# Invaluable insights into the dynamics and water-vapor isotopes of the planetary boundary layer above the Greenland Ice Sheet from fixed-wing uncrewed aircraft samplings

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# Slides outline

# Key messages:

## Isotopic profile uncrewed aerial system (UAS) measurements:

- Low correlation between d18O and temperature indicates that the isotopic composition of the atmosphere contains more information of the hydrological cycle than just temperature (slide 15)
- Specific humidity is a good predictor of the isotopic value as expected from a Rayleigh distillation process (slide 15)
- The atmospheric isotope profile shows an impact of snow surface-atmosphere exchange in the lower 300 m. (slides 12-14)

## Model evaluation:

- The overall performance of ERA-5 and MAR in simulating temperature and humidity in the lower 1500 m above the Greenland Ice Sheet is reasonable (slide 8)
- The vertical resolution of ERA-5 is too low to resolve the complex atmospheric structure in the planetary boundary layer (PBL) (example: slide 9)
- Increasing the vertical resolution in the regional climate model MAR improves the simulation of the PBL significantly (slide 8, example: slide 9)

# Site description

- East Greenland Ice Core Project (EGRIP) site: 75.63° N, 36.00° W
- ~ 2700 m a.s.l.
- Measurement period: June 2022

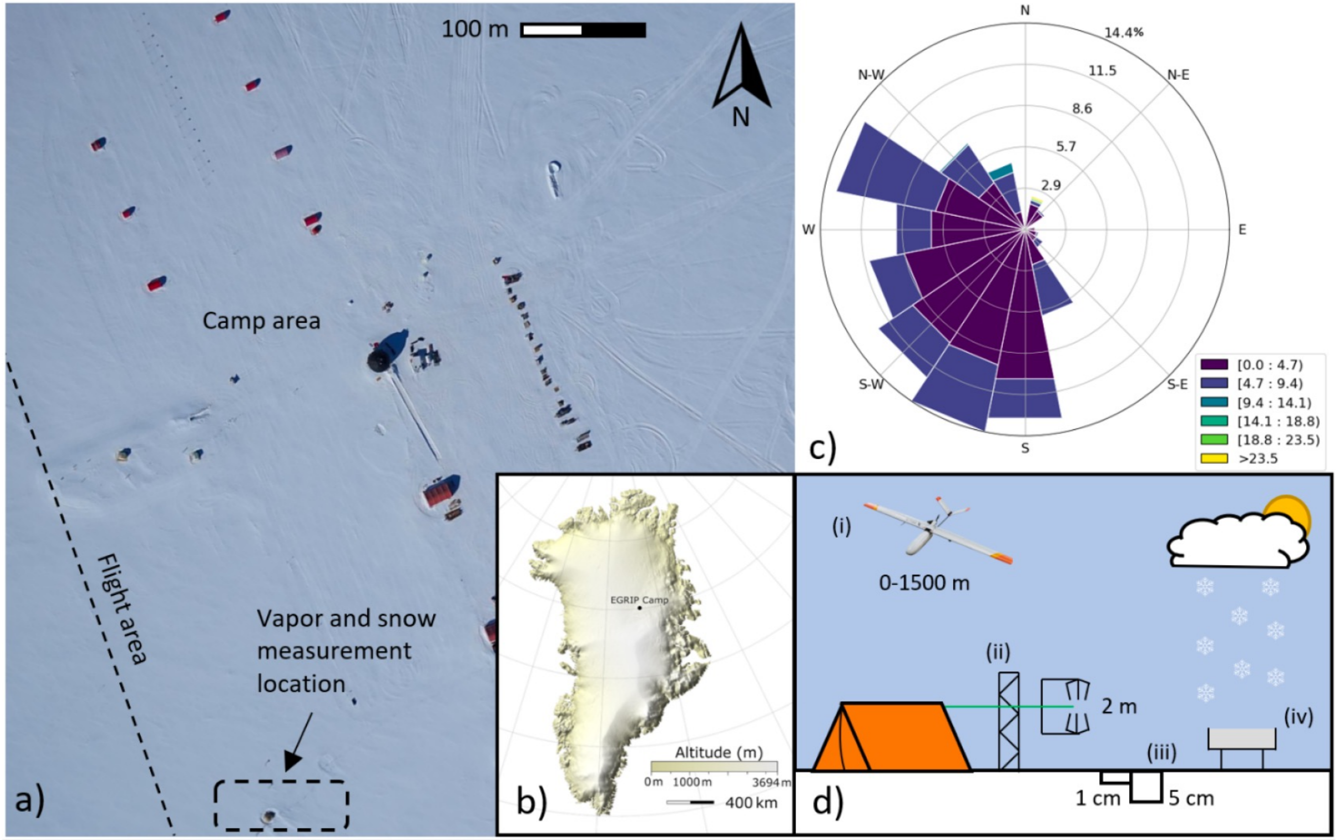
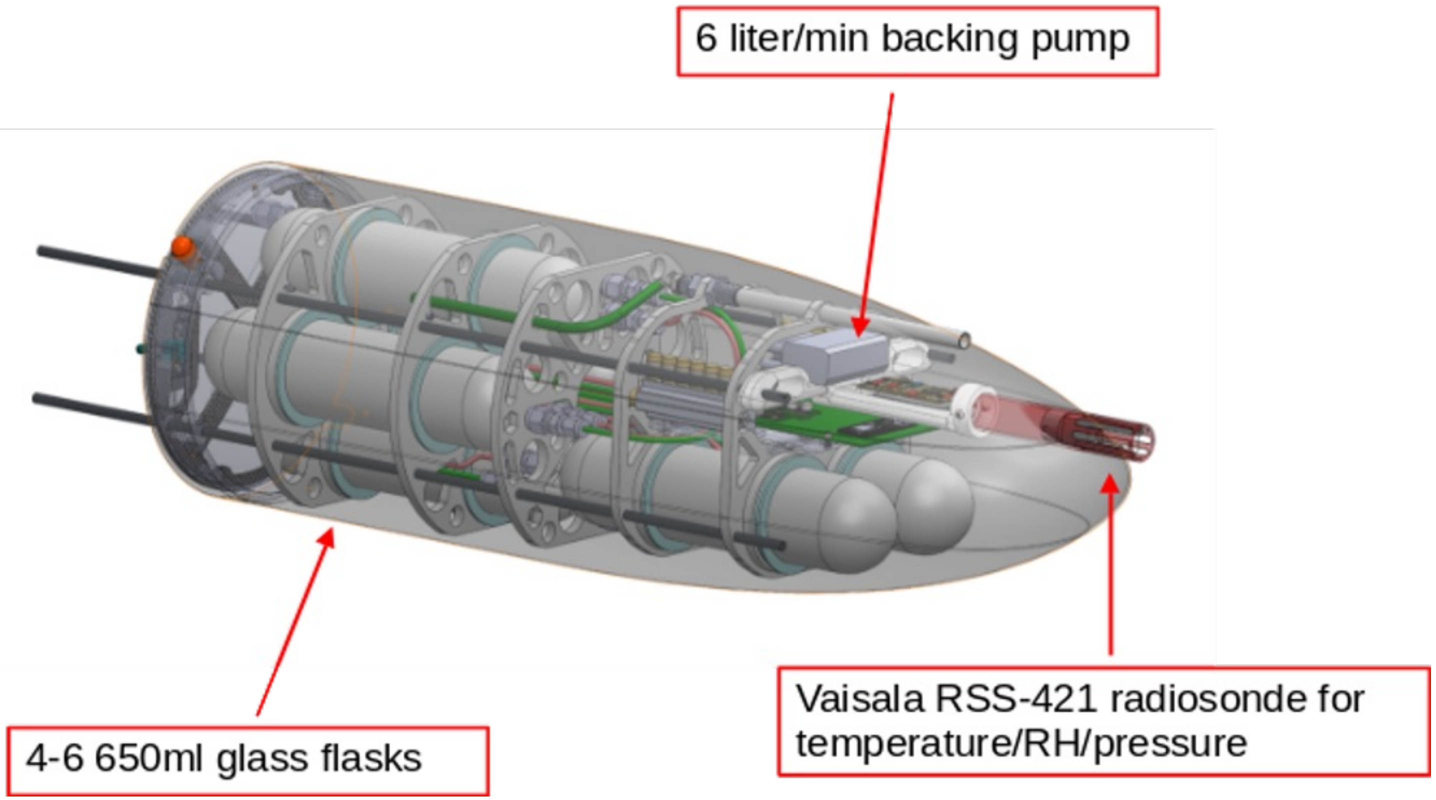



