

Perseverance MEDA Atmospheric Pressure Observations - Initial Results

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Key Points:

- The atmospheric pressure observations by Perseverance Rover have proved to be of excellent quality fulfilling expectations
- Jezero crater pressure exhibits significant differences to other Martian areas likely due to varying regional geography and solar forcing
- Overall, the diurnal and seasonal atmospheric pressure cycles at Jezero Crater follow an anticipated pattern of pressure variation

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24 **Abstract**

25 The Mars2020 Perseverance Rover landed successfully on the Martian surface
 26 on the Jezero Crater floor (18.44°N, 77.45°E) at Martian solar longitude, L_s , ~ 5
 27 in February 2021. Since then it has produced highly valuable environmental measure-
 28 ments with a versatile scientific payload including the MEDA (Mars Environmental
 29 Dynamics Analyzer) suite of environmental sensors. One of the MEDA systems is
 30 the PS pressure sensor system which weighs 40 grams and has an estimated absolute
 31 accuracy of better than 3.5 Pa and a resolution of 0.13 Pa. We present initial results
 32 from the first 414 sols of Martian atmospheric surface pressure observations by the
 33 PS whose performance was found to meet its specifications. Observed sol-averaged
 34 atmospheric pressures follow an anticipated pattern of pressure variation in the
 35 course of the advancing season and are consistent with data from other landing mis-
 36 sions. The observed diurnal pressure amplitude varies by ~ 2 -5 % of the sol-averaged
 37 pressure, with absolute amplitude 10-35 Pa in an approximately direct relationship
 38 with airborne dust. During a regional dust storm, which began at L_s 135° the diur-
 39 nal pressure amplitude roughly doubles. The diurnal pressure variations were found
 40 to be remarkably sensitive to the seasonal evolution of the atmosphere. In particular
 41 analysis of the diurnal pressure signature revealed diagnostic information likely re-
 42 lated to the regional scale structure of the atmosphere. Comparison of Perseverance
 43 pressure observations to data from other landers reveals the global scale seasonal
 44 behaviour of Mars' atmosphere.

45 **Plain Language Summary**

46 The Mars2020 Perseverance Rover successfully arrived at Mars in February
 47 2021. It landed during an early Martian spring afternoon in a crater north of Mars'
 48 equator called Jezero crater. The rover is equipped with meteorological instruments
 49 that have so far produced extensive and valuable data for understanding the Mar-
 50 tian atmosphere. One of the meteorological instruments is an accurate and precise
 51 pressure sensor. The pressure sensor has revealed large changes in the pressure over
 52 the seasons that are related to large changes in the actual mass of the Martian at-
 53 mosphere. This is in line with seasonal pressure changes measured during previous
 54 Mars missions and can be explained as the freezing of the atmosphere onto the
 55 Martian poles and its subsequent thaw. On a shorter time scale the pressure sensor
 56 revealed complex pressure changes over a Martian day. These variations are thought
 57 to be related to atmospheric dust whose ubiquitous nature is known to have a strong
 58 influence on the Martian climate. As the seasons progressed the daily pressure vari-
 59 ations morphed to exhibit different patterns likely related to the large-scale regional
 60 changes in the atmosphere. Comparison of Perseverance pressure observations to
 61 other landers revealed the global nature of the atmosphere.

62 **1 Introduction**

63 The Mars2020 Perseverance Rover landed successfully on the Martian sur-
 64 face on the Jezero Crater floor (18.44°N, 77.45°E) at the Martian solar longitude,
 65 L_s , 5° in February 2021. Since then, it has produced highly valuable environmental
 66 measurements with a versatile scientific payload including the MEDA (Mars Envi-
 67 ronmental Dynamics Analyzer) suite of environmental sensors (Rodriguez-Manfredi
 68 et al., 2021). One of the MEDA sensor systems is the pressure sensor (PS) whose
 69 observations and initial results utilizing the data acquired during the first 414 sols of
 70 the mission ($L_s 5 - 212^\circ$) will be addressed in this manuscript.

71 Martian atmospheric investigations through spacecraft observations began in
 72 the early to middle 1960s as reported by, *e.g.*, Kliore et al. (1969, 1973) and later

73 by Kieffer et al. (1973, 1977); Snyder and Moroz (1992); Zurek (1992); Zurek et
74 al. (1992a). Surface pressure of the atmosphere was firstly estimated using remote
75 sensing methods, both ground based by *e.g.* (Young, 1969) and from spacecraft
76 starting from Mariner as reported by, *e.g.* (Kliore et al., 1965). The Viking landers
77 in 1974-77 provided the first time series of *in situ* atmospheric observations that
78 turned out to be a treasure trove of data covering multiple Martian years (Kieffer
79 et al., 1977; Tillman et al., 1979; Zurek, 1978, 1981). Thereafter Mars Pathfinder
80 (M. P. Golombek et al., 1999; Schofield et al., 1997), the Phoenix lander (Taylor et
81 al., 2008; Savijärvi & Määttänen, 2010), the Mars Science Laboratory aka Curiosity
82 Rover (Gómez-Elvira et al., 2012), the InSight lander (M. Golombek et al., 2020)
83 and the Perseverance Rover (Rodriguez-Manfredi et al., 2021) have continued *in situ*
84 investigations of the Martian atmosphere including accurate atmospheric pressure
85 observations.

