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MEDA team

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# Initial results of the relative humidity observations by MEDA instrument onboard the Mars 2020 Perseverance Rover

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## Key Points:

- Humidity observations in Mars by M2020 Perseverance rover during the first 410 sols of operation are shown and discussed.
- Humidity sensor MEDA-HS operations and sensor accuracy are explained.
- Adsorptive single column model is tested and compared with humidity observations.

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## Abstract

The Mars 2020 mission rover “Perseverance”, launched on 30 July 2020 by NASA, landed successfully 18th Feb. 2021 at Jezero Crater, Mars (Lon. E 77.4509° Lat. N 18.4446°). The landing took place at Mars solar longitude  $L_s = 5.2^\circ$ , close to start of the northern spring. Perseverance’s payload includes the relative humidity sensor MEDA HS (Mars Environmental Dynamics Analyzer Humidity Sensor), which operations, performance, and the first observations from sol 80 to sol 410 ( $L_s 44^\circ - 210^\circ$ ) of Perseverance’s operations we describe. The relative humidity measured by MEDA-HS is reliable from late night hours to few tens of minutes after sunrise when the measured humidity is greater than 2% (referenced to sensor temperature). Data delivered to the Planetary Data System (PDS) includes relative humidity, sensor temperature, uncertainty of relative humidity and volume mixing ratio (VMR). VMR is calculated using the MEDA-PS pressure sensor values. According to observations, nighttime absolute humidity follows a seasonal curve in which release of water vapor from the northern cap with advancing northern spring and summer is visible. At ground level, frost conditions may have been reached a few times during this season ( $L_s 44^\circ - 210^\circ$ ). Volume mixing ratio values show a declining diurnal trend from the midnight toward the morning suggesting adsorption of humidity into the ground. Observations are compared with an adsorptive single-column model, which complies with observations and confirms adsorption. The model allows estimating daytime VMR levels. Short-term sub-hour time scales show large temporal fluctuations in humidity, which suggest vertical and spatial advection.

## Plain Language Summary

The Mars 2020 mission rover “Perseverance” landed successfully on 18 Feb. 2021 at Jezero Crater, Mars. The rover’s payload includes a versatile instrument suite which includes a relative humidity sensor, whose observations for the first 410 martian days are described here. The observations show how the lowest level of atmosphere is generally dry, but still exceeding saturation is feasible because of cold nights. Sensor operations and accuracy estimates are presented. Relative humidity together with MEDA pressure and air temperature observations allow calculating absolute water vapor content of air at the sensor level at nighttime. Humidity observations are also compared with models describing water vapor adsorption and desorption into and out from soil. The results show how atmospheric humidity at the rover’s site experiences large subhour variability. Humidity observations help to understand interchange of humidity between the soil and the atmosphere. Water is mandatory for life such as in earth, thus understanding these water cycle processes better are important for evaluating possibilities of past and current habitability of Mars. Perseverance is also collecting samples which maybe returned to Earth one day. Knowledge of the conditions at the times when samples were collected maybe useful.

## 1 Introduction

The Mars 2020 mission rover “Perseverance,” launched on 30 July 2020 by NASA, landed successfully on 18 Feb. 2021 at Jezero Crater, Mars (Lon. E 77.4509°, Lat. N 18.4446°) at solar longitude  $L_s = 5.2^\circ$ . Jezero is a 45-km wide impact crater located in the Nili Fossae region close to western edge of Isidis Planitia. It is thought that an ancient river flowed into Jezero, forming a delta, flooding the crater and forming a lake, both of which have dried out long ago (Mangold et al., 2021).

Perseverance’s science objectives include studying signatures of past habitability. It will also collect and store a set of samples for possible recovery by a later mission. To prepare for human exploration, environmental conditions are recorded by Perseverance’s Mars Environmental Dynamics Analyzer (MEDA) instrument package, which is one of the rover’s seven primary instruments. MEDA has a set of six sensors: Air Temperature

76 Sensor (ATS), Pressure Sensor (PS), Radiation and Dust Sensor (RDS), Relative Humid-  
77 idity Sensor (HS), Thermal Infrared Sensor (TIRS) and Wind Sensor (WS) (Rodriguez-  
78 Manfredi et al., 2021). In addition to MEDA’s importance to future human exploration,  
79 MEDA can be used to address environmental scientific goals, including understanding  
80 the near-surface atmosphere and its relationship to the surface over which the rover is  
81 driving. In this paper, we focus on the first results of the MEDA HS Relative Humid-  
82 ity Sensor.

83 The Relative Humidity Sensor (MEDA HS) is based on capacitive polymer sensors  
84 developed by Vaisala Oyj (Vaisala-Oyj., 2020). The MEDA HS provides nighttime in-  
85 situ observations of relative humidity. During the daytime, the relative humidity drops  
86 close to 0%, below the accuracy of the sensor.

87 This paper describes the observations by MEDA HS of the first 410 Sols of oper-  
88 ations of the Perseverance Rover, MEDA HS operational cycles, and the limitations of  
89 the sensor as well as some initial interpretations of those results. Section 2 describes the  
90 background of the MEDA HS and water vapor in Martian atmosphere. Section 3 gives  
91 a description of the sensor, section 4 describes how the MEDA HS has been operated  
92 onboard Perseverance, section 5 presents an overview of the observations, and section  
93 6 presents comparisons between a column water model and the observations. Conclu-  
94 sions and discussion are in Section 7.

## 95 2 Background

96 Robotic exploration of Mars has followed a strategy guided by scientific consen-  
97 sus on the most important goals collected and defined by Mars Exploration Program Anal-  
98 ysis Group (MEPAG) (Banfield et al., 2020), within which understanding the behavior  
99 of water remains high priority. Water is an obligatory solvent for earth-like life as we un-  
100 derstand it. Existence and cycles of water and water vapor on past and current Mars  
101 is of high scientific importance when investigating habitability potential and possibili-  
102 ties that microbiological life once existed. According to geological evidence liquid wa-  
103 ter flowed on Mars in the past, forming rivers, deltas, lakes and possibly seas (Milton  
104 (1973), Morris et al. (2006), Mangold et al. (2021)). Present water on Mars is thought  
105 to be mainly found in three reservoirs: (i) in the polar caps and surface ice, (ii) in the  
106 regolith and (iii) in the atmosphere. The surface reservoirs, i.e., the polar caps and re-  
107 golith hold several orders of magnitude more water than the atmosphere. Thus, if all the  
108 water of the surface reservoirs melted and spread evenly all over the planet, it would re-  
109 sult a layer of 20 – 30 m deep water (D. E. Smith et al., 1999).

110 Water vapor in the Mars atmosphere was first observed by Earth-based spectrom-  
111 eter observations in 1963 (Spinrad et al., 1963). Several ground-based observations of  
112 Martian water vapor were performed since then (e.g. Jakosky (1985); Jakosky and Haberle  
113 (1992); Clancy et al. (1992); Encrenaz et al. (1995); Encrenaz et al. (2001); Sprague et  
114 al. (1996); Sprague et al. (2003); and references therein). Orbital observations have also  
115 characterized the water vapor abundance in the Mars atmosphere, using data from Mariner  
116 9 (Conrath et al., 1973), Viking orbiters (Farmer et al. (1977); Jakosky and Farmer (1982);  
117 Fedorova et al. (2004)), Mars Global Surveyor (Christensen et al. (1992); M. D. Smith  
118 et al. (2001); M. D. Smith (2002); M. D. Smith (2004)), Mars Express (Encrenaz et al.  
119 (2005); Fedorova et al. (2006); Fedorova et al. (2021); Fouchet et al. (2007); Maltagliati  
120 et al. (2011); Sindoni et al. (2011)), Mars Reconnaissance Orbiter CRISM spectrom-  
121 eter (M. D. Smith et al., 2009) and ExoMars Trace Gas Orbiter (Aoki et al., 2019), in-  
122 cluding its seasonal, latitudinal and longitudinal variation and, recently, its vertical pro-  
123 files in the atmosphere.

124 Observations indicate that the Mars atmosphere has, on average, of order of 10  $\mu$   
125 m of precipitable water (pr- $\mu$  m; the thickness of the water layer if all the water vapor

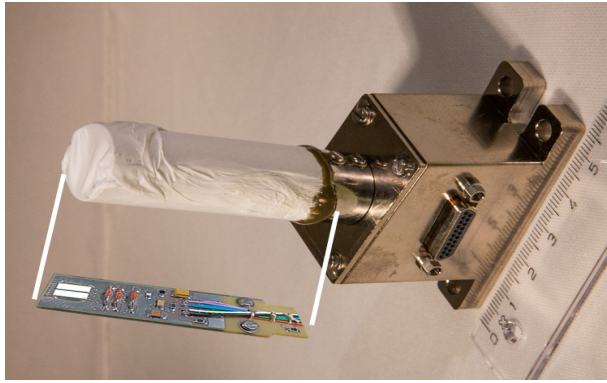
of the atmosphere were to be condensed onto the surface, 1  $\mu\text{m}$  being thus 1 g of water per square meter). The Earth's atmosphere has a few tens of mm precipitable water, thus compared to Earth, the Martian atmosphere is extremely dry (e.g. Jakosky and Haberle (1992)). Also, strong seasonal and spatial variability has been found to date, together with interannual variations mostly related to the effect of dust storms (e.g. M. D. Smith et al. (2001), with maximum abundances, as high as 80-100  $\mu\text{m}$ , during the northern summer at high northern latitudes, and minima in the southern hemisphere. The southern summer produces the opposite meridional effect but with a significantly lower amplitude, reaching a maximum water vapor abundance of about half that of the northern summer column abundance, possibly as a result of the orbit eccentricity of Mars (Clancy et al., 1996). The vertical profiles of water vapor are strongly variable and influenced by dust storms (e.g. Heavens et al. (2018); Aoki et al. (2019)), when water vapor is able to reach very high altitudes. However most of the water vapor remains in the lowest few kilometers of the atmosphere under normal conditions.

In situ water vapor observations are, however much more scarce, thus the water abundance in the near-surface atmosphere has not been well characterized. In fact, only two missions to date, Phoenix lander and Mars Science Laboratory (MSL), carried on instrumentation to measure relative humidity. Water mixing ratios were able to be inferred, together with concurrent measurements of atmospheric pressure and temperature.

The Phoenix mission landed on Mars at  $68.2^\circ\text{N}$ ,  $234.2^\circ\text{E}$  in 2008 (Ls  $78^\circ$  to  $147^\circ$ ) and operated for more than one hundred and fifty sols (P. H. Smith et al., 2009). The thermal and electrical conductivity probe (TECP) onboard the Phoenix lander returned the first in-situ relative humidity measurements (Rh) from the Martian surface (Zent et al. (2010); Zent et al. (2016); Fischer et al. (2019)). Observations showed a high Rh (even reaching water vapor saturation in the atmosphere) during the nighttime and average Rh less than 5% during the daytime, increasing to 10% late in the mission. The daytime mixing ratios were more than an order of magnitude greater than those inferred during nighttime. Complementary observations detected frost deposition on the surface, occurring in the latter half of the mission. Also, it was suggested that water vapor mixed upward by daytime turbulence and convection formed the observed water ice clouds at night that precipitated back toward the surface (Whiteway et al., 2009). However, another study indicated a marked confinement of water vapor below 2.5 kilometers of altitude during the daytime (Tamppari & Lemmon, 2020).

The study of water vapor from the Martian surface moved forward with the arrival of MSL at Gale Crater ( $4.6^\circ\text{S}$ ,  $137.5^\circ\text{E}$ ) in 2012. MSL rover carries the Rover Environmental Monitoring Station (REMS) instrument, which includes an Rh sensor (Gómez-Elvira et al., 2012). Initial results have shown a dry atmosphere, with Rh barely reaching 70% during the diurnal cycle (Harri et al. (2014); Martín-Torres et al. (2015); Martínez et al. (2016); Martínez et al. (2017)). A large seasonal cycle has been observed, with maximum values reached around the southern winter solstice during the nighttime. The diurnal cycle also shows dramatic variations, with Rh being close to zero during the daytime. However, due to the very low Rh values during the daytime, the associated water mixing ratios cannot be retrieved with accuracy.

The dramatic diurnal variation observed at both landing sites, together with previous orbital observations and modeling, strongly suggests that there is a significant regolith-atmosphere exchange mechanism on Mars, probably owing to adsorption/desorption in the regolith (e.g. Jakosky et al. (1997); Melchiorri et al. (2009); Savijärvi et al. (2015); Savijärvi et al. (2019); Savijärvi, Martinez, Fischer, et al. (2020); Steele et al. (2017); McConnochie et al. (2018)). In addition, the effects of a global dust storm (MY34/2018 GDS) on the humidity levels were also observed by MSL (Viúdez-Moreiras et al., 2019). The near-surface water mixing ratio suggested an overnight increase during the storm at MSL's general location and a decrease during the daytime. It was hypothesized that the combined ef-



**Figure 1.** Meda HS (HS) relative humidity instrument. Printed circuit board (PCB) with the electronics and the Humicap® humidity sensing-elements is located inside PTFE dust filter. The PCB is accommodated by electronics on both sides.

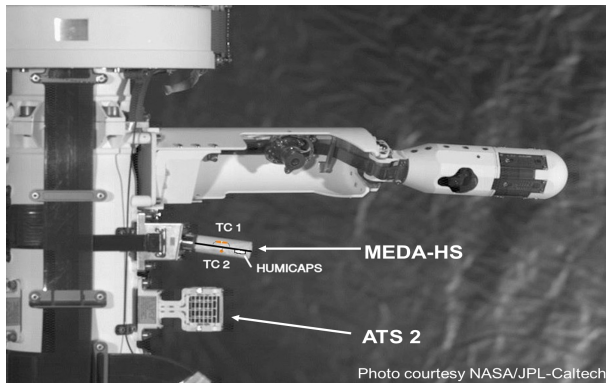
179 fect of a reduction in the strength of an adsorption and desorption mechanism in the re-  
 180 golith and the enhanced vertical mixing at night during the storm could be driving the  
 181 observed effect in the diurnal cycle assuming that the inferred water vapor abundances  
 182 during the GDS are correct. Savijärvi, Martinez, Harri, and Paton (2020) proposed an  
 183 additional source of water vapor to minimize the mismatch between modeling efforts and  
 184 observations.