**Figure 1.** a) Aerial overview of the EGRIP camp area. The area in which UAS data ("Flight area") and vapor measurements and snow samples were obtained are highlighted. b) Location of the EGRIP camp on the GrIS. c) Wind distribution at EGRIP during the observational period. d) Schematic overview of the different surface and atmospheric measurements that were taken during the campaign.

# Aircraft

- Max. flight height: 1500 m
- Flight duration: ~50 minutes (15 up, 35 down)
- Flask sampling: flushing with 10 flask volumes in a circular orbital at constant height (~3 minutes per flask sample)

# Instrumentation




# Observed average profiles

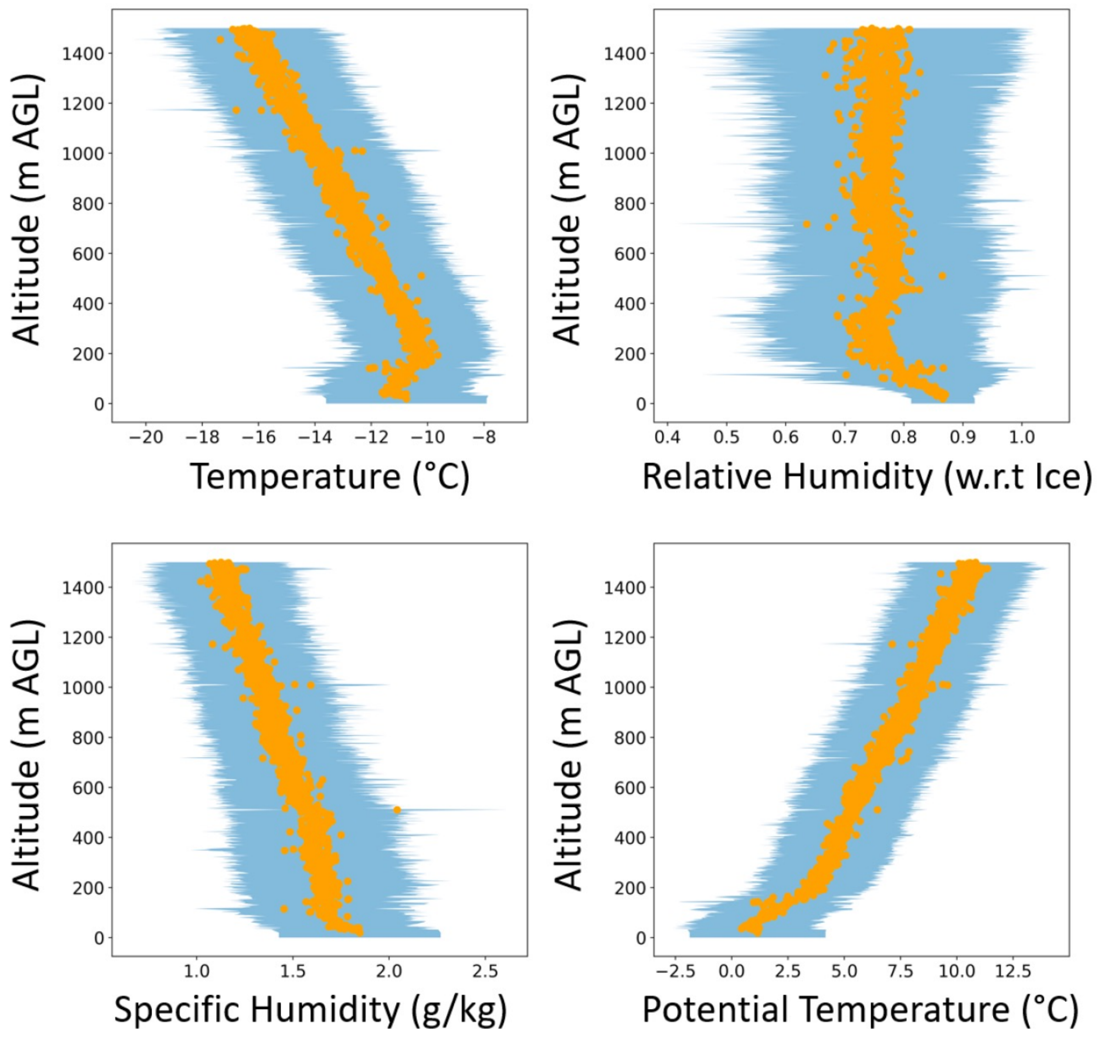



**Figure 2.** 1 m height binned UAS data for temperature (a), relative humidity (b), specific humidity (c), and potential temperature (d) from all flights in orange. The blue lines show the range of ± one standard deviation.

