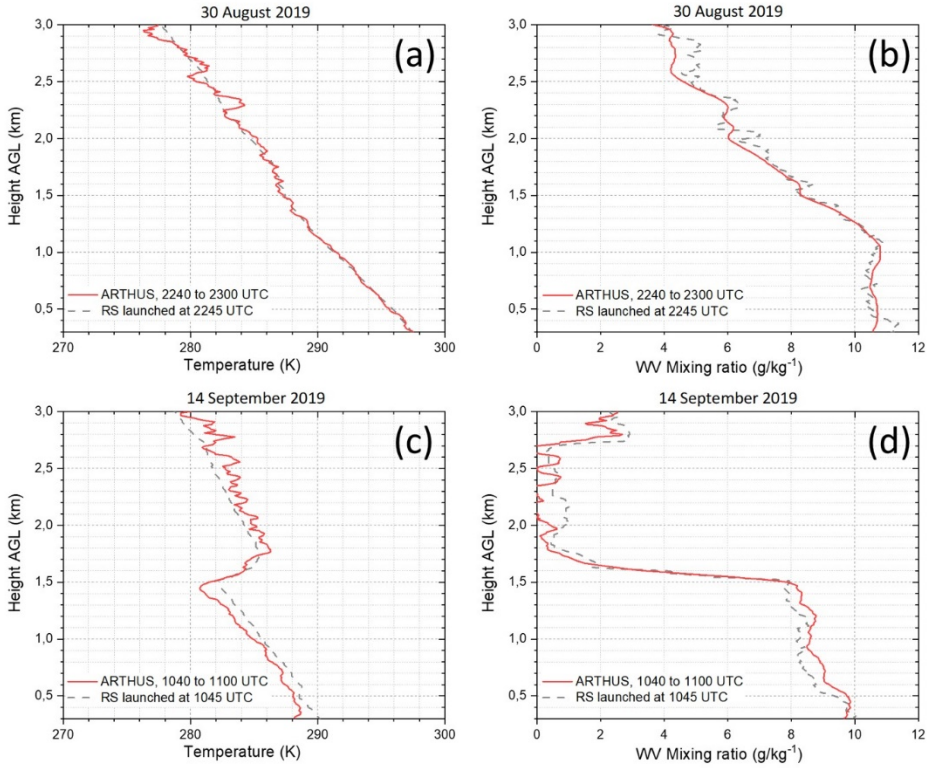
German Weather Service (DWD)
Stuttgart, Baden-Württemberg