### 185 3 MEDA HS Relative Humidity Instrument

186 The MEDA HS relative humidity instrument (HS) consists of printed circuit board  
 187 (PCB) of a 63 \* 15 \* 1 mm size, mechanical support, electrically grounded perforated  
 188 thin stainless steel cover shield and dust filter. The dust filter is made of polytetraflu-  
 189 oroethylene (PTFE) sheet and has pore size 0.20  $\mu$  m. PCB accommodates the Humi-  
 190 cap® humidity sensor elements, housekeeping temperature sensors, housekeeping refer-  
 191 ence capacitors and electronics based on a single application specific integrated circuit  
 192 (ASIC). Dimensions of the sensor are 55 \* 25 \* 90 mm and mass is 45 g. Power consump-  
 193 tion is 20 mW. MEDA HS sensor testing and calibrations are described in detail in Hieta  
 194 et al. (2022).

195 The MEDA HS is mounted onto a metallic interface box which accommodates elec-  
 196 tric connector. This box is mounted onto the rover's remote sensing mast (RSM) above  
 197 the MEDA Air Temperature Sensor ATS-2 and below the other MEDA Wind Sensor (WS).  
 198 The height of the sensor above the ground is 1.50 m. The HS-sensor is presented in Fig-  
 199 ure 1 and Figure 2 shows how the sensor is mounted. The humidity sensor element con-  
 200 tains also an integrated platinum temperature sensor, which has 1000 Ohm resistance  
 201 at 0 C°, thus this resistor is called Pt1000. The relative humidity output value is refer-  
 202 enced to this Pt1000 sensor output. The sensor element includes also a heating resistor,  
 203 which is used periodically for "regenerating" the sensor. Regeneration is a heat treat-  
 204 ment process, in which heating the sensor from ambient to +170 C° for a few minutes  
 205 will clean the sensor polymer from condensed volatiles which may have contaminated  
 206 the sensor. Regeneration heating has also a short term side effect. Sensor polymer mem-  
 207 brane adsorbs and is sensitive to carbon dioxide. Regeneration heating outgasses car-  
 208 bon dioxide out of sensor. Adsorbing gas back takes few days and sensor readings are  
 209 slightly compromised during this time.





**Figure 2.** Meda-HS is mounted onto the RSM mast above ATS-2 air temperature sensor and below the MEDA wind sensors. Height from the ground is 1.50 m. Orientation of the Meda HS circuit board is shown (inside the dust filter between TC1 and TC2 texts). The Humicap humidity sensor elements face upwards (through a hole in the printed circuit board). Locations of the Termocap® 1 and 2 housekeeping T sensors TC1 and TC2 are shown. Photo NASA/JPL-Caltech

MEDA HS works in conjunction with other sensors of the MEDA instrument suite. The atmospheric pressure data provided by the Pressure Sensor MEDA-PS is used to calculate the volume mixing ratio, VMR. MEDA Air Temperature Sensors ATS (five separate sensors), MEDA Thermal Infrared Sensor TIRS providing ground and 40 m level temperatures and MEDA Wind Sensor WS are most useful too in analyzing MEDA-HS results.

Uncertainty analysis of the sensor was performed by consultants specialized in metrology, VTT Technical Research Centre of Finland Ltd. (VTT-Ltd., 2022) following the guidelines of the Joint Committee for Guides in Metrology (JCGM, 2008). Factors contributing to calibration uncertainty were: uncertainty contributed by calibration model and non-linearity, uncertainty of the temperature sensors (calibration of the Pt1000 sensors in the Humicap sensor elements and calibration of a reference transfer sensor used in the Pt1000 calibrations, uncertainty of the dew/frost point temperatures in the calibrations (reference hygrometers), uncertainty of the pressure measurements, uncertainty contributed by transferring Ground Reference model results to Flight model (calibration was continued with the Ground Reference model after the delivery of the Flight and Spare models) and uncertainty contributed by water vapor enhancement factor (deviation of water vapor partial pressure from the water vapor saturation pressure approximations which are presumed to have no carrier gas mixed with the water vapor). Uncertainties were combined using quadratic law of error propagation (assuming no correlations between contributing uncertainties) (JCGM, 2008). The combined uncertainty is dominated by the uncertainty of the calibration model and non-linearity. Water vapor enhancement factor has a negligible effect because of the very low pressure. The water vapor enhancement factor was found to be less than 0.03 (VTT-Ltd., 2022).

The lowest calibration temperature was  $-70\text{ }^{\circ}\text{C}$ . Calibration and uncertainty analysis was extrapolated from  $-70\text{ }^{\circ}\text{C}$  to  $-90\text{ }^{\circ}\text{C}$  temperature. The best achieved combined standard uncertainty of MEDA-HS calibration for the full humidity range (0-100 % Rh) was found to be highly sensitive to the ambient temperature and the actual humidity level. With 95% confidence interval (coverage factor  $k=2$ ) the expanded standard uncertainty was analyzed to vary roughly between a) 2.2 to 6 % Rh units in  $-85\text{ }^{\circ}\text{C}$ , b) 1.2 to 4.4 % Rh units in  $-70\text{ }^{\circ}\text{C}$ , c) 0.8 to 3.8 % Rh units in  $-50\text{ }^{\circ}\text{C}$  and d) 0.8 to 3.6 % Rh

units in  $-30\text{ C}^\circ$ . These uncertainties are valid in stable conditions in pointwise measurements (stable pressure, temperature and humidity, MEDA HS switched on for 10 seconds for a measurement). The accuracy of the humidity measurements is demonstrated in Figure 3. Expanded standard uncertainty (coverage factor  $k=2$ , confidence interval 95%) is shown for sol 346. VMR standard uncertainty is calculated according to JCGM (2008) combining contributing uncertainties by Equation 1 and including standard uncertainty  $0.11\text{ C}^\circ$  for humidity sensor temperature calibration uncertainty (from calibrations) and assuming  $3.5\text{ Pa}$  pressure standard uncertainty (Harri and et al (2022) in this issue). Square of the VMR standard uncertainty  $u$  is given by Equation 1:

$$u^2 = \left| \frac{\partial \text{VMR}}{\partial Rh} \right|^2 u_{Rh}^2 + \left| \frac{\partial \text{VMR}}{\partial T} \right|^2 u_T^2 + \left| \frac{\partial \text{VMR}}{\partial P} \right|^2 u_P^2 \quad (1)$$

where  $u$  is VMR standard uncertainty and  $u_{Rh}$ ,  $u_T$  and  $u_P$  are standard uncertainties of relative humidity, temperature and pressure.

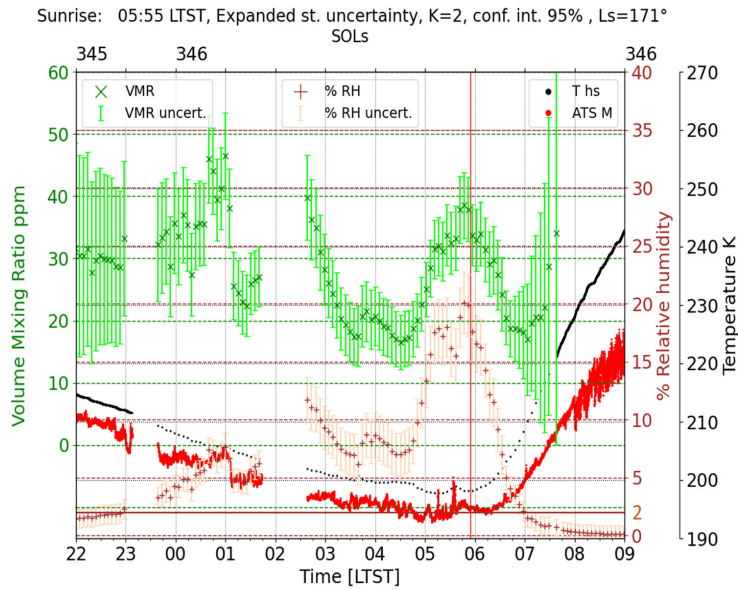
The VMR standard uncertainty is here practically dominated by the uncertainty of the relative humidity measurement. The effect of pressure uncertainty is negligible and could be omitted. The uncertainties shown here are deviations from the calibration standard and in principle valid in laboratory conditions. The repeatability is  $0.02\%$  Rh and reproducibility  $0.14\%$  Rh. The Rh uncertainty excludes time dynamic effects and the separate measurements made at the rover level (pressure uncertainty and resistance measurement uncertainty of the humidity sensor Pt1000 platinum resistor, their contribution to total uncertainty being small). Figure 3 also demonstrates why the VMR should not be calculated below about  $2\%$  Rh values. For the Figure 3, VMR values were calculated down to  $0.5\%$  Rh values. The expanded standard uncertainty ( $k=2$ , 95% confidence interval) of VMR values shown start increasing below about  $2\%$  Rh values so that VMR values become unreliable. Therefore  $2\%$  Rh is used in this work as lower limit for calculating VMR or other absolute humidity values. Usefull time ranges when  $Rh > 2\%$  for the VMR values are visible in Figure 7. In the Figure 3 we see that  $Rh > 2\%$  from  $23:00\text{ LTST}$  to about one hour after sunrise  $07:00\text{ LTST}$ . Although these timelimits are rather typical, using just time limits for VMR calculation alone is not recommended (Supporting Information Figure S2).

#### 4 MEDA-HS operations onboard Perseverance

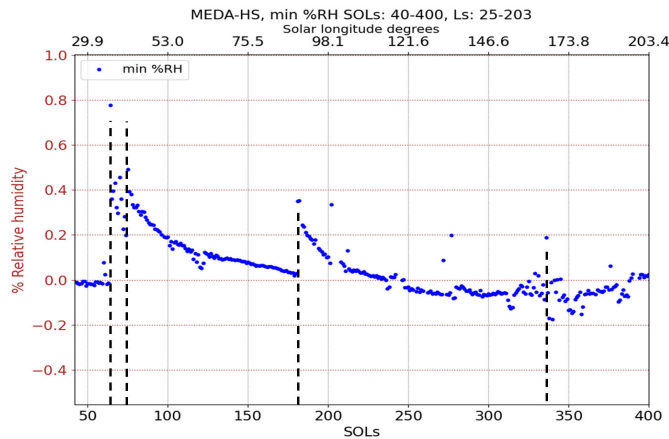
Health and performance of the MEDA-HS are monitored by examining the outputs of the housekeeping constant capacitors, temperature sensors, and the humidity sensor elements. The humidity sensor output during the daytime is practically the same as a dry value, as it goes below the uncertainty. This feature is used to check the stability of the sensor in flight and to monitor drift. Any significant deviation or drift of the electronics will be revealed by constant reference capacitors and multiple temperature sensors. Up to date, MEDA-HS electronics has been stable.

Humicap humidity sensors had some drifting upon landing on Mars, drifting was most probably caused by ingassing some volatile material during the interplanetary cruise phase or in the storage prior the launch. Drifting which was compensated by regeneration procedures at sols 63 and 73. Recovering from the regeneration itself takes few sols. Thus, the data before sol 80 is not used in this work. Regeneration has to be performed periodically to maintain accurate output and to date, the regeneration heating process has been applied four times. The first regeneration at sol 63 had a clear effect. The second regeneration was applied soon after at sol 73 showing a small effect. The sensor had obviously been contaminated after the last calibrations in 2018 either during storage or during the cruise phase or both. The third regeneration was applied on sol 180. A very small effect is barely visible after the sol 180 regeneration, well below the level of the sen-





**Figure 3.** Volume mixing ratios (green) and relative humidity (brown) expanded standard uncertainties ( $k=2$ , confidence interval 95%). The VMR is calculated here down to 0.5% Rh values for demonstrating how VMR uncertainty grows below 2% Rh becoming rather useless. T hs (black) is the humidity sensor temperature, ATS M (red) is most single value representing less contaminated air temperature calculated from ATS sensors 1...3 (Munguira et al. (2022) in this issue). Rh is referenced here to sensor T (T hs). We see here also how turbulence in ATS data bring or remove humidity (00:30-01:00 and 05:00-06:00). Gaps in the data around 23-00 and 02-03 LTST are because MEDA has been commanded off. Solar longitude Ls=171°



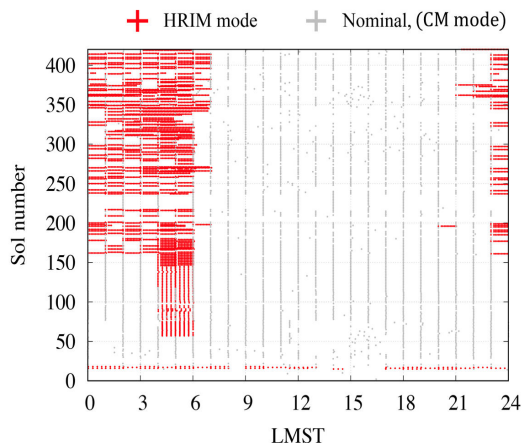
**Figure 4.** Minimum Rh values per sol show the effects of the regeneration in sols 63, 73, 180 and 335 (marked by vertical dashed lines). Regeneration in sol 335 is visible clearly only in the next sol. This indicates that there has been little contamination between sols 180-335. Small negative relative humidity values in the time serie result from the calibration equation not being optimized for very low day time rh values and the sensor operating outside the useful range.