# Model evaluation of the planetary boundary layer above the Greenland Ice Sheet

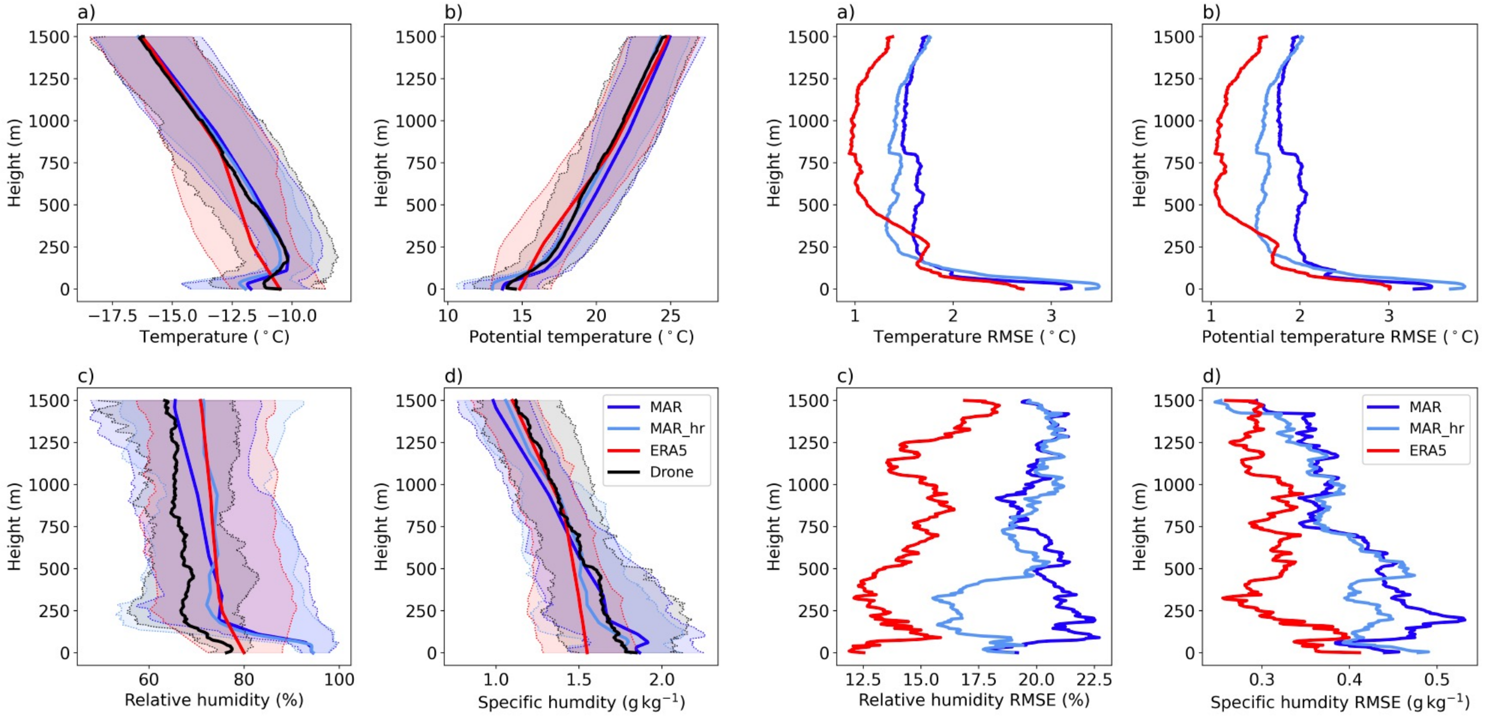



**Figure 3.** Left: Vertical profiles of a) temperature, b) potential temperature, c) relative humidity, and d) specific humidity averaged over 105 flights as measured by the aircraft (black) and simulated by MAR (blue), MAR_hr (light blue) and ERA-5 (red). Shading indicates inter-decile range of variability across the different flights. Right: Vertical profiles of the RMSE between modeled and observed a) temperature, b) potential temperature, c) relative humidity, and d) specific humidity across 105 flights for MAR (blue), MAR_hr (light blue), and ERA-5 (red).

Example of an improved meteorological simulation when increasing the vertical resolution

The UAS data (black lines) shows distinct atmospheric layers

ERA-5 (red lines) has 4 vertical levels below 1500 m

MAR is run on a 24 vertical layer resolution with 13 layers below 1500 m (dark blue lines), and run on a 40 vertical layer resolution with 28 below 1500 m (light blue lines)