We like to thank our colleagues of DWD
for their support

Real-Time Control, 21 Aug 2019, 13:18 - 15:33 UTC

10 s, 7.5 m





Radiosonde comparison shown before

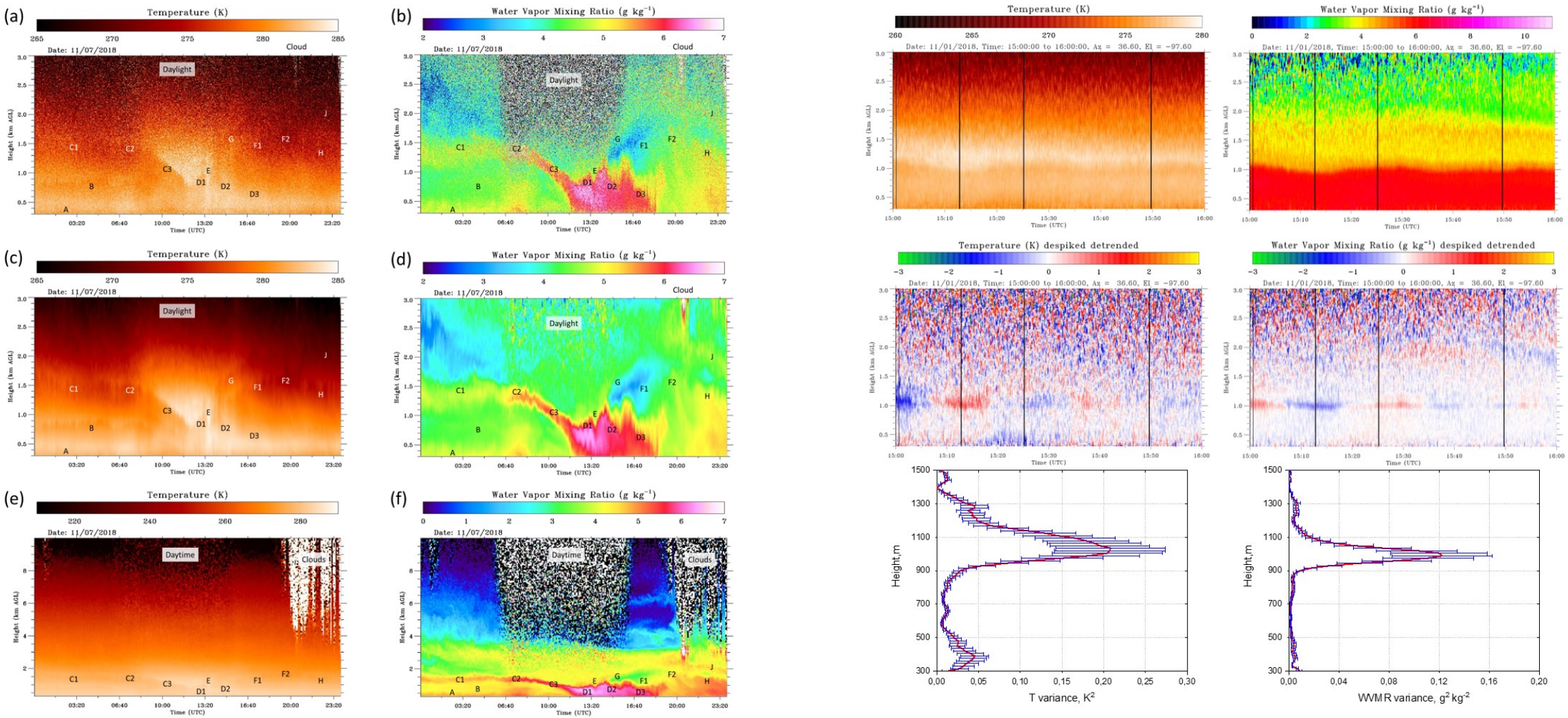
Conclusions & Outlook

- Automatic compact temperature and humidity (and aerosol) Raman lidar
  - → Geophysical Research Letters paper: *https://doi.org/10.1029/2019GL085774*
  - → Compares well with radiosondes (DWD comparison statistics)
  - → No elastic-signal leakage in clouds
  - → Profiler incl. gradients, turbulent fluctuations
    - from the surface to the lower troposphere
    - with uncertainty analysis for each profile.
  - → Thermodynamic measurements in the surface layer, atmospheric boundary layer and free troposphere up to the turbulence scale with very high resolution achieved, more info:
    - **Behrendt et.al. GI4.2** D734 EGU2020-7191 (Same session as this display) https://doi.org/10.5194/egusphere-egu2020-7191
- Robust, mobile, real-time data, well suited for data assimilation

Conclusions & Outlook (Cont.)

- Measurement campaigns:
  - → ScaleX (May – June 2019)
  - → EUREC4A (Jan. – Feb. 2020), some preliminary results shown in sessions:
    - **Lange et.al. GI4.1, Display D692 EGU2020-12144, Thursday, 07 May 2020, 10:45 – 12:30** https://doi.org/10.5194/egusphere-egu2020-12144
    - **Acquistapace et.al. AS1.26, Display D3125 EGU2020-6265, Thursday, 07 May, 08:30 – 10:15** https://doi.org/10.5194/egusphere-egu2020-6265
- Future campaigns:
  - → FESSTVal (2020?) http://fesstval.de/

Thanks!


(a)
Temperature (K)
Date: 11/07/2018
Daylight
Cloud
(b)
Water Vapor Mixing Ratio (g kg⁻¹)
Date: 11/07/2018
Daylight
Cloud
(c)
Temperature (K)
Date: 11/07/2018
Daylight
(d)
Water Vapor Mixing Ratio (g kg⁻¹)
Date: 11/07/2018
Daylight
Cloud
(e)
Temperature (K)
Date: 11/07/2018
Daytime
Clouds
(f)
Water Vapor Mixing Ratio (g kg⁻¹)
Date: 11/07/2018
Daytime
Clouds
Height (km AGL)
Time (UTC)
A
B
C1
C2
C3
D1
D2
D3
E
F1
F2
G
H
J
Temperature (K)
Water Vapor Mixing Ratio (g kg⁻¹)
Temperature (K) despiked detrended
Water Vapor Mixing Ratio (g kg⁻¹) despiked detrended
Date: 11/01/2018, Time: 15:00:00 to 16:00:00, Az = 36.60, El = -97.60
Height,m
T variance, K²
WVMR variance, g² kg⁻²