86 During the years of *in situ* and remote observations, Martian atmospheric
87 observations have been accompanied and supplemented by increasingly sophisti-
88 cated and varied modeling efforts in a range of spatial and temporal scales already
89 since late 1960s (Leovy & Mintz, 1969; Pollack et al., 1981, 1990; Haberle et al.,
90 1993; Barnes et al., 1993; Forget et al., 1999; Richardson et al., 2007; Savijärvi &
91 Kauhanen, 2008; Newman et al., 2017; Richardson & Newman, 2018; Newman et
92 al., 2019). Pressure observations from surface stations have prompted investiga-
93 tions of the CO₂ cycle and its connection to the poles, ice and dust *e.g.* Guo et al.
94 (2009); Kahre and Haberle (2010). The characterisation of pressure changes due
95 to large scale circulations (Wilson & Hamilton, 1996; Basu et al., 2004) and local
96 meteorology (Toigo & Richardson, 2003; Rafkin et al., 2016) have been predicted
97 and characterised using computer models.

98 Data assimilation using orbital data is an important activity to enable real-
99 istic predictions using atmospheric models and verifying the physics (Rogberg et
100 al., 2010; Lee et al., 2011; Montabone et al., 2014). Better understanding of the be-
101 haviour of the Martian atmosphere can help develop better predictions *e.g.* Battalio
102 and Lora (2021). A network of surface pressure stations could be key to char-
103 acterising fast evolving weather systems and dust lifting events (Newman et al.,
104 2021). Our current understanding of the Martian atmosphere and its processes is
105 still understandably far less detailed than our understanding of our own terrestrial
106 atmosphere, but the Martian atmospheric phenomena are presently clearly much
107 better understood than those of any other solar system atmospheres.

108 Some of the earlier Martian landing vehicles have operated at similar latitudes
109 or elevations to Perseverance, resulting in similarities in terms of climate zone or
110 annual mean atmospheric pressure. Figure 1 shows the locations of Martian land-
111 ing vehicles with Martian topography, giving a clear idea of the differences in the
112 altitude and type of terrain of the landing sites. In terms of longitude, however, Per-
113 severance seems to be relatively isolated, which has implications when comparing
114 to data from other landed missions. Perseverance observations also have particular
115 significance because they mean that for the first time, we have four *in situ* sets of
116 meteorological observations being carried out at the same time at different locations
117 on the Martian surface (including observations by MSL, InSight, Perseverance, and
118 also China's Zhurong rover, data from which are not currently publicly available).
119 We will present several interesting initial discoveries based on these facts, in addition
120 to the independent Perseverance pressure observations.

121 In addition to this article there are two companion articles in this journal uti-
122 lizing the pressure data focusing on atmospheric dynamics (Sánchez-Lavega et al.,
123 2023) and small-scale thermal vortices (Hueso et al., 2023).

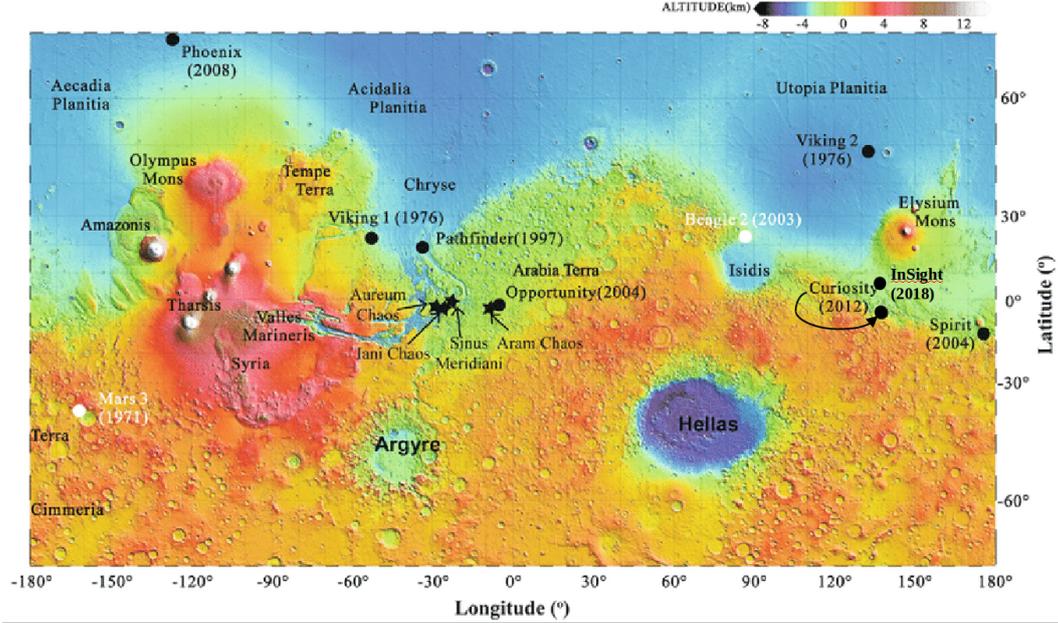


Figure 1. Landing sites of the seven spacecraft having provided *in situ* atmospheric data depicted on a topographic map of Mars (NASA JPL, 2021).