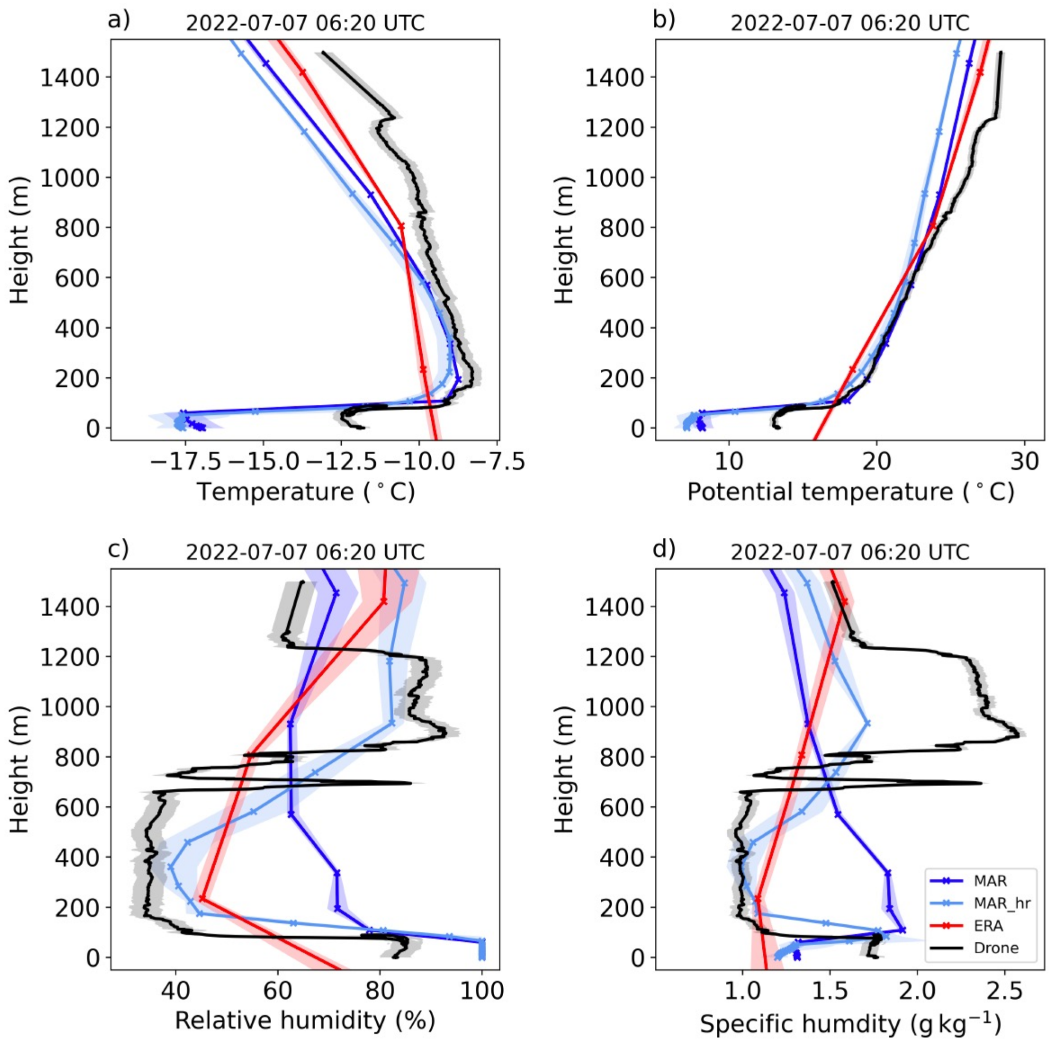



**Figure 10.** Vertical profiles of a) temperature, b) potential temperature, c) relative humidity and d) specific humidity for a drone flight on 07.07.2022 at 6:20 UTC as measured by the drone (black) and simulated by MAR (blue), MAR_hr (light blue) and ERA5 (red). Shading around the simulated values indicates the range across a 4-hour window around the flight time for each height.

# Temperature and humidity profile comparison UAS data (dots) to MAR model (contours)

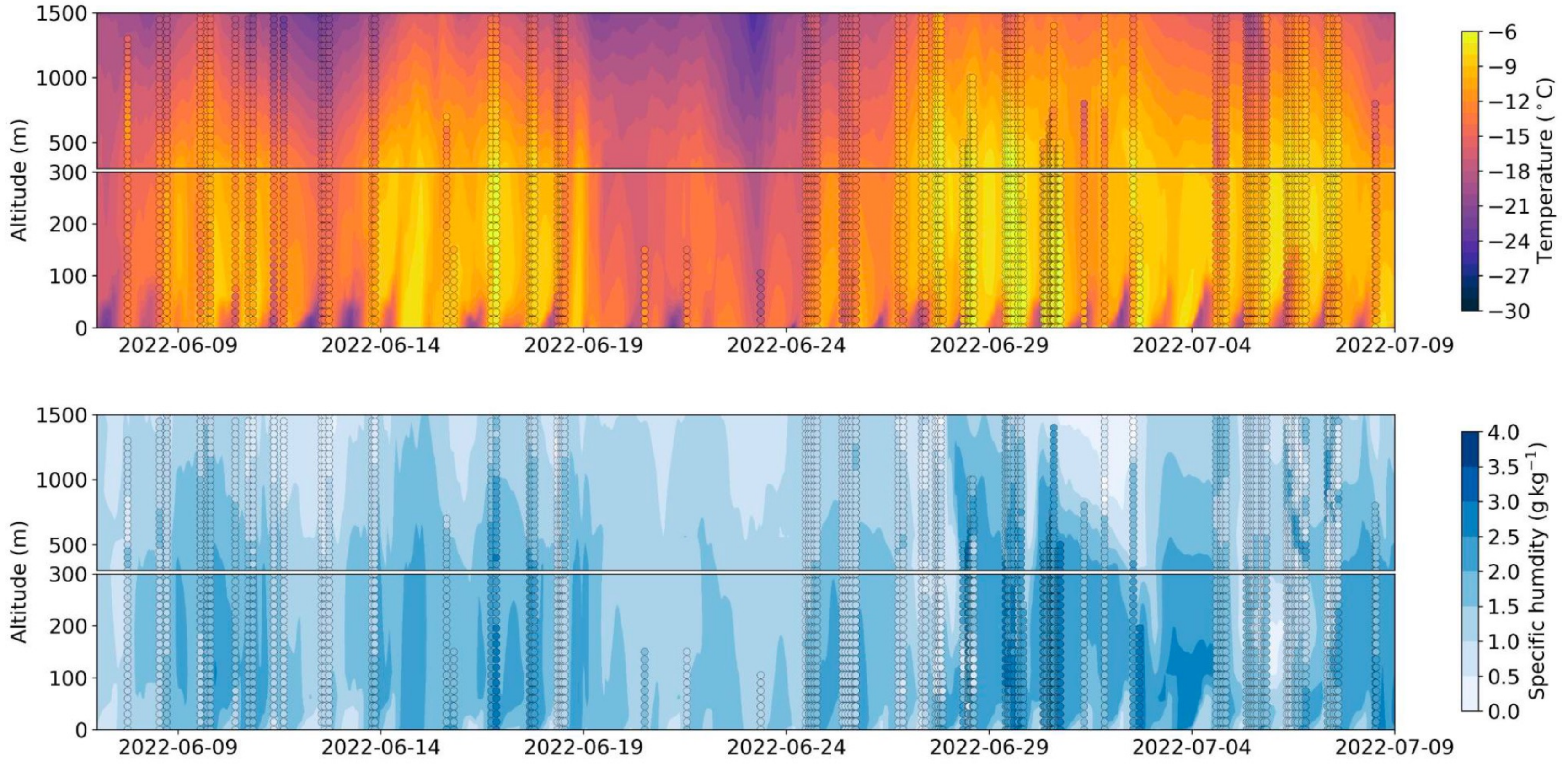



**Figure 4.** Temperature (upper panel) and specific humidity (lower panel) simulated with the MAR model in the observational period. The dots show height binned UAS data with a bin size of 15 m below 300 m height, and 50 m bins above 300 m height.