288 sor uncertainty. Regeneration effect in sol 335 had minor shift in zero %Rh level. Effects  
 289 of the three first regenerations is clearly seen in the dry daytime values of the sensor (min-  
 290 imum %Rh per sol) shown in the Figure 4.

291 MEDA-HS has two basic operational modes: Continuous mode (CM) and High-  
 292 resolution Interval Mode (HRIM). In the continuous mode, MEDA-HS is switched on  
 293 and output recorded once a second as long as the continuous mode continues. In the HRIM  
 294 mode, MEDA-HS is switched on for 10 seconds, recorded once a second and then switched  
 295 off. The HS relative humidity output value is calculated as average of the five values start-  
 296 ing from the third value of this 10-second time period for the both Humicap sensors sep-  
 297 arately and their average is the final value. Then this 10-second measurement is repeated  
 298 after 15 or 5 minutes. 15 minute interval was used in the beginning of the mission, but  
 299 it was later changed to 5 min beginning from the sol 146 (Ls 73.2°).

300 The MEDA-HS modes described above are modulated by MEDA basic measure-  
 301 ment strategy. Because of operational limitations, MEDA is not running all the time,  
 302 but typically every other hour. The measured hour varies between odd and even hours  
 303 of the SOL. Thus, typically MEDA-HS is powered continuously for an hour in the con-  
 304 tinuous mode or 4 or 12 times in an hour for a ten second measurement in the HRIM  
 305 mode. Occasionally MEDA has also other operational strategies and MEDA-HS is mea-  
 306 sured accordingly either in the CM or continuously running HRIM mode for period of  
 307 several hours. Observation modes up to sol 410 (Ls 210°) are presented in Figure 5.

308 MEDA-HS heats up usually 0.6 to 1.2 C° during continuous mode measurements.  
 309 At the start up, this causes a small deviation to the derived absolute humidity value dur-  
 310 ing the first few minutes, and a small increased uncertainty remains after a few minutes  
 311 power on time. This non-ideality is caused by small temperature gradients developing  
 312 in the circuitry, for which the algorithm compensating for thermal drift can't properly  
 313 compensate. The heating in the first few seconds of the HRIM mode, after power on,  
 314 is negligible, therefore the best accuracy is achieved by HRIM mode. The first few sec-  
 315 onds of the continuous-mode measurement are equivalent to the HRIM measurement.  
 316 The MEDA-HS was calibrated in an HRIM-like mode. Accurate value for HRIM and CM



**Figure 5.** MEDA-HS operational modes up to sol 410 (solar longitude 210°). Red crosses show HRIM observations and grey crosses show the continuous mode start times.

mode calibration difference can't be given at present. We assume the difference is on the order of 1-2 ppm in VMR based on laboratory tests and examination of the flight data. When CM mode observations were used, eight first minutes of data were not used to allow the sensor heat up and stabilize as CM starts may experience a short period extra fluctuation.

The MEDA-HS humidity value output has a time lag, which is on the order of minutes and depends on temperature. At the 222 K° temperature, a minute time lag was measured with the Ground Reference model (Hieta et al., 2022). At lower temperatures, the time lag increases and is estimated to be order of a few minutes in -70 C°. However, the tests never included the interface box which may have some effect on the time lag. Factors contributing to time lag are the Humicap sensor thin film membrane time constant, dust filter and internal volume. Internal volume consists of cylindrical part housing the actual sensor compartment (the white tubular part in Figure 1, white material is the dust filter) and interface box (Figure 1). There is a narrow wire leakthrough between the interface box and the sensor compartment and gas will ventilate through it. The interface box is not gas tight itself. The box was not present in the tests and therefore it is unknown how much it contributes to total time lag if anything.

## 5 MEDA-HS Observations and preliminary analyses

Volume mixing ratio (VMR) is defined and calculated by  $q = e/p$ , where  $e$  is water vapor pressure and  $p$  is ambient pressure. Ambient pressure is provided by the MEDA PS pressure sensor, and the value at the same time stamp as the humidity sensor value is used to calculate the VMR. If pressure data have not been available, VMR values have not been calculated. The number of these missing pressure-data gaps has been negligible. Water vapor saturation pressure is calculated using Buck-Ardenne equation (Buck, 1981), which is sufficiently accurate for our purposes (Savijärvi et al., 2015). Relative humidity (Rh) is expressed over ice,  $\%Rh = e/e_s \times 100\%$ , where  $e_s$  is water vapor saturation pressure over ice.

Seasonal development of nighttime humidity observations is presented in Figure 6 and Figure 7 shows diurnal values for sols 80-410 (Ls 44°-210°). Figure 6 shows nighttime volume mixing ratios (VMR) in HRIM mode per sol with expanded standard uncertainty (coverage factor  $k=2$ , 95% confidence interval) and max relative humidity val-

ues per sol for both the sensor and for the air stream. VMR values are calculated for Rh values above 2% (in the sensor). In practice, Rh is below 2% from half an hour to hour after sunrise to 21:00...24:00 LTST, depending of the sol and season (Figure 7). Max Rh in Figure 6 right is shown both for the sensor (the sensor output, relative humidity is referred to sensor temperature measured by a platinum Pt1000 termoresistor in the sensor) and for the environment in air stream. The latter value is calculated using MEDA-ATS air-temperature sensors. The ATS single-mast value represents an estimate for air temperature free of thermal contamination from the rover, remote-sensing mast (RSM) and RTG (Radioisotope Thermal Generator) power source. Depending of the wind speed and direction ATS sensors 1,2 and 3 located around the RSM at the same height 1.45 m feel different thermal contamination from rover's RTG. ATS Mast single value is calculated using the values of the ATS 1, 2 and 3. Practical nighttime approximation for the ATS Mast single value is the lowest value of the three ATS sensors which works for humidity sensor accuracy and time resolution. ATS 1...3 sensor values and ATS single mast value have been provided by MEDA-ATS team (Munguira et al. (2022) in this issue). ATS sensors react fast for turbulence. Moving average over 450 seconds was applied to ATS single mast values before calculating relative humidity. Rh errorbars are shown only for the sensor humidity values, it was not possible to calculate uncertainties for air stream humidity as ATS single value uncertainty is not available. We assume here that water vapor pressure is in the sensor (inside the dust filter) the same as in the air at about the same level from ground and calculate Rh in air directly  $Rh_{air} = e/e_s(T_{ATS}) \times 100\%$ , where  $e_s(T_{ATS})$  is water vapor saturation pressure over ice in air temperature  $T_{ATS}$  = ATS single value. Supporting Information Figures S1 and S2 show more details of seasonal VMR and diurnal cycles.

Rh values for air stream are significantly higher than the Rh sensor values. This is because the HS sensor temperature is few degrees higher than the ATS single mast value representing ATS remote sensing mast (RSM) temperature data with minimal thermal contamination from RTG. The MEDA-HS sensor receives conducted heat from the rover and RSM through mounting and electric wires. Also probably some radiated heat from the rover body and mast is received too. MEDA-HS is located above the ATS 2 sensor. ATS sensors 1...3 are 1.45 m from ground and MEDA-HS 1.50 m.

Seasonal changes from  $L_s=44^\circ$  to  $L_s=210^\circ$  are seen in both the relative humidity and volume mixing ratio time series. This is caused by the pulse of water vapor generated by evaporation from the Northern pole due to the heating by increased solar irradiation during Northern spring and summer. Airborne water vapor is deposited on the Northern polar cap during wintertime and released back to the atmosphere with seasonally increasing solar irradiation. This water pulse is detected by the MEDA-HS humidity observations a few sols earlier than by similar instrument REMS-H onboard Mars Science Laboratory (MSL) Curiosity rover due to the fact that Curiosity is located at a lower latitude ( $S 4.6^\circ$ ) than Perseverance ( $N 18.4^\circ$ ). MEDA-HS observed humidity peak is at around  $L_s=150^\circ$ . The Curiosity REMS-H instrument has seen this peak in close to  $L_s=160^\circ$  (this current Mars year  $MY=36$ ) (Figure 8). This peak humidity period was also covered by an increase of dust activity and the later dust storm from  $L_s=153^\circ$  to  $L_s=156^\circ$  (Lemmon et al., 2022).

Diurnal humidity cycles are shown in Figure 7. Relative humidity peaks near the coldest time of the night just before sunrise. During the daytime, the %Rh is below uncertainty of the sensor. The VMR slowly decreases during nighttime which is most likely caused by adsorption in the regolith (Savijärvi et al., 2019). The VMR nighttime trends for dry season and wet season are shown in the 9 right. The data also exhibits short-timescale (sub-hour) humidity fluctuations (Figure 9 left). They are too fast to be due to by adsorption/desorption by regolith but are rather caused by humidity advected through turbulence from above. The nighttime atmospheric humidity increases vertically and especially above the boundary layer there is reservoir of humid air (Savijärvi et al., 2019) that

401 can serve as a source of humidity for turbulence. The nighttime humidity fluctuations  
 402 are due to the wind capable of creating turbulence sufficient to bring humidity toward  
 403 lower altitudes. The great wind variability observed by Mars 2020 at night/early morn-  
 404 ing was consistent with an increase in mechanical turbulence caused by downslope con-  
 405 vergent flows on the crater floor (Viúdez-Moreiras, Lemmon, et al., 2022; Viúdez-Moreiras,  
 406 de la Torre, et al., 2022). Figure 10 shows continuous-mode observations of the nights  
 407 of sols 330/331 and 399/400. The changes of the humidity VMR levels at 01:50-02:20  
 408 LTST / sol 331 and 03:00-03:30 LTST / sol 400 are related to air temperature changes,  
 409 suggesting change in the wind direction (more thermal contamination from RTG is ob-  
 410 served by ATS sensors during those time periods). This turbulence in wind may also break  
 411 the nighttime boundary layer and bring humid air from there (Pla-García et al., 2020).  
 412 Figure 11 shows in detail temperature observations for the nights 330/331 and 399/400  
 413 including 40-m temperature provided by MEDA-TIRS sensor (Sebastián et al., 2021).  
 414 Temperature jump is visible in all the levels during the VMR level changes. This may  
 415 result from nocturnal downslope flow or from the peak of a nocturnal low level jet (Savijärvi  
 416 and Siili (1993), Chatain et al. (2021)).

417 Fluctuations are also shown in Figure 12 with HRIM observations. While the tem-  
 418 peratures are slowly declining and the Rh% is slowly increasing over the nighttime, no  
 419 average decline of absolute humidity level is visible in the VMR, actually a small increase  
 420 instead. Fluctuations seem to be related in turbulence shown by air temperature data  
 421 here too.

422 Both Figure 10 (left plot) and Figure 12 show an unexpected fall of VMR after sun-  
 423 rise when it is expected to be rising. Owing to heating of the surface and likely desorp-  
 424 tion of vapor, the VMR is expected to rise as the day warms, but because the relative  
 425 humidity drops below sensor’s sensitivity, this is not observed. This decrease in VMR  
 426 after dawn is seen in many sols (for example, in sols 319, 330, 334, 341, 342, 362). An  
 427 explanation for this “bending” VMR in dawn could be dry air advecting over the ter-  
 428 minator from the night side. More details shown in Supporting Information Figures S3  
 429 and S4.

430 Uncertainties of the MEDA-HS and -TIRS sensors were used to evaluate the prob-  
 431 ability for surface frosting conditions. Here we assume a well-mixed surface layer from  
 432 the ground to the 1.5-m sensor height so that the absolute humidity is vertically con-  
 433 stant. Surface temperature  $T_g$  observed by MEDA-TIRS ground temperature sensor has  
 434 fallen below the calculated frost point  $T_f$  on several nights (Figure 13).

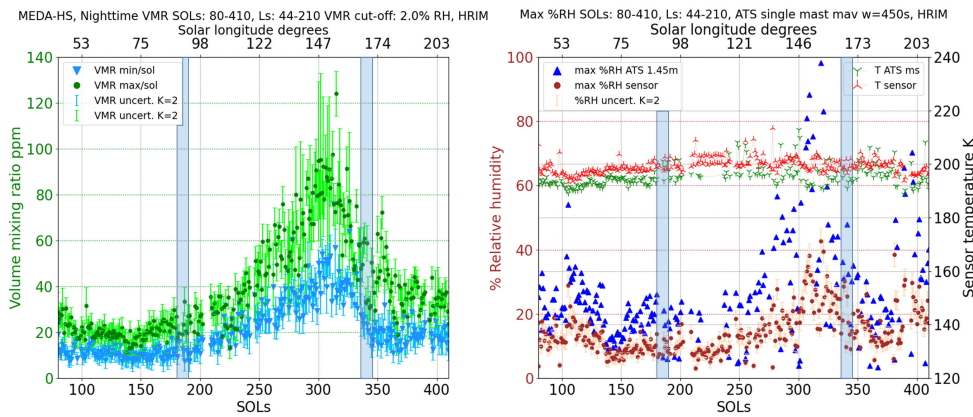
435 Most likely frost events have been in sols 381, 382 (Ls 192°), 398 (Ls 202°) and 402  
 436 (Ls 205°) where condition requirement  $T_g < T_f$  has been exceeded over confidence in-  
 437 terval 99.7%, coverage factor of standard uncertainty  $k=3$  filling  $T_g + ku(T_g) < T_f -$   
 438  $-ku(T_f)$ , where  $u(T_g)$  = standard uncertainty of ground temperature  $T_g$  and  $u(T_f)$  =  
 439 standard uncertainty of frost point  $T_f$  (Martínez et al., 2016). Likelihoods for frosting  
 440 conditions are presented in Figure 13 rightside plot.