124 **2 Brief MEDA PS device specification and performance**

125 **Instrument description.** The Perseverance pressure measurement device
 126 (MEDA PS) is based on the silicon-micro-machined pressure sensor head (Baro-
 127 cap®) and transducer technology developed by Vaisala Inc. The Barocap® version
 128 used by MEDA PS is optimized for the Martian near-surface atmospheric pressure.
 129 Changing ambient pressure is changing the sensor head capacitance by varying the
 130 distance of the sensor head capacitor plates. Besides being pressure dependent, the
 131 Barocap® capacitance is also sensitive to temperature, and thus accurate temper-
 132 ature measurements close to the sensor head are necessary. The supporting house-
 133 keeping temperature measurements are provided by Vaisala’s Thermocap® sensor
 134 heads.

135 MEDA PS consists of two transducers, each having its controlling ASIC (ap-
 136 plication specific integrated circuit) and 8 channels containing the Barocap sensor
 137 heads, Thermocap sensor heads and constant reference capacitors. Two types of
 138 Barocap sensors are used: the NGM type with high stability and relatively long
 139 warm-up time and the less stable but faster RSP2M type as a backup. Hence, the
 140 primary sensor for scientific investigations is the NGM type Barocap on transducer
 141 1 channel 8 and the secondary sensor the RSP2M Barocap on transducer 1 chan-
 142 nel 6. We provide a calibrated pressure reading for both sensor heads in the DER
 143 and CAL type data products in the PDS archive (Rodriguez-Manfredi & de la
 144 Torre Juarez, 2021) that are optimal for most investigations.

145 **Calibration and performance.** MEDA PS has been calibrated at the
 146 Finnish Meteorological Institute (FMI) laboratories over the expected operational
 147 pressure and temperature ranges. The calibration has been performed in stable tem-
 148 peratures from -45°C to +55°C and stable pressure points ranging from 0 hPa to
 149 14 hPa, which extend well beyond the pressure and temperature ranges prevailing
 150 within the electronics compartment housing the MEDA PS on Mars itself. Cali-

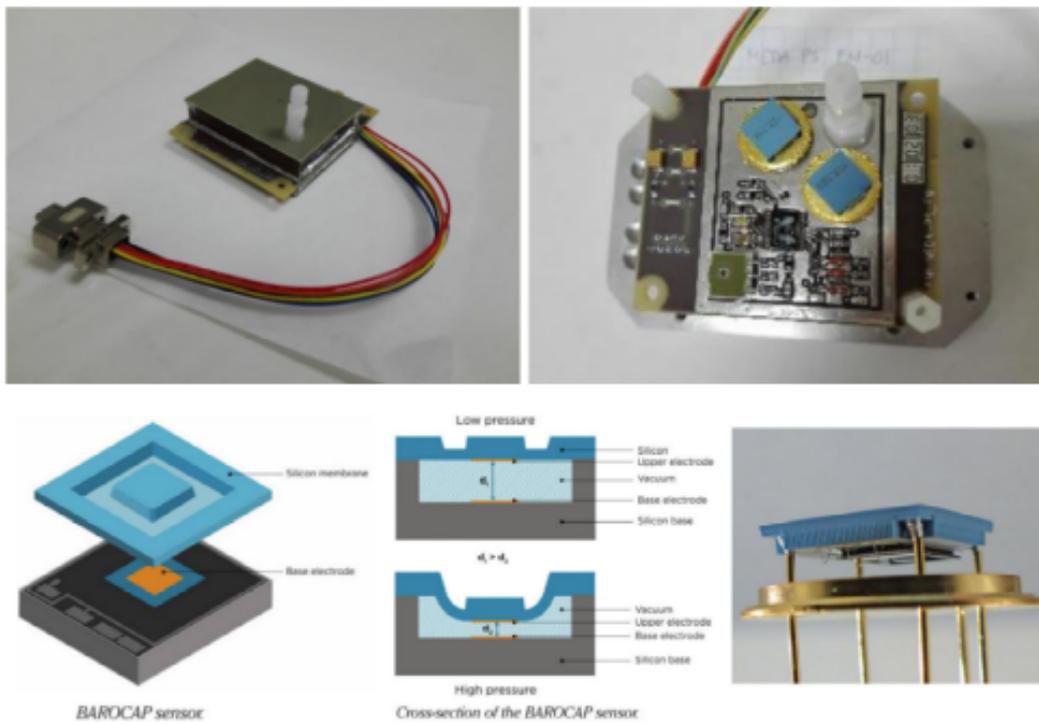


Figure 2. MEDA PS device within its Faraday cage made out of thin conductive foil (top left pane) and the instrument with its pressure sensor heads and part of the electronics visible without the Faraday cover (top right pane). The structure of the silicon micromachined sensor head is shown on the lower row.

151 bration measurements were also performed in changing pressure and temperature
 152 conditions. The Barocap sensors are known to have small changes in the tempera-
 153 ture dependence or sensor offset when introduced to a new electrical and thermal
 154 environment, and thus calibration checks were performed at all stages after the
 155 sensor-level calibration. The calibration checks were performed after integration
 156 to the MEDA electronics compartment (MEDA ICU), during the final rover-level
 157 thermal vacuum test, during the interplanetary cruise and soon after landing on
 158 Mars. The RSP2M Barocaps are also periodically cross-checked against the primary
 159 Barocap for possible drift compensation.