# Isotopic measurements

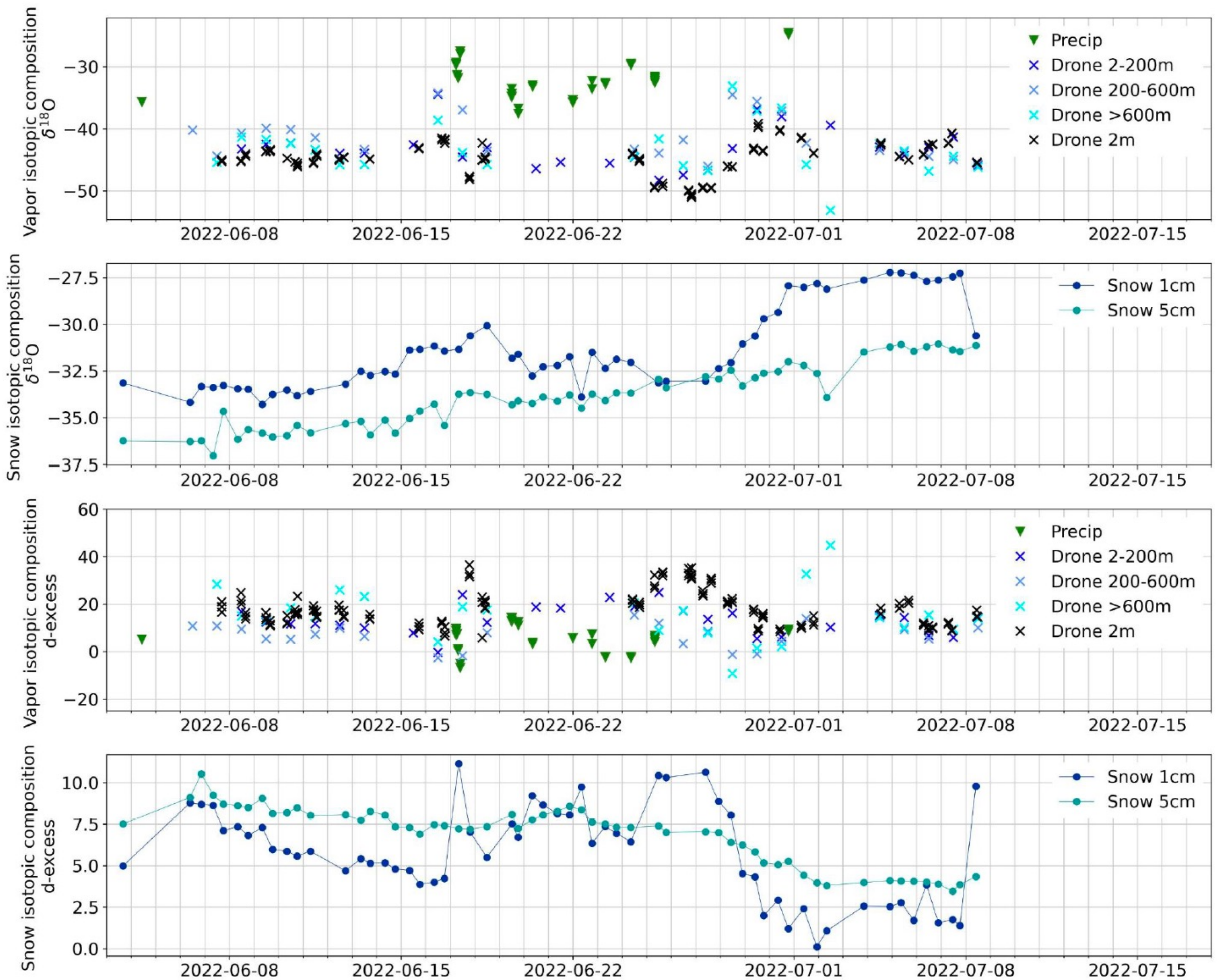



**Figure 5.** Overview of all isotopic measurements of the atmospheric vapor $\delta^{18}$O (a) and $d$ (c), and the snow $\delta^{18}$O (b) and $d$ (d) in the observational period. Green triangles show the precipitation samples. Black crosses show the ground flask samples taken contemporaneously with the UAS air sample flights. The UAS air samples are shown for three different height layers between 2–200 m in dark blue, between 200–600 m in light blue, and above 600 m in light turquoise.

# Surface impact on isotopic composition in the atmosphere

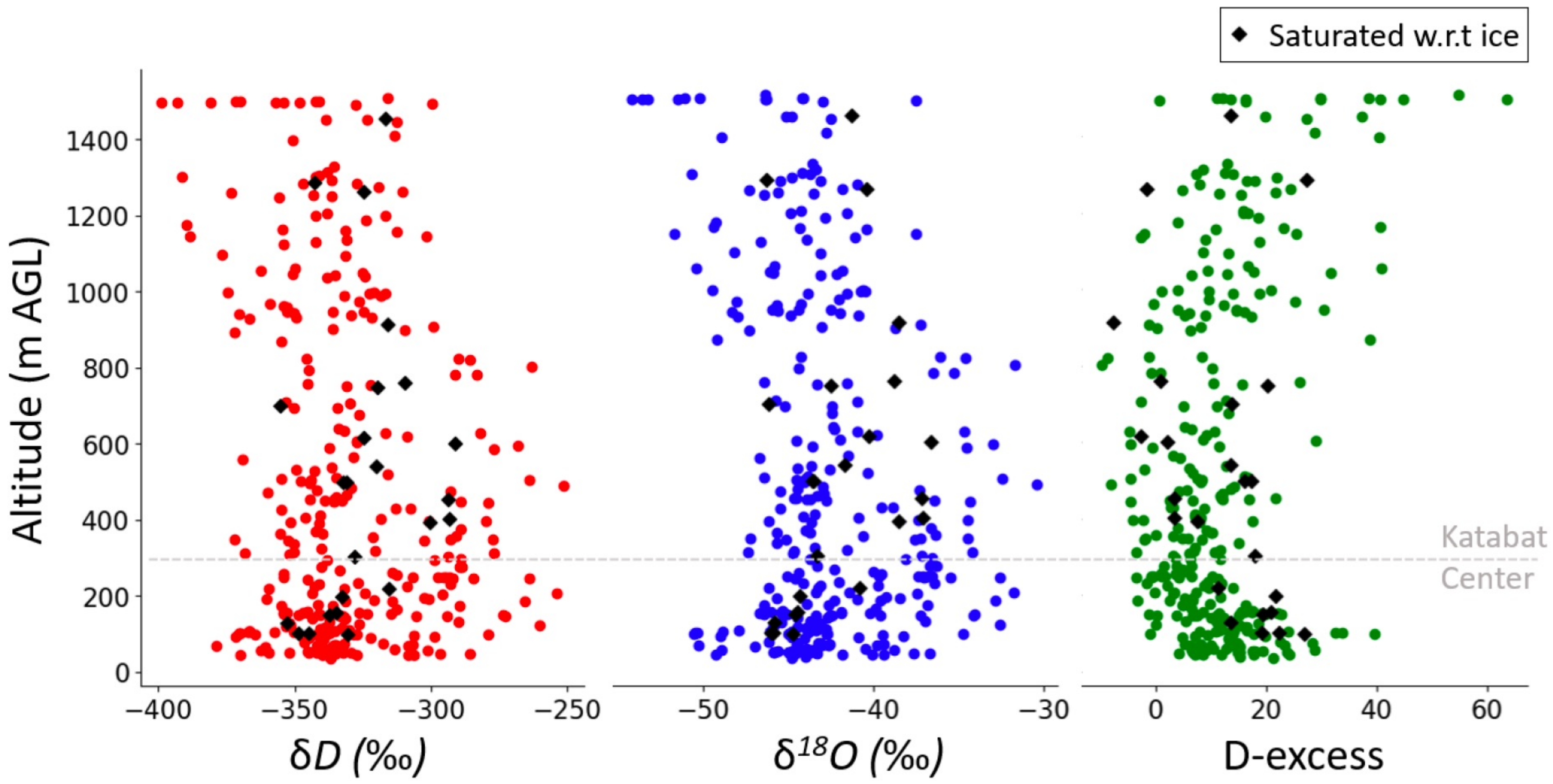



**Figure 6.** All isotopic UAS samples for $\delta$D (left), $\delta^{18}$O (center), and $d$ (right). The black dots indicate isotopic samples that were taken in saturated conditions with respect to ice ($RH_{ice}$=100 %). The grey dotted line shows the minimum in the relative humidity profile from Figure 2 b.