441 Figure 14 shows nighttime evolution of  $T_f$  and  $T_g$  for sols where  $k > 2$  for pos-  
 442 sible frost events. Events have been close to coldest time of the night. Figure 15 shows  
 443 the MEDA-TIRS field of view of the terrain for sols where  $k > 2$  has been reached. In  
 444 each case, the terrain was composed of fine-grained material with low thermal inertia (Martínez  
 445 and et al (2022) this issue), which results in relatively colder nighttime temperatures.  
 446 Thus the most possible frost events have been caused by ground temperature being un-  
 447 usually low, not humidity being high.

## 448 6 Single Column Model comparison with measurements

449 Here the diurnal cycles of MEDA HS observations are shown for sols 138-148 (Ls  
 450 70°-74°, low VMR) and sols 290-300 (Ls 141°-146°, high VMR) together with results from



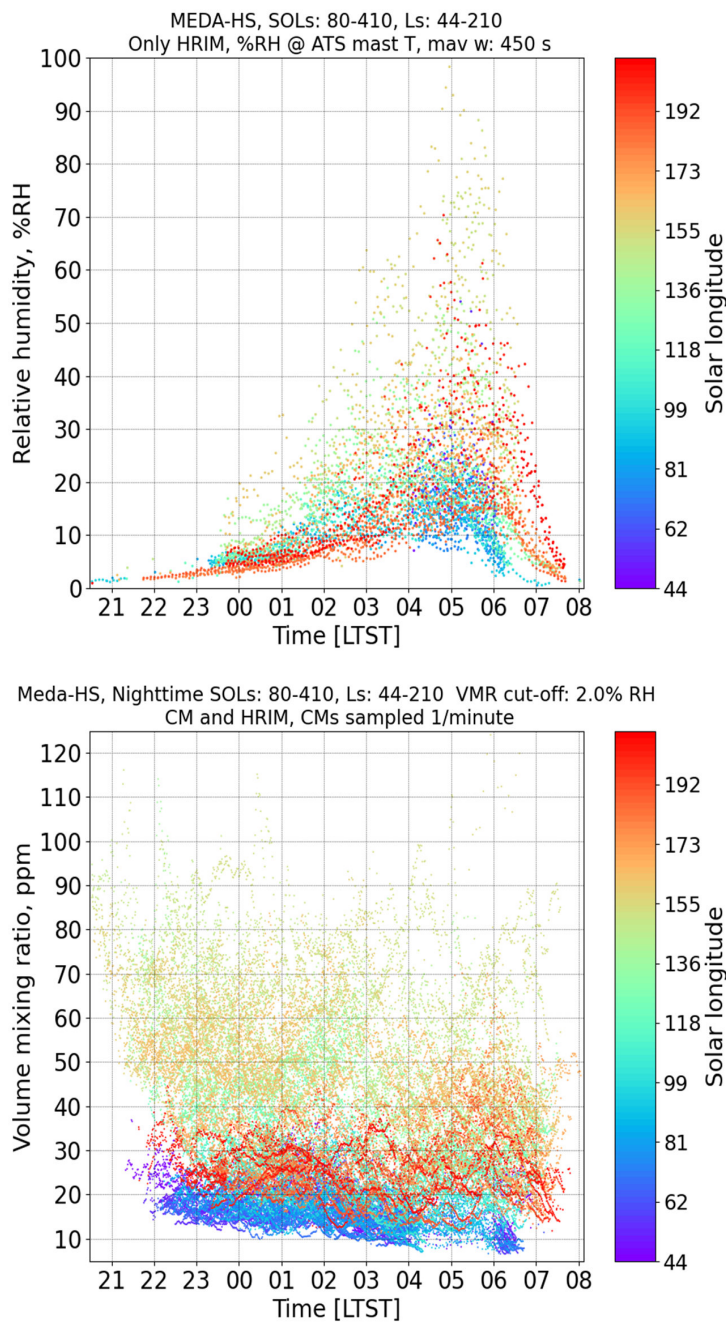


**Figure 6.** Nighttime volume mixing ratio max and min values per sol in the left, max %Rh values per sol in the right for sols 80 – 410 (Ls 44° - 210°). HRIM observations only are used here. Error bars show expanded standard uncertainty ( $k=2$ , confidence interval 95%). %Rh is shown both for the sensor (the output of the sensor) and the calculated %Rh for air stream using ATS air sensor values. "ATS ms" is "mast single value" representing RTG contamination free ATS sensor values in 1.45m level from ground. "T sensor" is HS sensor temperature, the temperatures are at the time of max Rh value. Nighttime here is typically from around 23:00 LTST up to 06:00-07:00, an hour or half after sunrise, the range when sensor output  $Rh > 2\%$ . Below 2% Rh relative uncertainty grows so that VMR can't be calculated reliably. Shaded bars show the compromised data after sensor regenerations in sols 180 and 335. Recovery time after regeneration takes few sols. It is recommended to avoid using the 10 sol data after recovery.

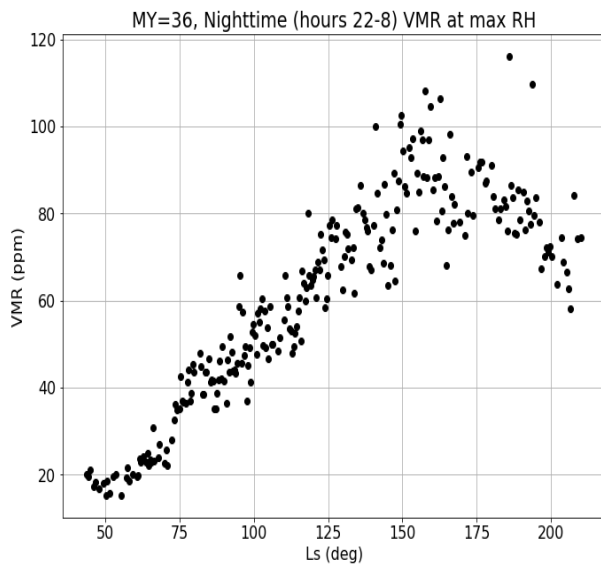
the UH/FMI adsorptive single-column model (SCM, Savijärvi et al. (2016), Savijärvi, Martinez, Harri, and Paton (2020), Savijärvi and Harri (2021), Savijärvi et al. (2022)).

During Ls 70°-74° in the aphelion period of very low moisture the rover was stationary with observed surface pressure of 750 hPa, dust opacity 0.4 and surface albedo 14%. TES Ls 60°-80° observations suggest precipitable water column (PWC) of about 5-6  $\mu\text{m}$  over Jezero (Steele et al., 2017). For well-mixed moisture the volume mixing ratio (VMR) is then about 70 ppm. These values initialized our SCM simulations for Ls 72° (sol 143). MEDA-TIRS ground temperature observations of this period suggest ground thermal inertia  $I$  of about 600 SI units, while Pla-García et al. (2020) used 260. Hence  $I$ -values of 300, 400 and 600 were tried. Figure 16 shows the resulting model-VMR curves. The dashed curve is a simulation without adsorption, where only diffusion to/from porous ground acts to slightly change the near-surface air-VMR from its daytime well-mixed value of 70 ppm. Porosity (air fraction of regolith) is here 25 % resulting in model-PWC staying around 5.3  $\mu\text{m}$  from sol to sol.

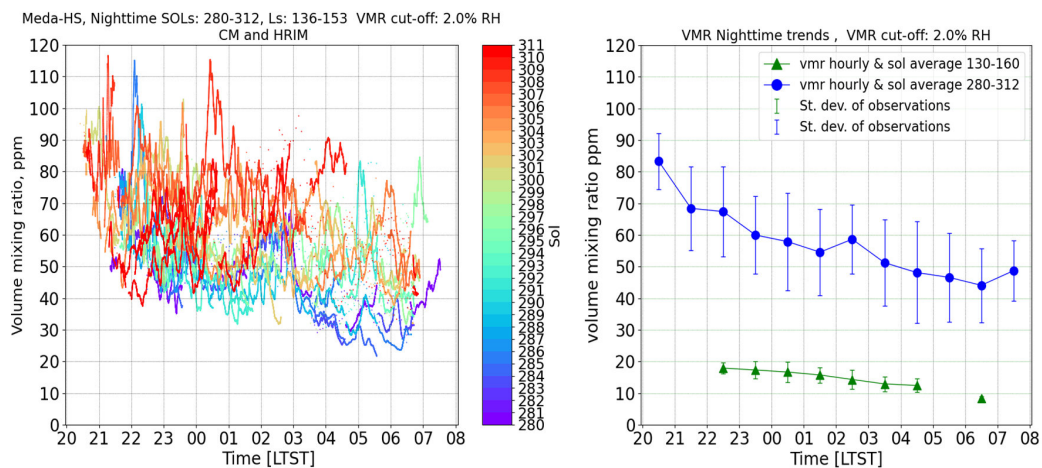
Figure 17 left displays for sols 138-148 the MEDA-HS humidity values at 1.5 m height and ATS mast single values for air temperature at 1.45m height together with the respective SCM curves, and also the SCM-predicted surface temperature and VMR. Rover's energy source RTG dissipates heat and this may occasionally disturb the ATS sensors. We see this effect from 22:00 – 00:00 LMST, the ATS mast single value dropping suddenly after midnight. Rover's stern with RTG was pointing the west and wind has been from west so that the heated plume hit directly RSM with ATS sensors. At midnight small changes in wind direction and speed removed this thermal contamination from the ATS sensors and their values dropped. This effect is also visible in relative humidity values, which are referred here to the ATS mast single values. The best model fit to observed



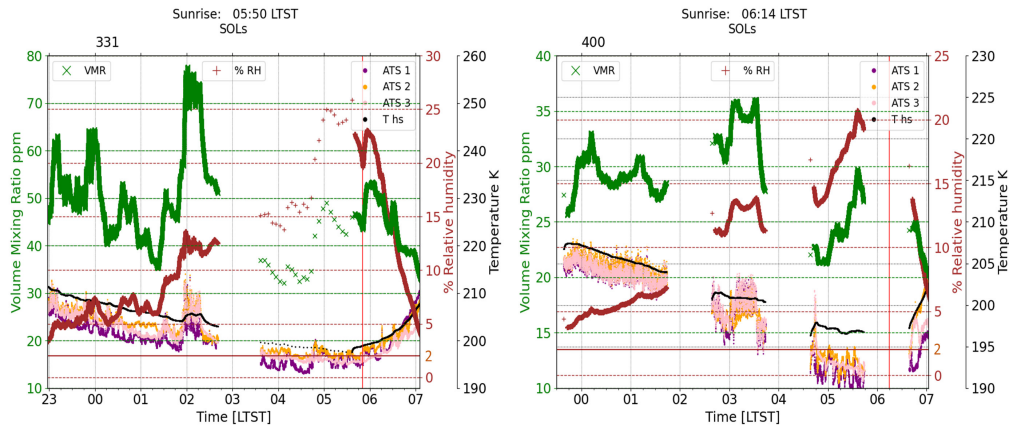
**Figure 7.** Upper: Nighttime relative humidity calculated for air stream (referenced to ATS mast single value temperature), Lower: Nighttime volume mixing ratios, for sols 80-410, Ls 44°-210°. Peak 100% Rh value was achieved at Sol 319, Ls 157°



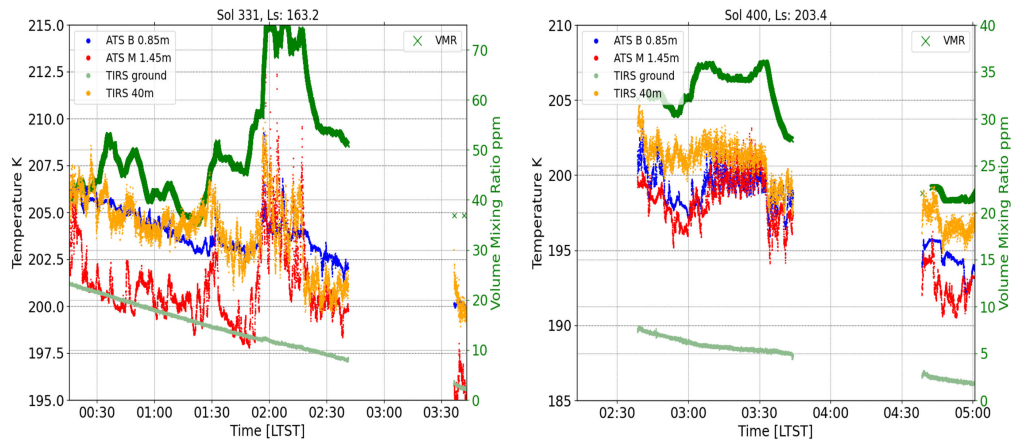
**Figure 8.** Mars Science Laboratory Curiosity relative humidity sensor REMS-H VMR time serie for Ls 44°- 210°. Seasonal humidity peak is around Ls 160°.