160 The estimated MEDA PS uncertainty based on the sensor- and rover-level
 161 measurements was analyzed to be better than 3.5 Pa. This includes the effects of
 162 the short-term repeatability, environmental effects and the pressure reference accu-
 163 racy. The resolution of the primary Barocap, restricted mostly by the electronics
 164 noise, is 0.13 Pa in nominal measurement mode, and 0.1 Pa in high-resolution mode,
 165 as determined in sensor-level measurements. According to the test data, the time
 166 response of MEDA PS is equal to or less than 1 s, having almost no effect on the
 167 measurements at the nominal sampling rate of 1 Hz. The effect of the warm-up time
 168 of the NGM Barocaps has been removed by the calibration.

169 The system resources required by the whole MEDA PS package are dimensions
 170 $62 \times 50 \times 17$ mm, mass 43 g and power consumption less than 15 mW. The MEDA
 171 PS detailed specification available before the launch of the Perseverance Rover is
 172 described in detail by (Rodriguez-Manfredi et al., 2021). The MEDA PS is located
 173 inside the MEDA Instrument Control Unit (ICU) in the rover body, with a filter-
 174 protected tube connecting it to the outside environment and conveying ambient
 175 pressure to be measured. The MEDA PS device is depicted in Figure 2 illustrat-
 176 ating the pressure sensor head and its encapsulation of the full pressure device in a
 177 Faraday cage giving shielding against electromagnetic interference.

178 During the first 414 Martian sols of Perseverance operations MEDA PS has
 179 been functioning as expected. The temperature dependence of the Barocap sensors
 180 was checked and corrected at the beginning of the operations against the primary
 181 Barocap, which is known to be very stable based on the test data. In the first drift
 182 offset check performed after 150 sols, the drift of the secondary Barocap was less
 183 than 0.3 Pa and slightly larger for the other RSP2M Barocaps.

184 **3 MEDA PS observation strategy and pressure data coverage**

185 MEDA has been designed for flexible operations that are being conducted
 186 according to the scheduling by the Perseverance rover. MEDA measures for five
 187 minutes at the top of each hour in local mean solar time (LMST) in every mission
 188 sol, other than during exceptional circumstances. In addition, on average, MEDA is
 189 operating continuously for every other hour. That enables us to generate data sets
 190 with averaged pressure measurements approximately at 1-hour intervals, as well as
 191 data sets with pressure observations at 1 second intervals for a period of one hour
 192 or a few hours in a row for *e.g.* turbulence-related studies. There are also periods,
 193 when MEDA is only able to measure for five minutes per hour (or sometimes fifteen
 194 or twenty minutes per hour) or is doing no measurements at all for a few hours, due
 195 to Perseverance resource allocation reasons.

196 In the present investigations we use data sets with 1-hour intervals. The 1-hour
 197 data sets are not complete but they do have gaps due to scheduling of Persever-
 198 ance and MEDA operations. Figure 3 illustrates how well the observed data sets
 199 cover each Perseverance sol. in the average about 50-70 % of the 24 hour of a sol
 200 throughout the season with some periods having 100 % coverage and few sols have

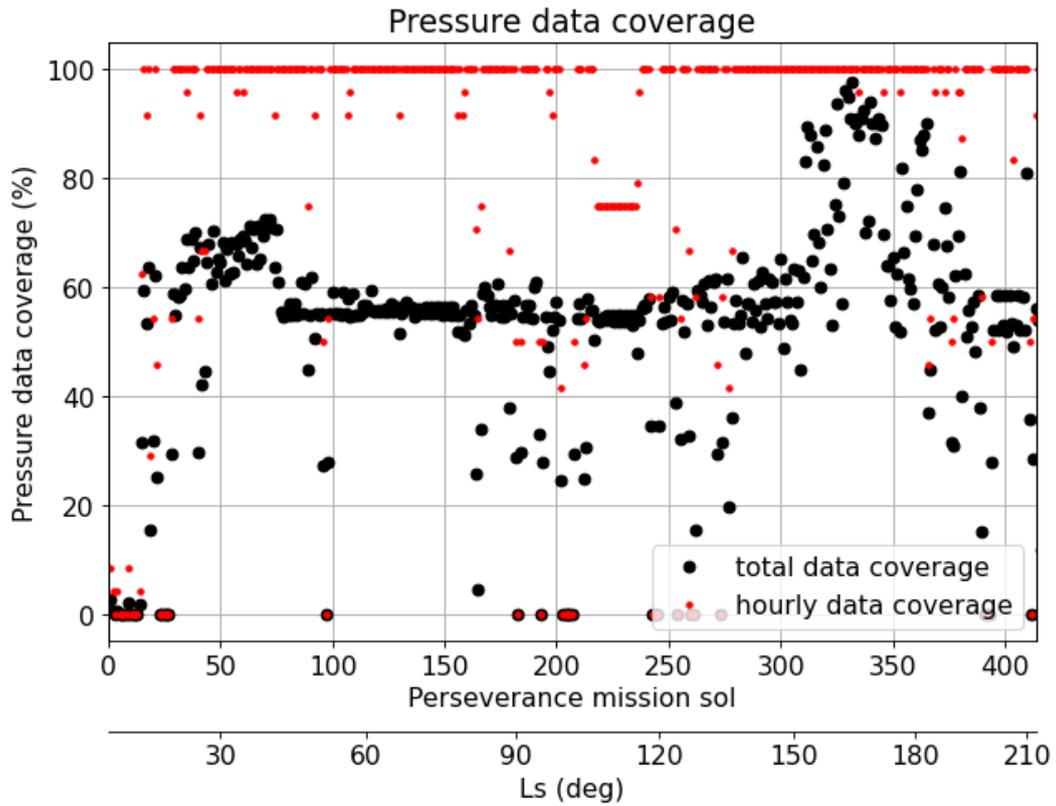


Figure 3. The coverage of atmospheric pressure observations made by the MEDA PS instrument. The black dots depict the overall percentage of pressure readings once per second in a sol, red dots the percentage of the pressure readings available at 1-hour intervals.