# Isotopic composition of the atmosphere

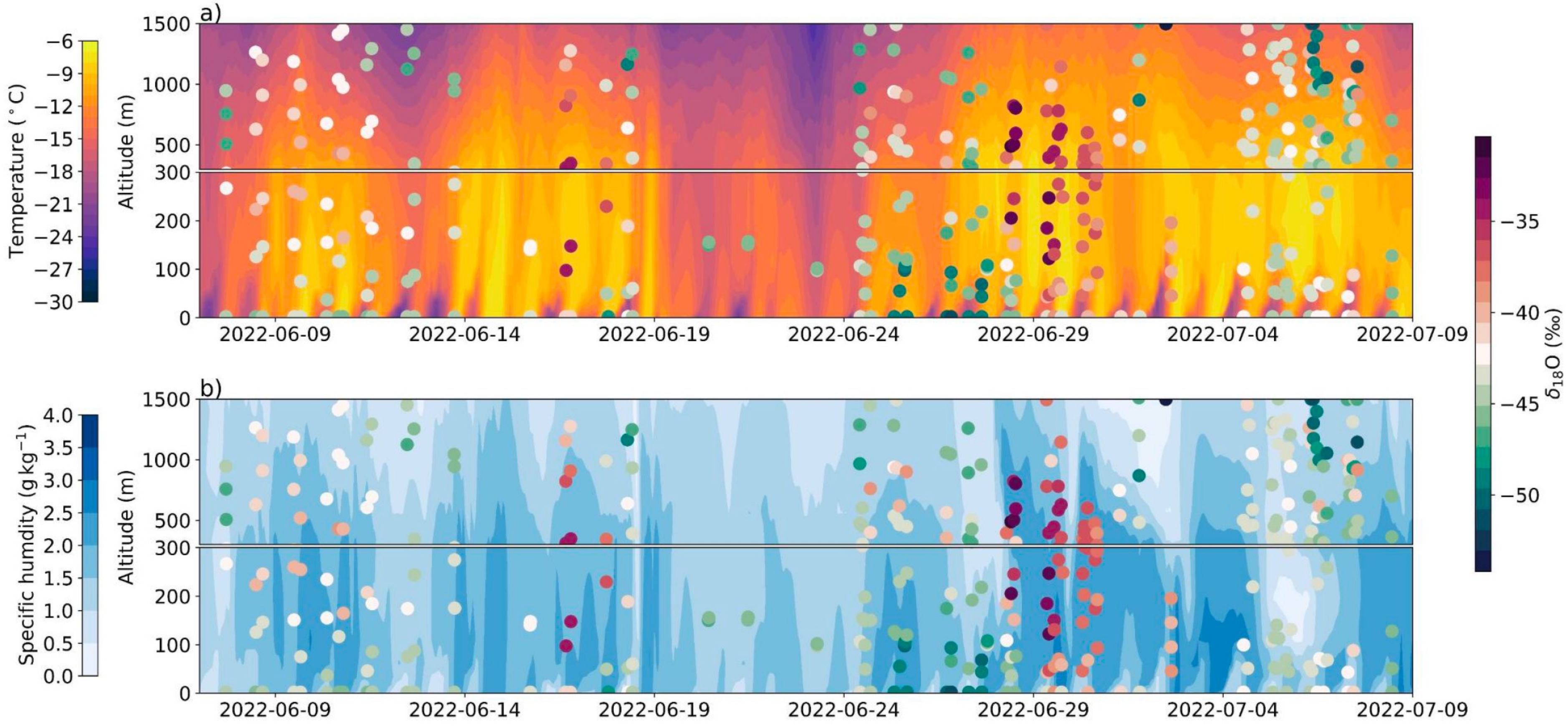
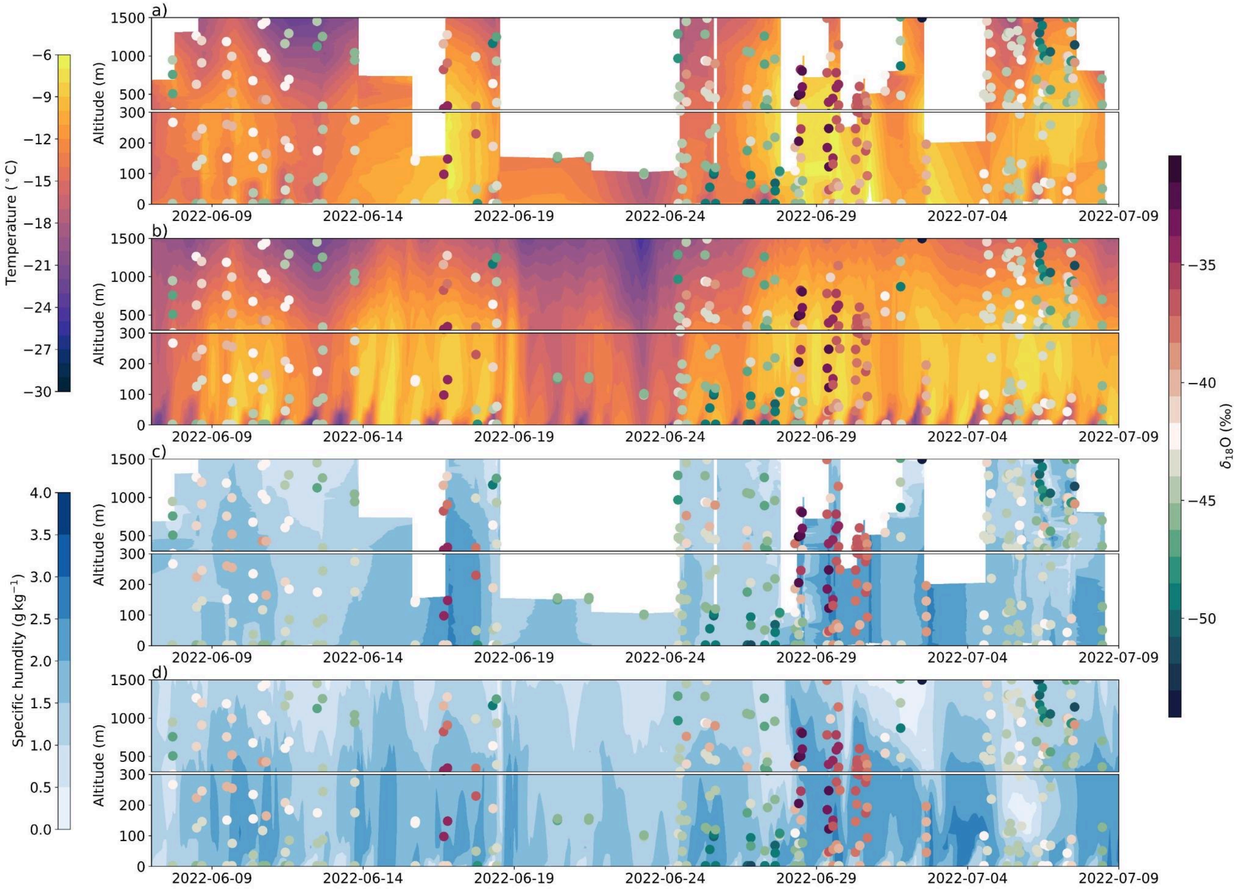