**Figure 9.** In the left: Short timescale humidity fluctuations in detail in the sols 280-312, Ls 136°-153°. In the right: VMR hourly averaged values over period of sols show nighttime trends for the dry season (sols 130-160, Ls 66°-80°, green) and the wet season (sols 280-312, blue). Errorbars show standard deviation of the observed values in the hour slice. Sunrises are in the sol 145, Ls 73° at 05:25 LTST and in the sol 296, Ls 144° 05:39 LTST. Continuous mode observations were used to calculate hourly averages. Gap in the sols 130-160 data in the 05-06 LTST hour slice is because of missing CM mode observations

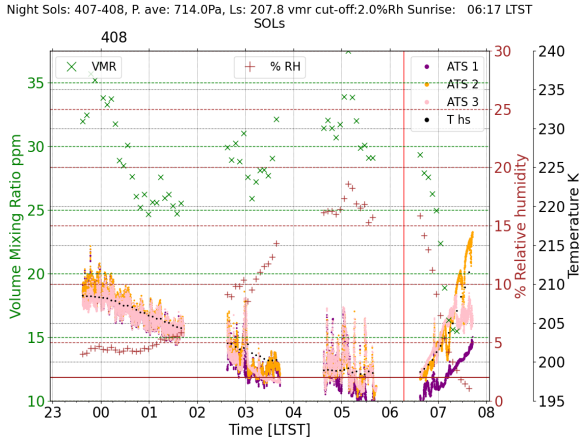


**Figure 10.** Typical short-term humidity fluctuations shown in sol 331 (Ls 163°) and sol 400 (Ls 203°). Red vertical line shows sunrise time. Rh shown here (%RH, brown) is at the HS sensor referred to HS temperature sensor (T hs, black), all three of the remote-sensing mast ATS sensors 1-3 are shown. In the left plot, 01:50 turbulence seen in the ATS data indicates a wind change, which brings more humid air. HS sensor T sensor warms up, too, but humidity pulse is strong enough to keep also Rh up. On the right, there is similar event from 03:00-03:45

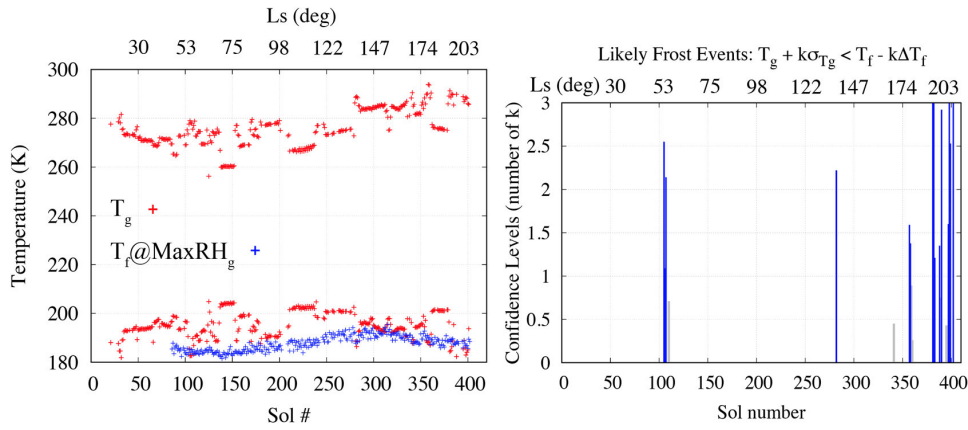


**Figure 11.** Turbulence in temperature data in more detail for early morning night events sol 331 and 400. In the left plot, at LTST 01:50...02:20 and in the right plot LTST 03:00...03:45, also the 40 m level temperature (TIRS 40m provided by MEDA-TIRS sensor) reacts as well as other levels. ATS M 1.45m is ATS single value at mast sensor level and ATS B 0.85m is single value representing ATS sensors 4 and 5 located at the front of rover body. TIRS ground is surface T provided by TIRS.



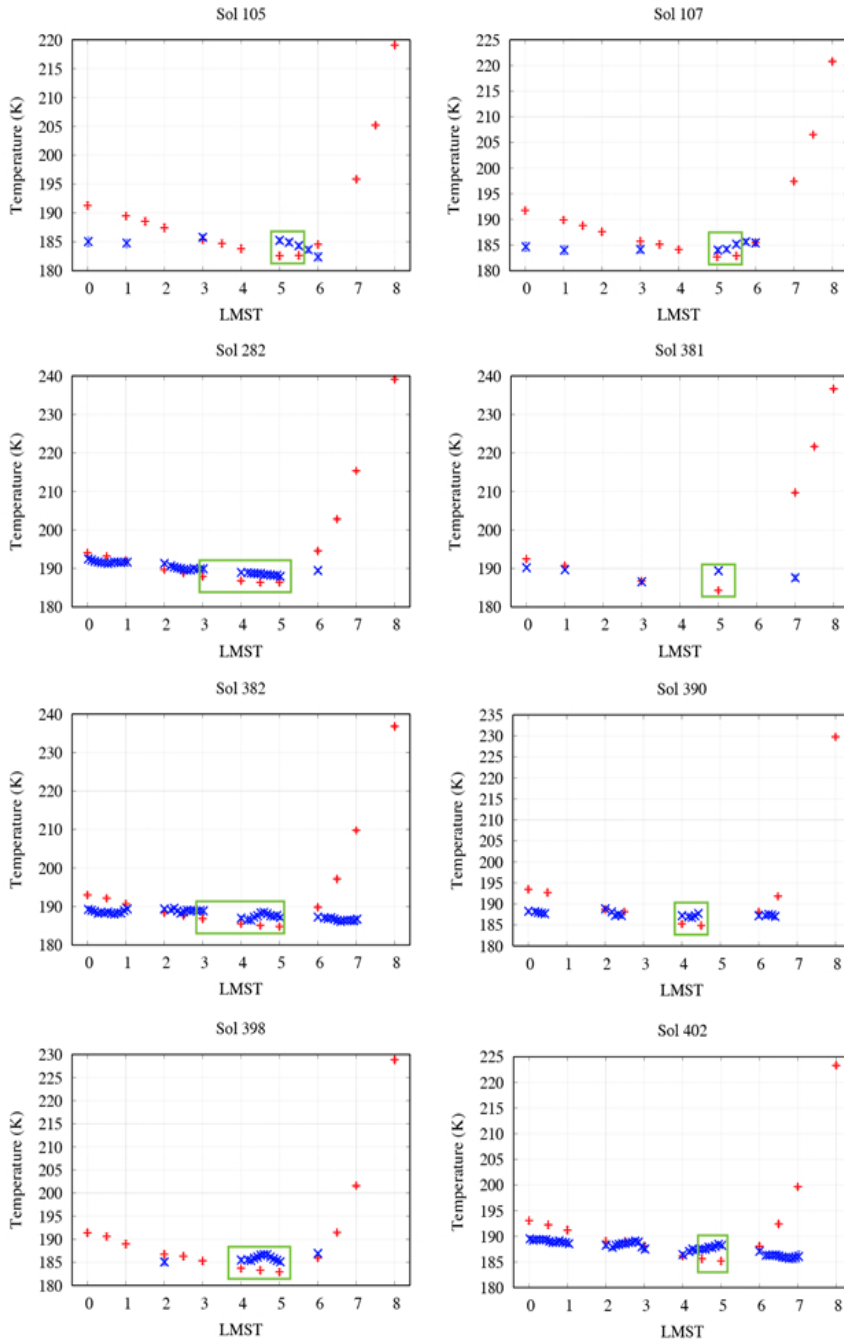


**Figure 12.** Typical short-term humidity fluctuations shown in sol 408 (Ls 208°) using HRIM mode data. Red vertical line shows sunrise time. Rh and ATS like in the Figure 10

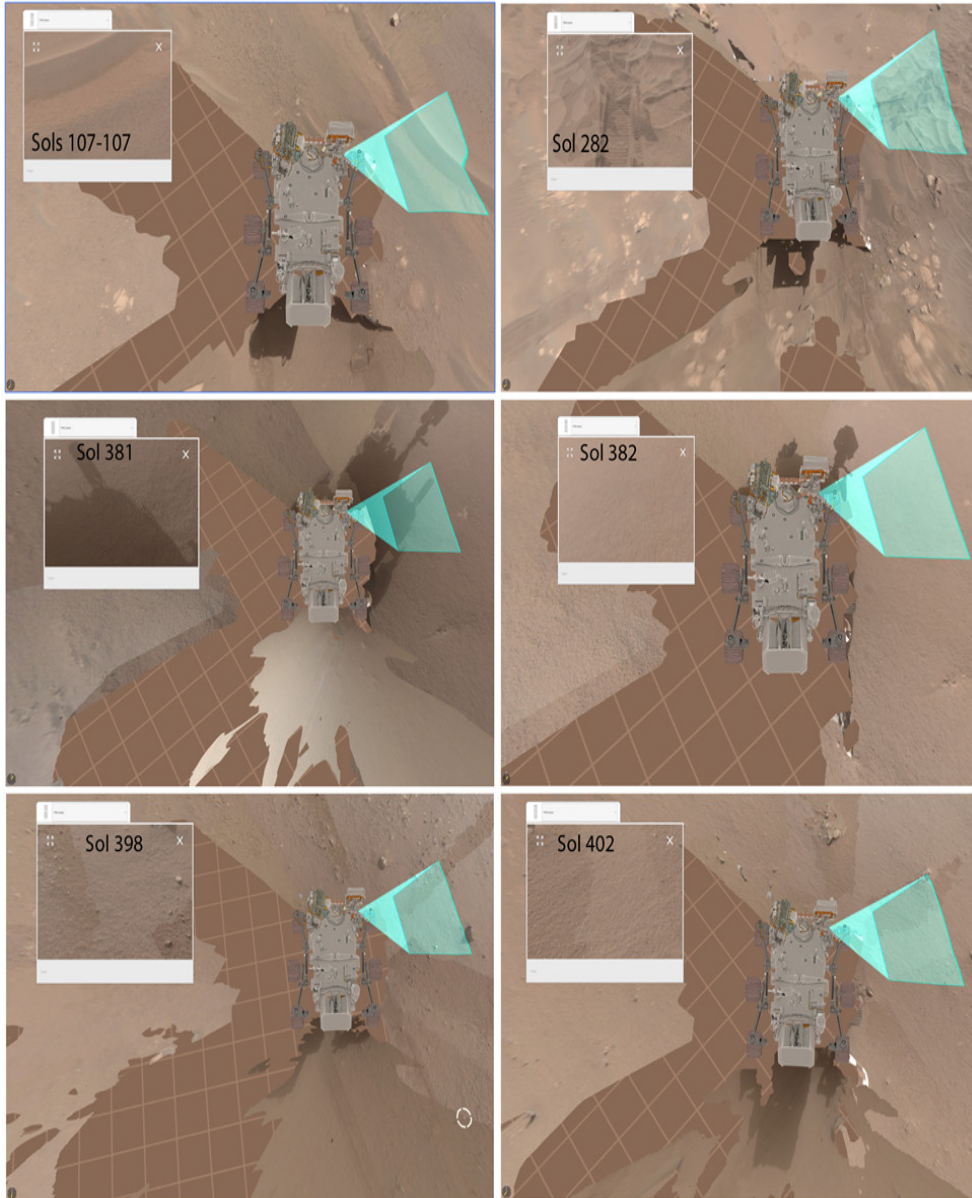


**Figure 13.** Daily maximum and minimum ground temperature (red) and frost point temperature when the Rh at the ground is maximum (blue) as a function of sol number and Ls during the first 410 sols of the M2020 mission. Potential frost events are identified when  $T_g < T_f$ . (Right) Likelihood of potential frost events represented by the number (coverage factor  $k$ ) of standard uncertainty in  $T_g$  and uncertainty in  $T_f$  for which the relation  $T_g + ku(T_g) < T_f - ku(T_f)$  is met.

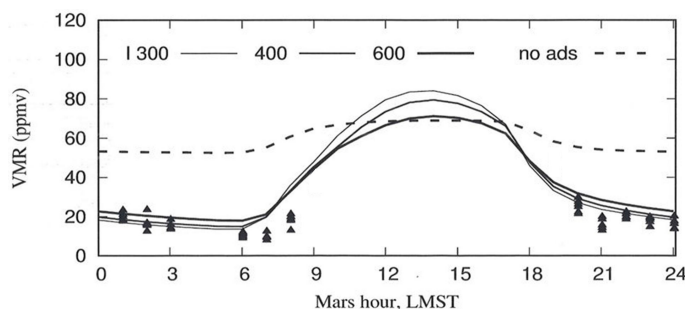




**Figure 14.** Nighttime evolution of ground temperature (red) and frost point temperature (blue) in sols when the likelihood of frost events is high ( $k > 1$ ). In these sols,  $T_g < T_f$  between 03:00 and 06:00 LMST, corresponding to the coldest time of the sol.



**Figure 15.** MEDA/TIRS field of view of the terrain in sols when the likelihood of frost events is high ( $k > 1$  in Figure 13). In each case, the terrain was composed of fine-grained material with low thermal inertia (Martínez et al., 2022, this issue), which results in relatively colder nighttime temperatures.



**Figure 16.** Tuning SCM parameters with different thermal inertias 300, 400, 600 for the sol 143. Dashed line show no adsorption case. Triangle dots are VMR hourly observations by MEDA-HS for sols 138-148.