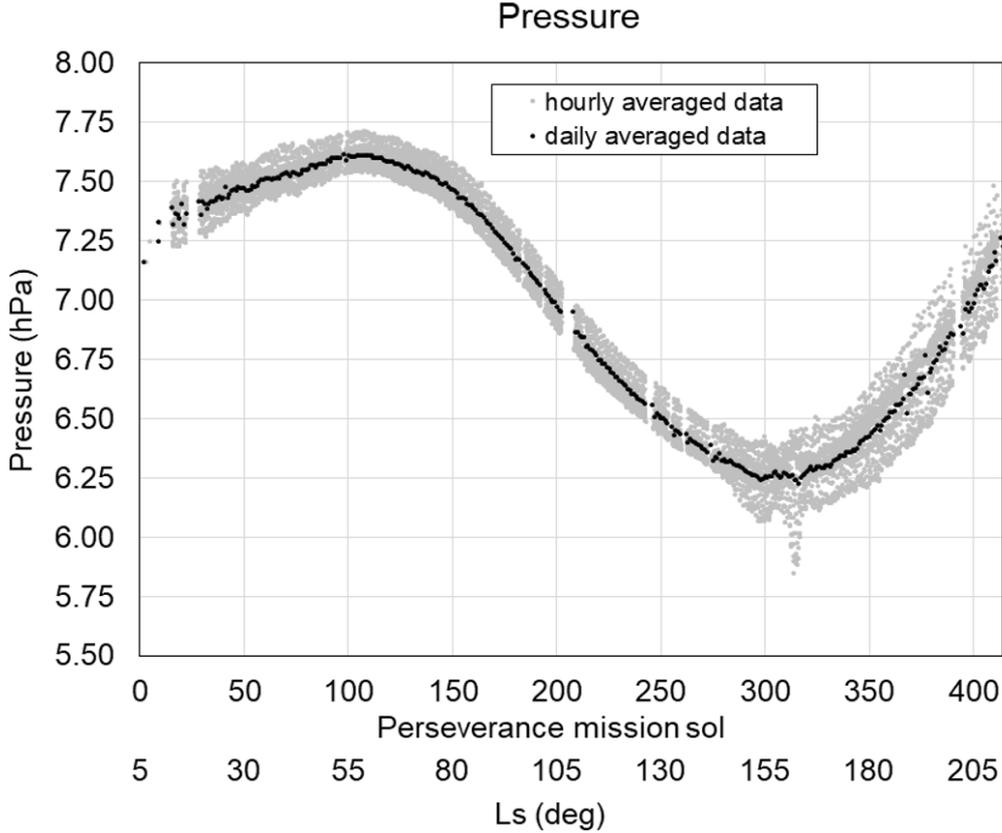


Figure 4. The sol averaged pressure data and the diurnal pressure amplitude (approximate total peak-to-peak range based on observations once per hour) for Perseverance during the period of the first 414 sols corresponding to approximately solar longitude range of L_s 5 – 212°.

201 no pressure data at all. The gaps in the 1-hour data set take place more or less ran-
 202 domly around the 24 hour Martian sol. The data coverage of this level allows good
 203 characterisation of both the diurnal and seasonal variations in the pressure.

204 **4 Changes in Jezero crater atmospheric pressure with seasonal** 205 **cycle**

206 The condensation and sublimation of CO₂ in the polar regions during win-
 207 ter and spring causes planetwide seasonal variations in the surface pressure, which
 208 were first detected by the Viking landers as reported by, *e.g.*, Kieffer et al. (1977);
 209 Tillman et al. (1979). The seasonal CO₂ cycle, which is largely controlled by the po-
 210 lar heat balance (Paige & Ingersoll, 1985, *e.g.*), can clearly be seen in the seasonal
 211 variation of daily average surface pressure.

212 This is nicely demonstrated at the Jezero crater site by the Perseverance Rover
 213 measurements. The daily averaged atmospheric surface pressure during the first 414
 214 sols of the Perseverance mission is depicted in Figure 4. The figure also includes the
 215 range of diurnal pressure variation plotted on both sides of the average pressure line
 216 with a gray color. Hence the gray area illustrates the approximate total range of di-
 217 urnal pressure variation around the average pressure of a sol. The minimum pressure

218 peak at around Ls 153 shown in Figure 4 was likely caused by a regional dust storm
219 (Lemmon et al., 2022).