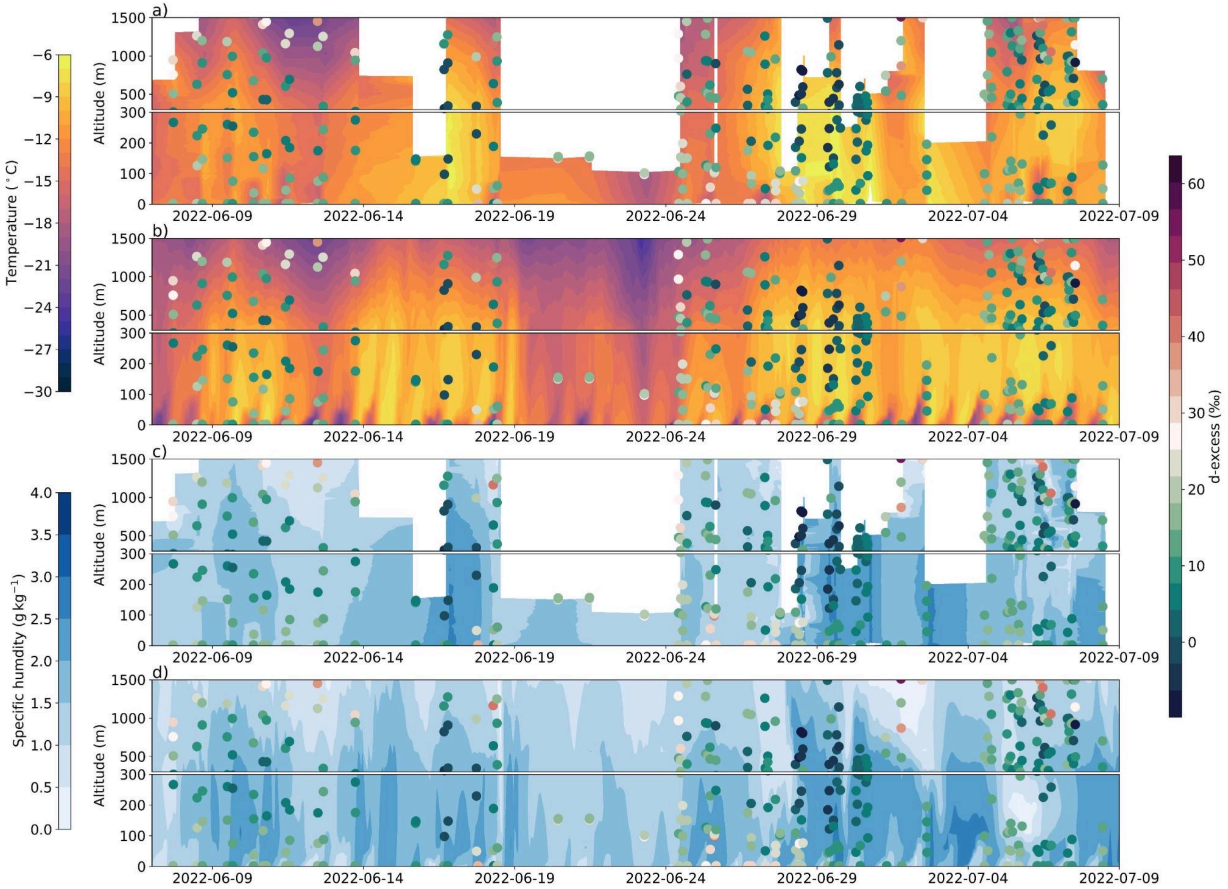

**Figure 7.** Dots: Isotopic measurements of $\delta^{18}$O(‰). Background colors: MAR simulation of the temperature (a) and relative humidity in hourly resolution.

# Isotopic composition of the atmosphere

## d18O




## d-excess




Same as in the Figure on slide 14 but a and c show the UAS data as contours instead of the the MAR model data (b,d). The left Figure shows d18O, and the right d-excess.