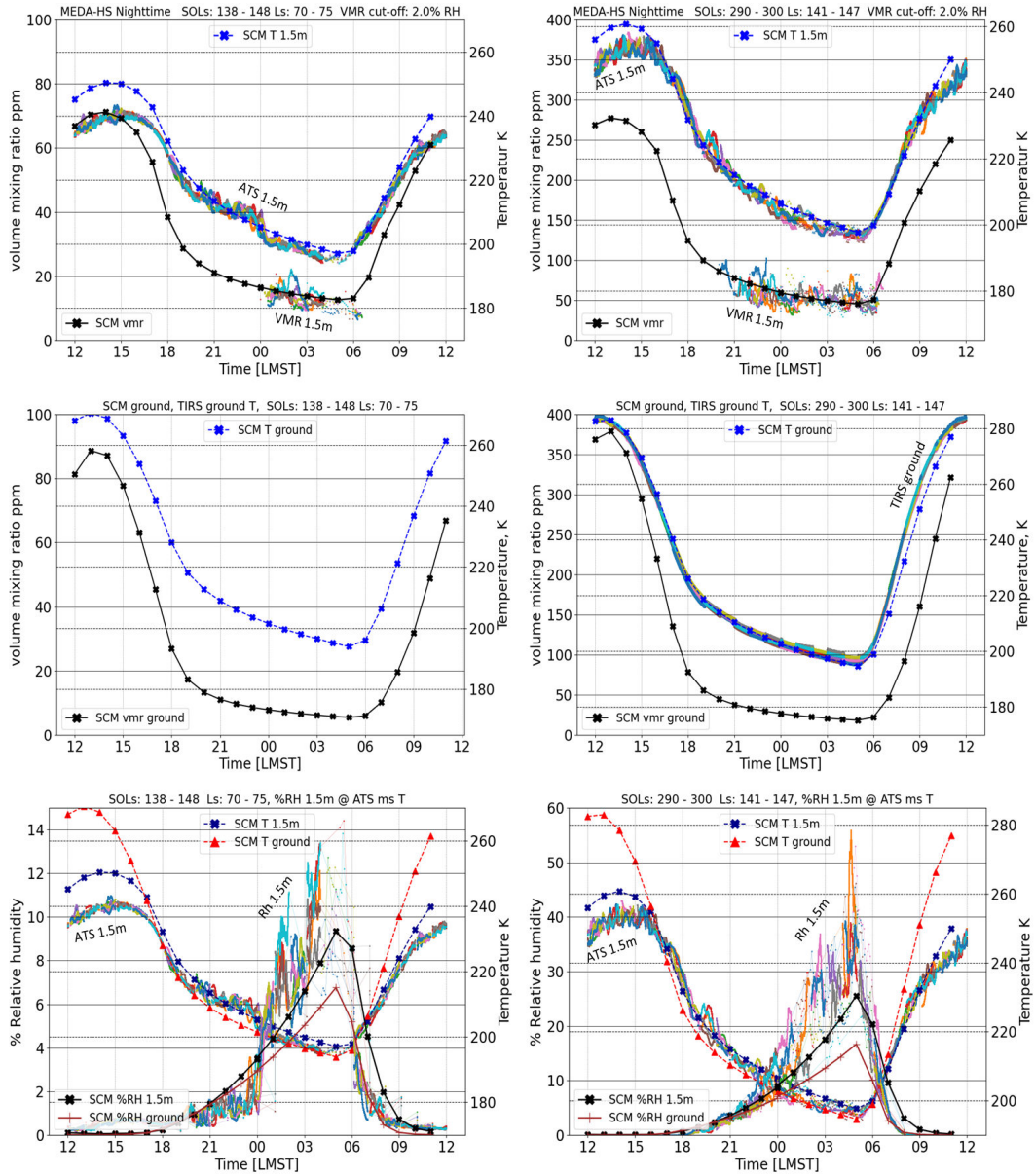
Rh is obtained with  $I = 350$  SI units. The minimum VMR around sunrise is here only about 15 ppm, which fits to the MEDA-HS observations. Maximum daytime model-VMR is slightly above 70 ppm, which fits to the TES PWC of 5-6  $\mu$  m. Thus with adsorption the model results become quite close to the MEDA-derived very low nighttime VMR during this period.

For the humid period at Ls 141°-146° (sol 295 nominal), the CRISM mean value of 14.4  $\mu$  m PWC of the season over Jezero (M. D. Smith et al., 2018) was used for initialization. Observed surface pressure was here 626 Pa, dust opacity 0.5 and albedo 12%. With thermal inertia of 320 SI units and porosity of 25% the SCM results then fit here well to the observed air and ground temperatures and to the high air moistures (Fig. 17, right), conserving the well-mixed daytime VMR at 270 ppm and PWC at 14.4  $\mu$  m from sol to sol with VMR dropping to 50 ppm at each sunrise. Model output at 1.5m and ground level can then be used for estimating ground level relative humidities and VMR from the 1.5 m observations, assuming the same proportional relation as the model respectively had.

The model results (Figs. 16, 17) hence indicate that adsorption/desorption is here the main reason for the diurnal water exchange between atmosphere and regolith, suggesting enthalpy of about 22 kJ/mol for the process (independently of the mineralogy, Savijärvi and Harri (2021)) with porosity of regolith being about 25% at the two sites.

## 7 Conclusions and discussion

The MEDA-HS relative humidity sensor on board the M2020 Perseverance rover has produced in situ relative humidity observations useful from the sol 80 (Ls 44°) onwards. Two observational modes have been used, pointwise measurements, High resolution Interval mode (HRIM) has been taken once per 15min or 5 min while continuous mode observations (CM) provide readings once per second. Time lag of the sensor is estimated to be order of few minutes in nighttime temperatures. HRIM mode offers better accuracy than CM mode. Exact difference between the modes will be studied further later. Sensor output is used to calculate derived volume mixing ratio VMR when relative humidity of the sensor is above 2%, when below, VMR values become too inaccurate. VMR values are available thus for nighttime only, from around 22:00 LTST to few tens of minutes after sunrise. Peak relative humidity is reached around the coldest time of the night which is usually just before sunrise. At daytime relative humidity is below resolution of the sensor. MEDA-HS temperature is few degrees higher than air temperature at the same level from the ground, thus if relative humidity value is used, it should be transferred to air temperature using MEDA-ATS air temperature sensors.



**Figure 17.** SCM results compared to observations. Left: Sol 143 model compared to sols 138-148. Right: Sol 295 model compared to sols 290-300. Upper: HS and ATS observations at 1.5m level compared to SCM at 1.5m. Middle: SCM VMR and ground T compared to MEDA TIRS ground temperature observations. In the sol 138-148 range TIRS ground sensor was pointing to a spot which was not representative for the area and produced too high readings, so they are not shown. Lower: SCM Rh and SCM T at 1.5m and ground level shown together with 1.5m HS and ATS observations. 600 second moving average was applied to ATS values.



510 Initial results from the sols 80 – 410 (Ls 44° - 210°) show how seasonal water va-  
511 por pulse is released from northern ice cap reaching peak at Ls 150°. The highest recorded  
512 nighttime VMR value was 120 ppm at sol 315 (Ls 154°) and peak Rh value was 100%  
513 (referenced to ATS air temperature at 1.45m level) at sol 319 (Ls 157°). These values  
514 were single peaks at isolated sols while the seasonal peak appears to have been few sols  
515 earlier. Pointing exact sol and peak values depends on whether CM mode measurements  
516 are included. It's not likely this difference depends of possible calibration level difference  
517 between HRIM and CM mode, but rather availability of measurements and operational  
518 cadences which alternate from time to time. There have been more CM mode observa-  
519 tions at early night hours.

520 Nighttime observations show large short time scale (sub hour) humidity fluctua-  
521 tions. VMR levels show slowly declining level at night average over several sols , but there  
522 are large variations. On some single sols, VMR level may be even at higher level just be-  
523 fore sunrise than early night hours. Fluctuations are most likely caused by humid air en-  
524 tering from above the rover or even from above boundary layer because of turbulences.  
525 The level changes often coincide with strong turbulence seen in ATS air temperature data.

526 Frost point may have been reached on ground on few sols between Ls 192° and 205°,  
527 assuming constant volume mixing ratio profile from the sensor level to ground.

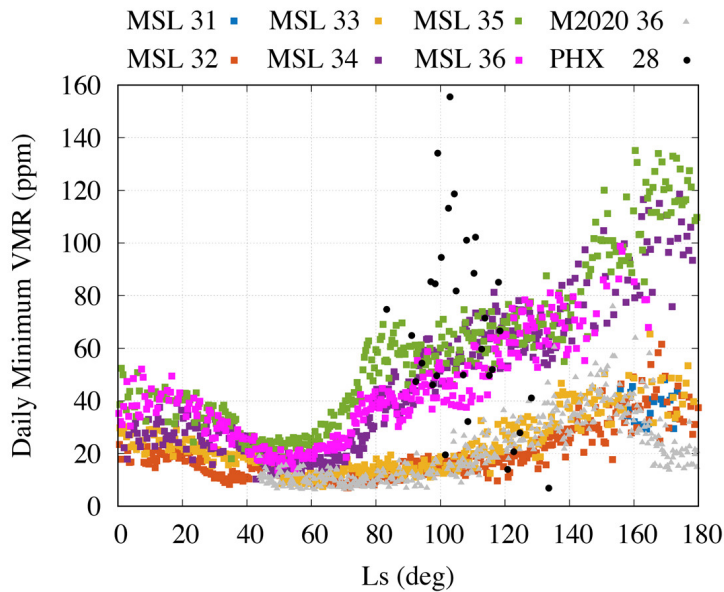
528 Adsorptive single column model was tested and compared with the MEDA-HS ob-  
529 servations for two cases, sol 143 (dry season) and sol 295 (humid season). Good model  
530 fits to observed nighttime T, Rh and the derived VMR were obtained assuming adsorp-  
531 tion. The observation-based VMR indicates strong nighttime adsorption of water vapor  
532 into soil. The SCM model can be used for estimating surface humidity by transferring  
533 observations at 1.5 m to ground level. The model is also able to include underground  
534 humidity as water vapour in airspaces of the porous ground.

535 The Mars Science Laboratory (MSL), Phoenix (PHX) and M2020 Perseverance hu-  
536 midity observations are compared in the Figure 18. The daily VMR minimum typically  
537 occurs between 03:00 and 06:00 LMST at MSL and M2020, and between 02:00 and  
538 04:00 LMST at PHX. Interestingly, VMR values in Martian Year (MY) 36 at MSL (ma-  
539 genta) are higher than at M2020 (gray), despite column abundances of water vapor be-  
540 ing larger at M2020 than at MSL. At PHX (black), VMR values peaked around Ls 105°  
541 when column abundances were largest due to the sublimation of the northern polar cap.  
542 Then, VMR values rapidly decreased when temperatures dropped and water vapor was  
543 deposited on the surface (Martínez et al. (2017); Fischer et al. (2019)).

544 Liquid water is a requirement for life as we know it on Earth, which is why its abun-  
545 dance and distribution on Mars are key metrics with regard to characterizing the hab-  
546 itability potential of Mars, past and present. Measurements that facilitate an understand-  
547 ing of the present hydrologic cycle at the surface of Mars in Jezero Crater likely provide  
548 a glimpse of the lower limit of water abundance, near the surface and potentially avail-  
549 able to the shallow subsurface (to perhaps a few mm). If water is transferred to the sur-  
550 face as our nocturnal volume mixing ratios suggest, the adsorbed water could be avail-  
551 able to hydrate a shallow subsurface cryptoendolithic habitat, if one exists. Such a habi-  
552 tat, a community of organisms living in the pore spaces of rock, can be observed in sand-  
553 stones in the McMurdo Dry Valleys of Antarctica on Earth (Imre Friedmann, 1982). If  
554 the current water cycle is a historic lower bound on the amount of water transferable to  
555 the surface material, possible past microbial life that required more water may have left  
556 chemical biosignatures in the coarser grained rocks. Such putative life may have adapted  
557 to an environment that could provide some protection from desiccation and radiation  
558 as the surface of Mars grew more arid.

559 On Earth, rock dwelling consortia of organisms may contain different species than  
560 soil dwelling organisms proximal to the rock, e.g. Young et al. (2008). As Choe et al.





**Figure 18.** Comparison of MSL, Phoenix (PHX) and M2020 Perseverance in-situ humidity observations. Number after mission refers to Martian Year

561 (2021) and others have observed, climate is a dominant factor in the diversity of both  
 562 types of communities, and in particular, relative humidity and precipitation (e.g., Böhm  
 563 et al. (2020); CáCeres et al. (2007)). Desiccation resistant organisms have been well stud-  
 564 ied in both hot and cold deserts on Earth in search of suitable Mars analog environments  
 565 from which to model microbial survival strategies for an environment as water poor as  
 566 the present martian surface. What we know from the most arid environment on Earth,  
 567 the Atacama Desert of Chile, is that even in this most arid of environments, various micro-  
 568 organisms have adapted to these conditions. Navarro-González et al. (2003) have iden-  
 569 tified the Atacama Desert’s Yungay region as a good martian analog because it is near  
 570 the dry limit of life. Azua-Bustos et al. (2015) described another site, Maria Elena South  
 571 (MES), that is even drier than Yungay. Interestingly the mean Rh of the soil at a depth  
 572 of 1m is 14%, even when atmospheric Rh drops to 0 during diurnal cycles. This is as-  
 573 sociated with no decrease in microbial diversity at this depth relative to the diversity at  
 574 the surface, which enjoys a mean value of 27.5 %. Thus the driest environment on Earth  
 575 supports microbial communities with a mean soil Rh of 14%. Our measurements would  
 576 suggest a mechanism for attaining sufficient hydration to speculate that a refugium en-  
 577 vironment could have been supported even with present levels of water exchange with  
 578 the martian surface and be consistent with the most hyper arid conditions we can iden-  
 579 tify on Earth.

## 580 8 Data Availability and Open Research

581 Observation data used for this work is available in Planetary Data System Atmo-  
 582 spheres node (Rodriguez-Manfredi & de la Torre Juarez, 2021). Derived data and SCM  
 583 model data are available in the Finnish Meteorological Institute repository archive (Polkko,  
 584 2022). Mars Science Laboratory REMS-H instrument data used for comparison is avail-  
 585 able in Planetary Data System Atmospheres node (Gomez-Elvira, 2013).