220 In seasonal-to-annual time scales the CO₂ condensation-sublimation cycle at
221 the polar regions gives rise to a seasonal pressure variation on the order of as much
222 as 30 % of the local surface pressure (Kieffer et al., 1977; Tillman et al., 1979, e.g.).
223 The observed sol-averaged atmospheric pressure during the 414 first Perseverance
224 sols, from the landing time at early Northern springtime to Northern fall, follows an
225 anticipated pattern of total pressure variation in the course of the advancing sea-
226 son. The data has the first maximum in late spring roughly on Perseverance sol 110
227 and a minimum on sol 310, whereas by the Perseverance sol 414 (corresponding to
228 approximately L_s 212°) the atmospheric pressure is climbing higher than the first
229 maximum toward the annual maximum. When comparing Perseverance with concu-
230 rrent observations by the Curiosity Rover and the Insight lander as well as with the
231 historical Viking Landers data, we can see distinct differences in the amplitude of
232 the seasonal pressure variations that are due to different surface elevations.

233 The sol-averaged MEDA PS atmospheric pressure data together with the
234 hourly-averaged pressure depicted in Figure 4 is nicely showing the evolution of
235 the atmospheric pressure over first 414 Perseverance sols at the Jezero crater site.
236 In the beginning of the data set the pressure is going down during the Northern
237 spring and summer seasons and turning to an increasing leg during the late sum-
238 mer. The diurnal amplitude, shown approximately by the gray area in Figure 4,
239 shows a clear increase during periods with increased amounts of airborne dust start-
240 ing approximately from Perseverance sol 270 and staying high until sol 414 (when
241 our investigation period ends). There seems to be a direct relationship between the
242 range of diurnal pressure variation and the amount of airborne dust as has been
243 earlier discovered by, e.g., Zurek (1978, 1981); Paige and Ingersoll (1985).

244 The seasonal dependence of the Martian atmospheric pressure drives the at-
245 mosphere to the extent that about one third of the mass of the Martian atmosphere
246 is deposited on the polar caps during Northern and Southern winters and evapo-
247 rated back to the atmosphere during summertime. This results in the characteristic
248 atmospheric pressure pattern having two local maxima and minima during a Mar-
249 tian year, with the maxima occurring approximately at solar longitudes L_s 60°
250 and L_s 260°. This pattern can clearly be seen in Figure 5, which compares the sol-
251 averaged pressure of Perseverance with Curiosity Rover, Insight Lander, Viking
252 Landers and the Pathfinder mission. Table 1 gives the basic characteristics of each
253 mission.

254 Investigations of the seasonal pressure cycle together with observations from
255 other Martian landing missions enhance our understanding of the CO₂ cycle, the
256 annual heat balance of the polar caps and the global scale atmospheric circulation of
257 Mars (Paige & Ingersoll, 1985; Guo et al., 2009). Major drivers behind the seasonal
258 variation are solar radiation and surface and subsurface thermal properties (Wood
259 and Paige, 1992). Atmospheric dust loading and regional circulation will influence
260 short scale variations (Haberle et al., 1993; Hess et al., 1980). The annually aver-
261 aged atmospheric pressure is largely depending on the elevation of the site and hence
262 the atmospheric pressures are differing between observation sites (Hess et al., 1980;
263 Richardson & Newman, 2018).

264 In order to investigate the relative evolution of the pressure cycle at different
265 latitudes figures 5 (c) and 5 (d) show the differences in pressure between the Perse-
266 verance landing site and the other four landers, excluding Pathfinder. In figures 5
267 (c) and (d) a more negative pressure signifies a higher pressure compared to Perse-
268 verance. The results from MCD data shown in figure 5 (d) tracks in the evolution
269 of the results for the observational data shown in figure 5 (c). For Curiosity there

Table 1. Essential characteristics of seven Martian lander missions performing atmospheric observations. The elevations are based on MOLA data (Smith et al., 2001)

Vehicle	Lat (°N)	Lon (°E)	Elevation (km)	Climate Zone	Operational (years)	Platform Type
Viking lander 1	22	-48	-3.6	North sub-tropics	1976-82	Stationary
Viking lander 2	48	134	-4.4	North mid-latitudes	1976-80	Stationary
Mars Pathfinder	19	-34	-3.7	North sub-tropics	1997	Stationary
Phoenix	68	-126	-4.1	North polar regions	2008	Stationary
Curiosity	-4.6	137	-4.5	Equatorial regions	2012-	Mobile
InSight	4.5	136	-2.6	Equatorial regions	2020-	Stationary
Perseverance	18	77	-2.6	North sub-tropics	2021-	Mobile

270 are two sets of lines in figure 5 (c). These correspond to years 2 and 3 of the mission
 271 with year 3 being at a higher elevation which explain the difference in the mean
 272 pressure. There are a number of interesting dip or hump-like features over timescales
 273 of 100-200 sols in figure 5 (c) and (d) that need explaining.

274 The dips and humps in the season pressures in figure 5 (c) and (d) are most
 275 likely connected to latitude dependant processes that include the orographic, i.e.
 276 the large difference in elevation between the northern and southern hemisphere,
 277 and the dynamical effects on the pressure cycle (Hourdin et al., 1993). Regarding
 278 the orographic effect, during northern hemisphere winter a large mass of cool air is
 279 trapped in the low elevation of the northern hemisphere basin. In the winter a low
 280 atmospheric scale height traps a large portion of the atmosphere. The result is a
 281 higher winter maximum at higher latitudes in the northern hemisphere in winter.
 282 For example the heights of the winter and summer pressure peaks for Viking landers
 283 1 is much more symmetric than for Viking lander 2. We will not cover dynamical
 284 effect here, which is related to the winds, as it apparently has little influence at the
 285 equatorial and middle latitudes considered here. An explanation of the dynamical
 286 effect can be found in Hourdin et al. (1993).