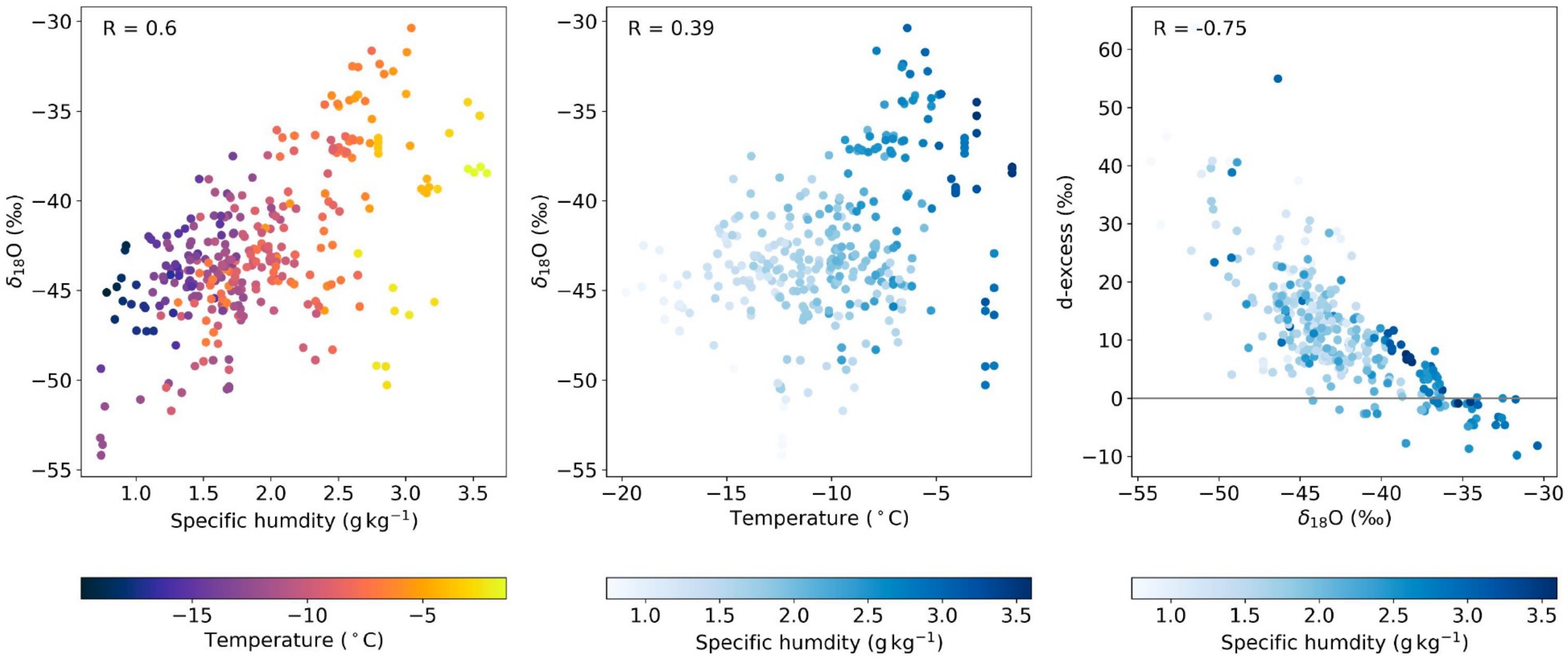
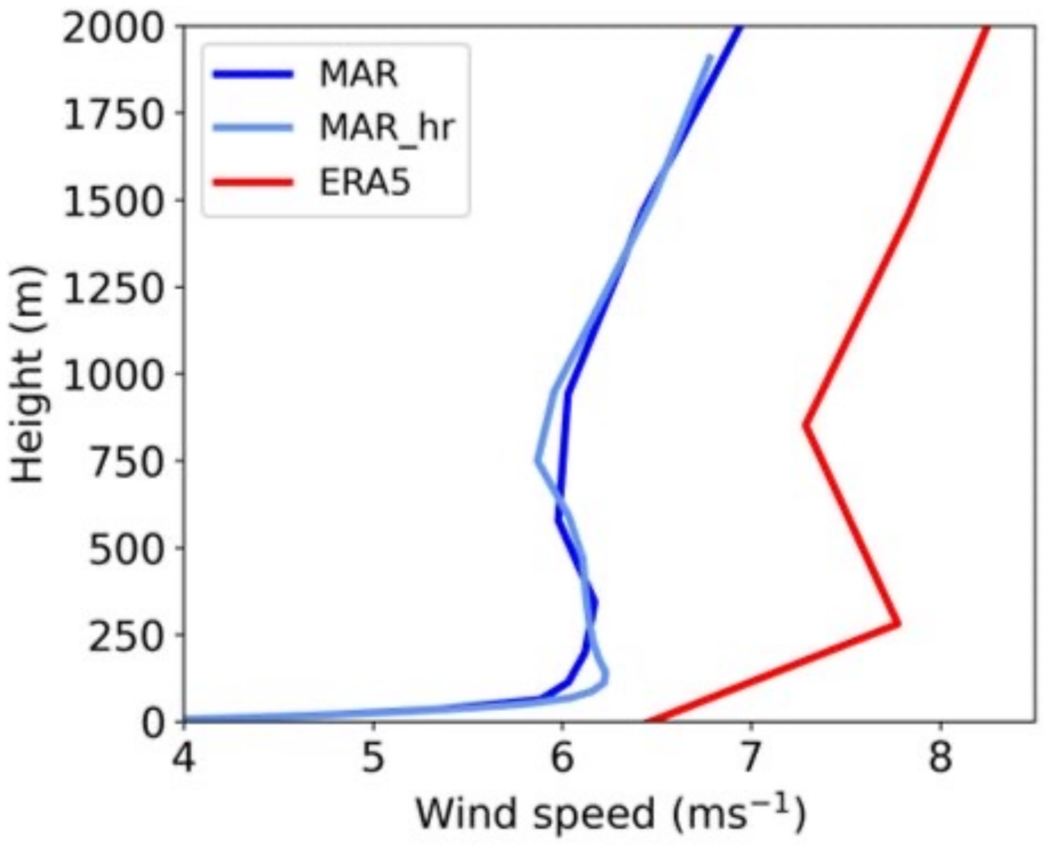



**Figure 8.** Isotopic composition from UAS air samples, as well as atmospheric specific humidity, and temperature measurements were taken contemporaneously with the radiosonde integrated into the UAS. a) Atmospheric specific humidity scattered against $\delta^{18}$O. Colors show the atmospheric temperature. b) Atmospheric temperature scattered against $\delta^{18}$O. Colors show the atmospheric specific humidity. c) $\delta^{18}$ scattered against $d$. Colors show the atmospheric specific humidity. The R-value of the correlation is given in the top left corner.

# Simulation of the katabatic wind layer

- Simulated maximum of katabatic wind layer between 150 and 400 m.
- Wind UAS data in process, soon available



# Calibration & isotopic measurement uncertainties

The CRDS has differing isotopic responses at different levels of specific humidity. Suites of measurements were made to characterize this response described in Rozmiarek et al. (2021). Standard calibrations in this way were performed for the CRDS instrument used for UAS flask system analysis. To prevent large interruptions in continuous sampling, the calibration procedure described in (Wahl et al., 2022) was used for the additional CRDS system. In both methods, the range of 500 to 25 000 ppm water vapor was calibrated across four different standards. The standards, their values, and uncertainties can be found in Table 1. Additional details on the calibration scheme can be found in Jones, White, et al. (2017).

**Table 1.** Tracing of uncertainties is provided for primary reference water standards (∗) and secondary water standards developed in the laboratory, which are reported in units of per mil. The four secondary standards (BSW, ASW, PSW, and SPGSW) are previously calibrated in the laboratory and are defined relative to the primary standards (VSMOW2, SLAP2, and GISP) on which values and uncertainty are reported by the IAEA. Secondary standards are reported with uncertainty determined across multiple IRMS and CRDS platforms. In parentheses is the combined uncertainty of both the primary and secondary standard tie, added in quadrature.

| Standard | $\delta$D (‰) | $\delta$D uncertainty | $\delta^{18}$O (‰) | $\delta^{18}$O uncertainty |
|---|---|---|---|---|
| VSMOW2∗ | 0 | 0.3 | 0 | 0.02 |
| SLAP2∗ | -427.5 | 0.3 | -55.5 | 0.02 |
| GISP∗ | -189.5 | 1.2 | -24.76 | 0.09 |
| BSW | -111.65 | 0.2 (1.3) | -14.15 | 0.02 (0.10) |
| ASW | -239.13 | 0.3 (1.3) | -30.30 | 0.04 (0.10) |
| PSW | -355.18 | 0.2 (1.3) | -45.41 | 0.05 (0.11) |
| SPGSW | -434.47 | 0.2 (1.3) | -55.18 | 0.05 (0.11) |

Rozmiarek et al., 2021: https://amt.copernicus.org/articles/14/7045/2021/
Wahl et al., 2022: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GL099529
Jones et al., 2017: https://amt.copernicus.org/articles/10/617/2017/