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## References

- Aoki, S., Vandaele, A. C., Daerden, F., Villanueva, G. L., Liuzzi, G., Thomas, I. R., ... Lopez-Moreno, J. J. (2019, December). Water Vapor Vertical Profiles on Mars in Dust Storms Observed by TGO/NOMAD. *Journal of Geophysical Research (Planets)*, *124*(12), 3482-3497. doi: 10.1029/2019JE006109
- Azua-Bustos, A., Caro-Lara, L., & Vicua, R. (2015). Discovery and microbial content of the driest site of the hyperarid atacama desert, chile. *Environmental Microbiology Reports*, *7*(3), 388-394. Retrieved from <https://sfamjournals.onlinelibrary.wiley.com/doi/abs/10.1111/1758-2229.12261> doi: <https://doi.org/10.1111/1758-2229.12261>
- Banfield, D., et al. (Eds.). (2020). *Mepag (2020), mars scientific goals, objectives, investigations, and priorities: 2020* (White Paper). (white paper posted March, 2020 by the Mars Exploration Program Analysis Group (MEPAG) at <https://mepag.jpl.nasa.gov/reports.cfm>)
- Böhm, C., Reyers, M., Schween, J. H., & Crewell, S. (2020, July). Water vapor variability in the Atacama Desert during the 20th century. *Global and Planetary Change*, *190*, 103192. doi: 10.1016/j.gloplacha.2020.103192
- Buck, A. L. (1981, December). New Equations for Computing Vapor Pressure and Enhancement Factor. *Journal of Applied Meteorology*, *20*(12), 1527-1532. doi: 10.1175/1520-0450(1981)020<textless{}1527:NEFCVP<textgreater{}2.0.CO;2
- CáCeres, L., Gómez-Silva, B., Garró, X., Rodríguez, V., Monardes, V., & McKay, C. P. (2007, December). Relative humidity patterns and fog water precipitation in the Atacama Desert and biological implications. *Journal of Geophysical Research (Biogeosciences)*, *112*(G4), G04S14. doi: 10.1029/2006JG000344
- Chatain, A., Spiga, A., Banfield, D., Forget, F., & Murdoch, N. (2021, November). Seasonal Variability of the Daytime and Nighttime Atmospheric Turbulence Experienced by InSight on Mars. *grl*, *48*(22), e95453. doi: 10.1029/2021GL095453
- Choe, Y.-H., Kim, M., & Lee, Y. K. (2021). Distinct microbial communities in adjacent rock and soil substrates on a high arctic polar desert. *Frontiers in Microbiology*, *11*. Retrieved from <https://www.frontiersin.org/article/10.3389/fmicb.2020.607396> doi: 10.3389/fmicb.2020.607396
- Christensen, P. R., Anderson, D. L., Chase, S. C., Clark, R. N., Kieffer, H. H., Malin, M. C., ... Silverman, S. (1992, May). Thermal Emission Spectrometer Experiment: Mars Observer Mission. *Journal of Geophysical Research*, *97*(E5), 7719-7734. doi: 10.1029/92JE00453
- Clancy, R. T., Grossman, A. W., & Muhleman, D. O. (1992, November). Mapping Mars water vapor with the very large array. *Icarus*, *100*(1), 48-59. doi: 10.1016/0019-1035(92)90017-2
- Clancy, R. T., Grossman, A. W., Wolff, M. J., James, P. B., Rudy, D. J., Billawala, Y. N., ... Muhleman, D. O. (1996, July). Water Vapor Saturation at Low

- 639 Altitudes around Mars Aphelion: A Key to Mars Climate? *Icarus*, 122(1),  
640 36-62. doi: 10.1006/icar.1996.0108
- 641 Conrath, B., Curran, R., Hanel, R., Kunde, V., Maguire, W., Pearl, J., ... Burke,  
642 T. (1973, January). Atmospheric and Surface Properties of Mars Obtained by  
643 Infrared Spectroscopy on Mariner 9. *Journal of Geophysical Research*, 78(20),  
644 4267-4278. doi: 10.1029/JB078i020p04267
- 645 Encrenaz, T., Lellouch, E., Cernicharo, J., Paubert, G., & Gulkis, S. (1995, Jan-  
646 uary). A Tentative Detection of the 183-GHz Water Vapor Line in the Martian  
647 Atmosphere: Constraints upon the H<sub>2</sub>O Abundance and Vertical Distribution.  
648 *Icarus*, 113(1), 110-118. doi: 10.1006/icar.1995.1009
- 649 Encrenaz, T., Lellouch, E., Paubert, G., & Gulkis, S. (2001, June). The wa-  
650 ter vapor vertical distribution on mars from millimeter transitions of  
651 HDO and H<sub>2</sub><sup>18</sup>O. *Planetary and Space Science*, 49(7), 731-741. doi:  
652 10.1016/S0032-0633(01)00009-5
- 653 Encrenaz, T., Melchiorri, R., Fouchet, T., Drossart, P., Lellouch, E., Gondet, B.,  
654 ... Forget, F. (2005, October). A mapping of martian water sublimation  
655 during early northern summer using OMEGA/Mars Express. *Astronomy and*  
656 *Astrophysics*, 441(3), L9-L12. doi: 10.1051/0004-6361:200500171
- 657 Farmer, C. B., Davies, D. W., Holland, A. L., Laporte, D. D., & Doms, P. E. (1977,  
658 September). Mars: Water vapor observations from the Viking orbiters. *JGR*,  
659 82(B28), 4225-4248. doi: 10.1029/JS082i028p04225
- 660 Fedorova, A., Korablev, O., Bertaux, J.-L., Rodin, A., Kiselev, A., & Perrier, S.  
661 (2006, September). Mars water vapor abundance from SPICAM IR spectrom-  
662 eter: Seasonal and geographic distributions. *Journal of Geophysical Research*  
663 (*Planets*), 111(E9), E09S08. doi: 10.1029/2006JE002695
- 664 Fedorova, A., Montmessin, F., Korablev, O., Lefèvre, F., Trokhimovskiy, A., &  
665 Bertaux, J.-L. (2021, January). Multi-Annual Monitoring of the Water Va-  
666 por Vertical Distribution on Mars by SPICAM on Mars Express. *Journal of*  
667 *Geophysical Research (Planets)*, 126(1), e06616. doi: 10.1029/2020JE006616
- 668 Fedorova, A., Rodin, A. V., & Baklanova, I. V. (2004, September). MAWD obser-  
669 vations revisited: seasonal behavior of water vapor in the martian atmosphere.  
670 *Icarus*, 171(1), 54-67. doi: 10.1016/j.icarus.2004.04.017
- 671 Fischer, E., Martínez, G. M., Rennó, N. O., Tamppari, L. K., & Zent, A. P. (2019,  
672 November). Relative Humidity on Mars: New Results From the Phoenix  
673 TECP Sensor. *Journal of Geophysical Research (Planets)*, 124(11), 2780-2792.  
674 doi: 10.1029/2019JE006080
- 675 Fouchet, T., Lellouch, E., Ignatiev, N. I., Forget, F., Titov, D. V., Tschimmel,  
676 M., ... Encrenaz, T. (2007, September). Martian water vapor: Mars  
677 Express PFS/LW observations. *Icarus*, 190(1), 32-49. doi: 10.1016/  
678 j.icarus.2007.03.003
- 679 Gómez-Elvira, J., Armiens, C., Castañer, L., Domínguez, M., Genzer, M., Gómez,  
680 F., ... Martín-Torres, J. (2012, August). REMS: The Environmental Sensor  
681 Suite for the Mars Science Laboratory Rover. *Space Science Reviews*, 170(1-4),  
682 583-640. doi: 10.1007/s11214-012-9921-1
- 683 Gomez-Elvira, J. (2013). *Mars science laboratory rover environmental monitor-*  
684 *ing station edr data v1.0, msl-m-rem-s-2-edr-v1.0, nasa planetary data system,*  
685 *2013*. [dataset]. NASA. Retrieved from <https://doi.org/10.17189/1523032>  
686 doi: 10.17189/1523032
- 687 Harri, A. M., & et al. (2022). Initial results of the atmospheric pressure observa-  
688 tions onboard the Mars 2020 Perseverance Rover. *Journal of Geophysical Re-*  
689 *search (Planets)*. (in this issue)
- 690 Harri, A. M., Genzer, M., Kempainen, O., Gomez-Elvira, J., Haberle, R., Polkko, J.,  
691 ... Urqui, R. (2014, September). Mars Science Laboratory relative humid-  
692 ity observations: Initial results. *Journal of Geophysical Research (Planets)*,  
693 119(9), 2132-2147. doi: 10.1002/2013JE004514

- 694 Heavens, N. G., Kleinböhl, A., Chaffin, M. S., Halekas, J. S., Kass, D. M., Hayne,  
695 P. O., ... Schofield, J. T. (2018, February). Hydrogen escape from Mars en-  
696 hanced by deep convection in dust storms. *Nature Astronomy*, *2*, 126-132. doi:  
697 10.1038/s41550-017-0353-4
- 698 Hieta, M., Genzer, M., Polkko, J., Jaakonaho, I., Tabandeh, S., Lorek, A., ... Ro-  
699 driguez Manfredi, J. A. (2022, November). MEDA HS: Relative humidity  
700 sensor for the Mars 2020 Perseverance rover. *Planetary and Space Science*,  
701 *223*, 105590. doi: 10.1016/j.pss.2022.105590
- 702 Imre Friedmann, E. (1982, February). Endolithic Microorganisms in the Antarc-  
703 tic Cold Desert. *Science*, *215*(4536), 1045-1053. doi: 10.1126/science.215.4536  
704 .1045
- 705 Jakosky, B. M. (1985, June). The Seasonal Cycle of Water on Mars. *Space Science*  
706 *Review*, *41*(1-2), 131-200. doi: 10.1007/BF00241348
- 707 Jakosky, B. M., & Farmer, C. B. (1982, April). The seasonal and global behavior  
708 of water vapor in the Mars atmosphere - Complete global results of the Viking  
709 atmospheric water detector experiment. *Journal of Geophysical Research*, *87*,  
710 2999-3019. doi: 10.1029/JB087iB04p02999
- 711 Jakosky, B. M., & Haberle, R. M. (1992). The seasonal behavior of water on Mars.  
712 In M. George (Ed.), *Mars* (p. 969-1016).
- 713 Jakosky, B. M., Zent, A. P., & Zurek, R. W. (1997, November). The Mars Water  
714 Cycle: Determining the Role of Exchange with the Regolith. *Icarus*, *130*(1),  
715 87-95. doi: 10.1006/icar.1997.5799
- 716 JCGM. (2008). Evaluation of measurement data Guide to the expres-  
717 sion of uncertainty in measurement, JCGM 100:2008 [Computer soft-  
718 ware manual]. Pavillon de Breteuil, F-92312 Svres CEDEX, France.  
719 (<https://www.bipm.org/en/publications/guides>)
- 720 Lemmon, M. T., Smith, M. D., Viudez-Moreiras, D., de la Torre-Juarez, M.,  
721 Vicente-Retortillo, A., Munguira, A., ... Apestigue, V. (2022, September).  
722 Dust, Sand, and Winds Within an Active Martian Storm in Jezero Crater.  
723 *Geophysical Research Letters*, *49*(17), e00126. doi: 10.1029/2022GL100126
- 724 Maltagliati, L., Montmessin, F., Fedorova, A., Korablev, O., Forget, F., & Bertaux,  
725 J. L. (2011, September). Evidence of Water Vapor in Excess of Sat-  
726 uration in the Atmosphere of Mars. *Science*, *333*(6051), 1868. doi:  
727 10.1126/science.1207957
- 728 Mangold, N., Gupta, S., Gasnault, O., Dromart, G., Tarnas, J. D., Sholes, S. F.,  
729 ... Williford, K. H. (2021, November). Perseverance rover reveals an an-  
730 cient delta-lake system and flood deposits at Jezero crater, Mars. *Science*,  
731 *374*(6568), 711-717. doi: 10.1126/science.abl4051
- 732 Martín-Torres, F. J., Zorzano, M.-P., Valentín-Serrano, P., Harri, A.-M., Genzer, M.,  
733 Kemppinen, O., ... Vaniman, D. (2015, May). Transient liquid water and  
734 water activity at Gale crater on Mars. *Nature Geoscience*, *8*(5), 357-361. doi:  
735 10.1038/ngeo2412
- 736 Martínez, G. M., & et al. (2022). Surface Energy Budget, Albedo and Thermal  
737 Inertia at Jezero Crater, Mars, as Observed from the Mars 2020 MEDA Instru-  
738 ment. *Journal of Geophysical Research (Planets)*. (in this issue)
- 739 Martínez, G. M., Fischer, E., Rennó, N. O., Sebastián, E., Kemppinen, O., Bridges,  
740 N., ... REMS Team (2016, December). Likely frost events at Gale crater:  
741 Analysis from MSL/REMS measurements. *Icarus*, *280*, 93-102. doi:  
742 10.1016/j.icarus.2015.12.004
- 743 Martínez, G. M., Newman, C. N., De Vicente-Retortillo, A., Fischer, E., Renno,  
744 N. O., Richardson, M. I., ... Vasavada, A. R. (2017, October). The Mod-  
745 ern Near-Surface Martian Climate: A Review of In-situ Meteorological Data  
746 from Viking to Curiosity. *Space Science Reviews*, *212*(1-2), 295-338. doi:  
747 10.1007/s11214-017-0360-x
- 748 McConnochie, T. H., Smith, M. D., Wolff, M. J., Bender, S., Lemmon, M., Wiens,