287 The greatest dip seen is for the Viking lander 2 in 5 (d) which is at a lati-
 288 tude of 48°N. This results from the pressure observed by Viking lander 2 increasing
 289 more rapidly than the pressure observed by Perseverance most likely due to the oro-
 290 graphic effect. For the other landers the, except maybe for Curiosity, the pressure
 291 differences in figures 5 (c) and (d) are fairly level indicating the pressures at these
 292 landing site increase more or less at the same rate.

293 A shallow but distinct dip can be seen for Curiosity in figures 5 (c) and (d)
 294 over the spring-summer time period. A possible reason for a dip at this time of year

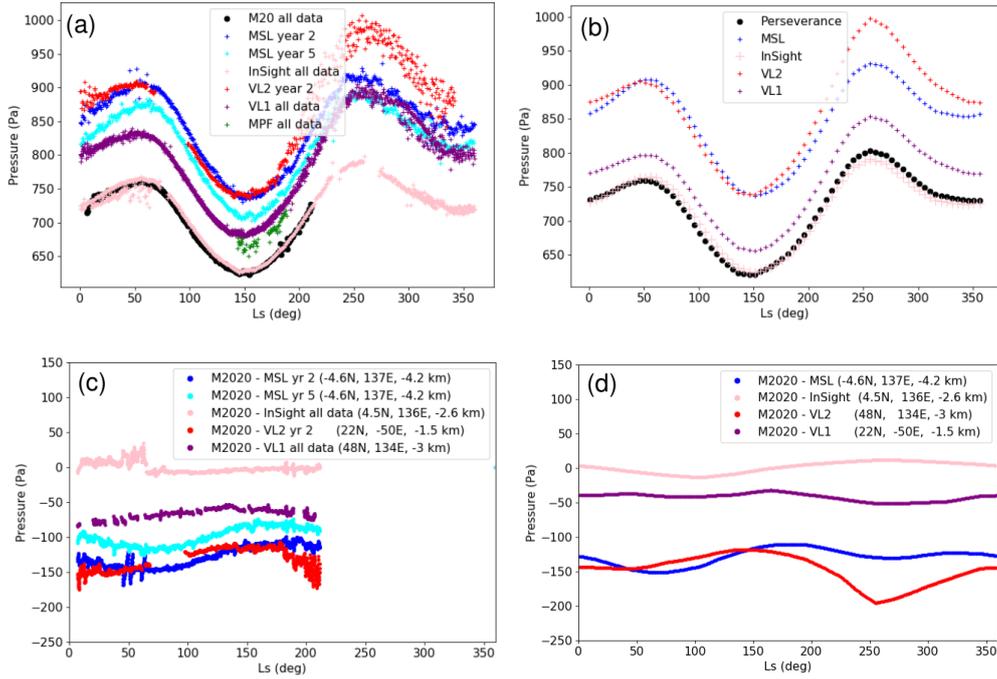


Figure 5. Comparisons of pressure between different lander missions. The top row shows the sol averaged observed pressure data, and the bottom row sol-averaged pressure data by different lander missions subtracted from Perseverance pressures. The left column shows results from the observations while on the right are the same results from the Mars Climate Database.

295 is that the cold air trapped in the northern hemisphere trapped during the winter
 296 is now being released as it is the summer. This lowers the pressure faster at the
 297 Perseverance landing site than at the Curiosity landing site, which is located near
 298 the equator in the southern hemisphere. This would result a relative increase in the
 299 pressure between Curiosity and Perseverance as seen in figure 5 (c) and (d). Both
 300 plots for Curiosity exhibit a dip around the summer solstice indicating that the pro-
 301 cess driving the evolution of the pressure, i.e. the dip, is not related to the change in
 302 elevation.

303 There are shallow dips and and troughs in the data for other landers in figures
 304 5 (c) and (d) but these are less obvious and probably cannot be interpreted with
 305 much certainty. For example there appears to be a small dip in the MCD data for
 306 InSight in figure 5 (d). This might be expected because InSight is located at a more
 307 southerly latitude than Perseverance with InSight being less sensitive to the ejection
 308 of summer time air from the northern basin than Perseverance. Interestingly this dip
 309 cannot be seen in Figure 5 (c) perhaps suggesting some other process or mechanism
 310 is masking the effect in the observations or limits with the model.

311 5 Diurnal atmospheric pressure and small scale atmospheric phe- 312 nomena

313 *In situ* pressure observations by several landed missions have shown that the
 314 Martian atmospheric surface pressure is composed of variations over several time
 315 scales and amplitudes. They include, *e.g.*, the overarching seasonal CO₂ cycle,
 316 regional-scale perturbations caused by planetary waves and thermal tides, including
 317 their interactions with topography, hydrostatic adjustment flows, and baroclinic and
 318 barotropic disturbances. Small scale eddies and disturbances, *e.g.* convective vortices
 319 are a usual cause of the shortest pressure variations of the order of a few tens of sec-
 320 onds (Harri et al., 2014, *e.g.*). If the vortices carry an optically distinguishable dust
 321 load they are called dust devils.

322 Thermal tides driven by solar irradiation cause distinct detectable diurnal pres-
 323 sure variations and are especially significant at low latitudes. In the Martian thin
 324 atmosphere the thermal tides - and hence the range of diurnal pressure variation
 325 - are much larger than in Earth's atmosphere due to the relatively stronger solar
 326 forcing at the surface (Zurek, 1982; Kieffer et al., 1992).