- 749 R. C., ... Bell, J. F. (2018, June). Retrieval of water vapor column abundance  
750 and aerosol properties from ChemCam passive sky spectroscopy. *Icarus*, *307*,  
751 294-326. doi: 10.1016/j.icarus.2017.10.043
- 752 Melchiorri, R., Encrenaz, T., Drossart, P., Fouchet, T., Forget, F., Titov, D.,  
753 ... Bibring, J. P. (2009, May). OMEGA/Mars Express: South Pole  
754 Region, water vapor daily variability. *Icarus*, *201*(1), 102-112. doi:  
755 10.1016/j.icarus.2008.12.018
- 756 Milton, D. J. (1973, July). Water and processes of degradation in the Mar-  
757 tian landscape. *Journal of Geophysical Research*, *78*, 4037-4047. doi:  
758 10.1029/JB078i020p04037
- 759 Morris, R. V., Klingelhöfer, G., Schröder, C., Rodionov, D. S., Yen, A., Ming,  
760 D. W., ... Arvidson, R. E. (2006, December). Mössbauer mineralogy  
761 of rock, soil, and dust at Meridiani Planum, Mars: Opportunity's journey  
762 across sulfate-rich outcrop, basaltic sand and dust, and hematite lag de-  
763 posits. *Journal of Geophysical Research (Planets)*, *111*(E12), E12S15. doi:  
764 10.1029/2006JE002791
- 765 Munguira, A., Hueso, R., Sánchez-Lavega, A., de la Torre, M., Martínez, G., New-  
766 man, C., ... Torres, J. (2022). Near Surface Atmospheric Temperatures at  
767 Jezero from Mars 2020 MEDA measurements. *Journal of Geophysical Research*  
768 (*Planets*). (in this issue)
- 769 Navarro-González, R., Rainey, F. A., Molina, P., Bagaley, D. R., Hollen, B. J., de  
770 la Rosa, J., ... McKay, C. P. (2003, November). Mars-Like Soils in the Ata-  
771 cama Desert, Chile, and the Dry Limit of Microbial Life. *Science*, *302*(5647),  
772 1018-1021. doi: 10.1126/science.1089143
- 773 Pla-García, J., Rafkin, S. C. R., Martinez, G. M., Vicente-Retortillo, Á., Newman,  
774 C. E., Savijärvi, H., ... Harri, A.-M. (2020, December). Meteorological Predic-  
775 tions for Mars 2020 Perseverance Rover Landing Site at Jezero Crater. *Space*  
776 *Science Reviews*, *216*(8), 148. doi: 10.1007/s11214-020-00763-x
- 777 Polkko, J. (2022). *Data for the manuscript "initial results of the relative*  
778 *humidity observations by meda instrument onboard the mars 2020 per-*  
779 *severance rover" submitted to jgr planets m2020 special issue "crater*  
780 *floor"* [dataset]. FMI. Retrieved from [https://doi.org/10.23728/](https://doi.org/10.23728/fmi-b2share.daab03d71fc94bcd893b6c97adce497f)  
781 [fmi-b2share.daab03d71fc94bcd893b6c97adce497f](https://doi.org/10.23728/fmi-b2share.daab03d71fc94bcd893b6c97adce497f) doi: 10.23728/  
782 [fmi-b2share.daab03d71fc94bcd893b6c97adce497f](https://doi.org/10.23728/fmi-b2share.daab03d71fc94bcd893b6c97adce497f)
- 783 Rodriguez-Manfredi, J. A., de la Torre Juárez, M., Alonso, A., Apéstigue, V.,  
784 Arruego, I., Atienza, T., ... MEDA Team (2021, April). The Mars En-  
785 vironmental Dynamics Analyzer, MEDA. A Suite of Environmental Sen-  
786 sors for the Mars 2020 Mission. *Space Science Reviews*, *217*(3), 48. doi:  
787 10.1007/s11214-021-00816-9
- 788 Rodriguez-Manfredi, J. A., & de la Torre Juarez, M. (2021). *Mars 2020 meda bundle*  
789 [dataset]. NASA. Retrieved from <https://doi.org/10.17189/1522849> doi:  
790 10.17189/1522849
- 791 Savijärvi, H. I., & Harri, A. M. (2021, March). Water vapor adsorption on Mars.  
792 *Icarus*, *357*, 114270. doi: 10.1016/j.icarus.2020.114270
- 793 Savijärvi, H. I., Harri, A. M., & Kempainen, O. (2015, May). Mars Science Labo-  
794 ratory diurnal moisture observations and column simulations. *Journal of Geo-*  
795 *physical Research (Planets)*, *120*(5), 1011-1021. doi: 10.1002/2014JE004732
- 796 Savijärvi, H. I., Harri, A.-M., & Kempainen, O. (2016, February). The diurnal water  
797 cycle at Curiosity: Role of exchange with the regolith. *Icarus*, *265*, 63-69. doi:  
798 10.1016/j.icarus.2015.10.008
- 799 Savijärvi, H. I., Martinez, G., Harri, A.-M., & Paton, M. (2020, February). Curiosity  
800 observations and column model integrations for a martian global dust event.  
801 *Icarus*, *337*, 113515. doi: 10.1016/j.icarus.2019.113515
- 802 Savijärvi, H. I., Martinez, G. M., Fischer, E., Renno, N. O., Tamppari, L. K.,  
803 Zent, A., & Harri, A. M. (2020, June). Humidity observations and col-



- 804       umn simulations for a warm period at the Mars Phoenix lander site: Con-  
 805       straining the adsorptive properties of regolith. *Icarus*, 343, 113688. doi:  
 806       10.1016/j.icarus.2020.113688
- 807       Savijärvi, H. I., Martínez, G. M., Vicente-Retortillo, A., & Harri, A. M. (2022,  
 808       April). Surface energy budget at Curiosity through observations and column  
 809       modeling. *Icarus*, 376, 114900. doi: 10.1016/j.icarus.2022.114900
- 810       Savijärvi, H. I., McConnochie, T. H., Harri, A.-M., & Paton, M. (2019, July). Wa-  
 811       ter vapor mixing ratios and air temperatures for three martian years from  
 812       Curiosity. *Icarus*, 326, 170-175. doi: 10.1016/j.icarus.2019.03.020
- 813       Savijärvi, H. I., & Siili, T. (1993, January). The Martian slope winds and the noc-  
 814       turnal PBL jet. *Journal of Atmospheric Sciences*, 50(1), 77-88. doi: 10.1175/  
 815       1520-0469(1993)050<0077:TMSWAT>2.0.CO;2
- 816       Sebastián, E., Martínez, G., Ramos, M., Pérez-Grande, I., Sobrado, J., & Rodríguez  
 817       Manfredi, J. A. (2021, May). Thermal calibration of the MEDA-TIRS ra-  
 818       diometer onboard NASA's Perseverance rover. *Acta Astronautica*, 182, 144-  
 819       159. doi: 10.1016/j.actaastro.2021.02.006
- 820       Sindoni, G., Formisano, V., & Geminale, A. (2011, February). Observations of  
 821       water vapour and carbon monoxide in the Martian atmosphere with the  
 822       SWC of PFS/MEX. *Planetary and Space Science*, 59(2-3), 149-162. doi:  
 823       10.1016/j.pss.2010.12.006
- 824       Smith, D. E., Zuber, M. T., Solomon, S. C., Phillips, R. J., Head, J. W., Garvin,  
 825       J. B., ... Duxbury, T. C. (1999, May). The Global Topography of  
 826       Mars and Implications for Surface Evolution. *Science*, 284, 1495. doi:  
 827       10.1126/science.284.5419.1495
- 828       Smith, M. D. (2002, November). The annual cycle of water vapor on Mars as  
 829       observed by the Thermal Emission Spectrometer. *Journal of Geophysical*  
 830       *Research (Planets)*, 107(E11), 5115. doi: 10.1029/2001JE001522
- 831       Smith, M. D. (2004, January). Interannual variability in TES atmospheric observa-  
 832       tions of Mars during 1999-2003. *Icarus*, 167(1), 148-165. doi: 10.1016/j.icarus  
 833       .2003.09.010
- 834       Smith, M. D., Daerden, F., Neary, L., & Khayat, A. (2018, February). The climatol-  
 835       ogy of carbon monoxide and water vapor on Mars as observed by CRISM and  
 836       modeled by the GEM-Mars general circulation model. *Icarus*, 301, 117-131.  
 837       doi: 10.1016/j.icarus.2017.09.027
- 838       Smith, M. D., Pearl, J. C., Conrath, B. J., & Christensen, P. R. (2001, October).  
 839       Thermal Emission Spectrometer results: Mars atmospheric thermal structure  
 840       and aerosol distribution. *Journal of Geophysical Research*, 106(E10), 23929-  
 841       23945. doi: 10.1029/2000JE001321
- 842       Smith, M. D., Wolff, M. J., Clancy, R. T., & Murchie, S. L. (2009, June). Compact  
 843       Reconnaissance Imaging Spectrometer observations of water vapor and carbon  
 844       monoxide. *Journal of Geophysical Research (Planets)*, 114(E9), E00D03. doi:  
 845       10.1029/2008JE003288
- 846       Smith, P. H., Tamppari, L. K., Arvidson, R. E., Bass, D., Blaney, D., Boynton,  
 847       W. V., ... Zent, A. P. (2009, July). H<sub>2</sub>O at the Phoenix Landing Site. *Sci-  
 848       ence*, 325(5936), 58. doi: 10.1126/science.1172339
- 849       Spinrad, H., Münch, G., & Kaplan, L. D. (1963, May). Letter to the Editor: the De-  
 850       tection of Water Vapor on Mars. *Astrophysical Journal*, 137, 1319. doi: 10  
 851       .1086/147613
- 852       Sprague, A. L., Hunten, D. M., Doose, L. R., & Hill, R. E. (2003, May). Mars at-  
 853       mospheric water vapor abundance: 1996-1997. *Icarus*, 163(1), 88-101. doi: 10  
 854       .1016/S0019-1035(03)00072-1
- 855       Sprague, A. L., Hunten, D. M., Hill, R. E., Rizk, B., & Wells, W. K. (1996, Oc-  
 856       tober). Martian water vapor, 1988-1995. *Journal of Geophysical Research*,  
 857       101(E10), 23229-23254. doi: 10.1029/96JE02265
- 858       Steele, L. J., Balme, M. R., Lewis, S. R., & Spiga, A. (2017, June). The water cy-

- 859 cle and regolith-atmosphere interaction at Gale crater, Mars. *Icarus*, 289, 56-  
860 79. doi: 10.1016/j.icarus.2017.02.010
- 861 Tamppari, L. K., & Lemmon, M. T. (2020, June). Near-surface atmospheric water  
862 vapor enhancement at the Mars Phoenix lander site. *Icarus*, 343, 113624. doi:  
863 10.1016/j.icarus.2020.113624
- 864 Vaisala-Oyj. (2020). *Humicap technology description* (Tech. Rep. No. B210781EN-  
865 D). Retrieved from [https://www.vaisala.com/sites/default/files/  
866 documents/HUMICAP-Technology-description-B210781EN.pdf](https://www.vaisala.com/sites/default/files/documents/HUMICAP-Technology-description-B210781EN.pdf) (Ref.  
867 B210781EN-D)
- 868 Viúdez-Moreiras, D., de la Torre, M., Gómez-Elvira, J., Lorenz, R., Apéstigue,  
869 V., Guzewich, S., ... Bell, J. (2022). Winds at the mars 2020 landing  
870 site.part 2: Wind variability and turbulence. *Journal of Geophysical Re-  
871 search: Planets*, n/a(n/a), e2022JE007523. Retrieved from [https://  
872 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JE007523](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JE007523)  
873 (e2022JE007523 2022JE007523) doi: <https://doi.org/10.1029/2022JE007523>
- 874 Viúdez-Moreiras, D., Lemmon, M., Newman, C., Guzewich, S., Mischna, M.,  
875 Gómez-Elvira, J., ... Bell, J. (2022). Winds at the mars 2020 landing  
876 site: 1. near-surface wind patterns at jezero crater. *Journal of Geophysi-  
877 cal Research: Planets*, 127(12), e2022JE007522. Retrieved from [https://  
878 agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JE007522](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2022JE007522)  
879 (e2022JE007522 2022JE007522) doi: <https://doi.org/10.1029/2022JE007522>
- 880 Viúdez-Moreiras, D., Newman, C. E., de la Torre, M., Martínez, G., Guzewich, S.,  
881 Lemmon, M., ... Gómez-Elvira, J. (2019, July). Effects of the MY34/2018  
882 Global Dust Storm as Measured by MSL REMS in Gale Crater. *Jour-  
883 nal of Geophysical Research (Planets)*, 124(7), 1899-1912. doi: 10.1029/  
884 2019JE005985
- 885 VTT-Ltd. (2022). *Uncertainty evaluation of meda hs humidity measurements* (Tech.  
886 Rep.). ("State Research Center (VTT) consultation report with Finnish Mete-  
887 orological Institute, 2022 by Tabandeh, S. and Högström, R.")
- 888 Whiteway, J. A., Komguem, L., Dickinson, C., Cook, C., Illnicki, M., Seabrook, J.,  
889 ... Smith, P. H. (2009, July). Mars Water-Ice Clouds and Precipitation.  
890 *Science*, 325(5936), 68. doi: 10.1126/science.1172344
- 891 Young, I., Crawford, J., Nunan, N., Otten, W., & Spiers, A. (2008). Chapter  
892 4 microbial distribution in soils: Physics and scaling. In (Vol. 100, p. 81-  
893 121). Academic Press. Retrieved from [https://www.sciencedirect.com/  
894 science/article/pii/S0065211308006044](https://www.sciencedirect.com/science/article/pii/S0065211308006044) doi: [https://doi.org/10.1016/  
895 S0065-2113\(08\)00604-4](https://doi.org/10.1016/S0065-2113(08)00604-4)
- 896 Zent, A. P., Hecht, M. H., Cobos, D. R., Wood, S. E., Hudson, T. L., Milkovich,  
897 S. M., ... Mellon, M. T. (2010, March). Initial results from the thermal and  
898 electrical conductivity probe (TECP) on Phoenix. *Journal of Geophysical  
899 Research (Planets)*, 115(2), E00E14. doi: 10.1029/2009JE003420
- 900 Zent, A. P., Hecht, M. H., Hudson, T. L., Wood, S. E., & Chevrier, V. F. (2016,  
901 April). A revised calibration function and results for the Phoenix mission  
902 TECP relative humidity sensor. *Journal of Geophysical Research (Planets)*,  
903 121(4), 626-651. doi: 10.1002/2015JE004933