327 At the Jezero crater site measured by Perseverance rover the diurnal atmo-
 328 spheric pressure range seems to be approximately 20 Pa during the first 270 sols of
 329 the mission and thereafter during mission sols 270-414 extending to roughly 40 Pa.
 330 The wider range of diurnal pressure is likely due to increased amounts of airborne
 331 dust measured by Perseverance. Several earlier investigations have found the direct
 332 relationship between the amount of airborne dust and the range of diurnal pressure
 333 variation as shown by, *e.g.*, Zurek (1981, 1982); Guzewich et al. (2016).

334 The Perseverance *in situ* pressure observations show variations ranging from
 335 microscale to seasonal scale as has been observed by earlier *in situ* pressure mea-
 336 surements of Viking (Soffen, 1976; Soffen, 1977), Pathfinder (M. P. Golombek et
 337 al., 1999), Phoenix (Taylor et al., 2008) and Curiosity missions (Harri et al., 2014;
 338 Haberle et al., 2014). The advancing Martian season has a clear signature in the at-
 339 mospheric pressure as clearly manifested by Figure 6 depicting the diurnal pressure
 340 variation by data stacked in steps of 10 sols. It shows the gradual increase of the ob-
 341 served Perseverance pressure levels during the Northern spring until approximately
 342 sol 110, then gradual decrease bypassing the Northern midsummer (Ls 90) until sol
 343 320, and thereafter again showing increasing pressure until the last sol (414) of this
 344 investigation when the season advances further into the Northern fall. The data of

345 this investigation covers only 60 % of the Martian year, but this kind of seasonal
 346 dependence will be seen throughout the Martian year.

347 When inspecting the structure of diurnal pressure, 2-4 peaks appear in the
 348 data on each sol in Figure 6. A clear evolution of the peaks can be seen in the
 349 stacked diurnal pressure data. During Northern summer (Figure 6, second row
 350 from top) diurnal pressure exhibits two distinct and regular peaks, one in the morn-
 351 ing around 6-7 AM and the other one around 8-9 PM LTST. During the Northern
 352 spring (Figure 6, top row) and fall (Figure 6, lowest rows) this summertime regular
 353 pattern is broken into more like four separate peaks whose amplitudes vary along
 354 with advancing season.

355 It seems that during springtime - at the start of the mission, Perseverance sols
 356 0-150 - smaller peaks are superimposed on the larger peaks. These smaller peaks dis-
 357 appear between about sols 150 and 250 (Northern summertime) and return around
 358 sol 300 in early Northern fall. The wintertime has not yet come during the first 414
 359 Perseverance sols. The features in the plots give clues on the behaviour of regional
 360 atmospheric dynamics and circulation patterns in the Martian atmosphere (Read &
 361 Lewis, 2004, e.g.).

362 The largely repeatable two-peak shape of the daily surface pressure profile
 363 especially during the Northern summertime (Figure 6) is likely due to the strong
 364 semi-diurnal thermal tidal component as indicated in Figure 7. Abundant amount of
 365 airborne dust is one cause responsible for amplified semi-diurnal tidal component as
 366 shown by, e.g., (Zurek, 1981; Newman et al., 2021). Similar two-peak structure was
 367 also discovered during Pathfinder mission Schofield et al. (1997).

368 The harmonic components – principal components - of daily pressure variations
 369 sheds light on our understanding on the atmospheric phenomena behind the com-
 370 plex structure of daily pressure cycle. The principal components of the atmospheric
 371 diurnal pressure variation can be revealed by decomposing the pressure observations
 372 through Fourier transformation. The estimated diurnal, semi-, ter- and quad-diurnal
 373 amplitudes are represented by the first four components of the resulting series repre-
 374 sentation, respectively, as shown in Figure 7 together with the Perseverance optical
 375 thickness observations.

376 The Fourier transformations shown in Figure 7 were calculated using a fast
 377 Fourier transform (FFT) scheme. The input data series was created by generating
 378 hourly bins of observations from a window of three sols to get at least one observa-
 379 tion per hour. In case of multiple observations per hour the bin value was achieved
 380 by averaging. The middle sol of the three-sol window was the one that was assigned
 381 the calculated amplitudes and phases. When using this procedure it was assumed
 382 that the three consecutive sols were sufficiently similar for calculating the principal
 383 components. The analysis was performed by sliding the three-sol window over the
 384 first 414 sols of Perseverance observations.

385 The principal components of the Perseverance diurnal pressure variation seem
 386 to be smaller than those measured by the Curiosity rover at Gale crater where tidal
 387 forcing is stronger due to the location close to the equator and also due to the fact
 388 that, at Curiosity’s longitude sector, eastward and westward modes are expected to
 389 interact constructively (Wilson and Hamilton, 1996; Haberle et al., 2013; Harri et
 390 al., 2014).

391 In the light of the strong semi-diurnal component shown in Figure 7 during the
 392 Northern summer (sols 150-250), the prevailing stable 2-peak diurnal pressure cycle
 393 may be due to the strong summertime tidal forcing by relatively high amount of re-
 394 gional airborne dust creating a strong and stable semidiurnal component (Figure 7,
 395 top panel). This situation resembles that in the terrestrial tropics, where diurnal

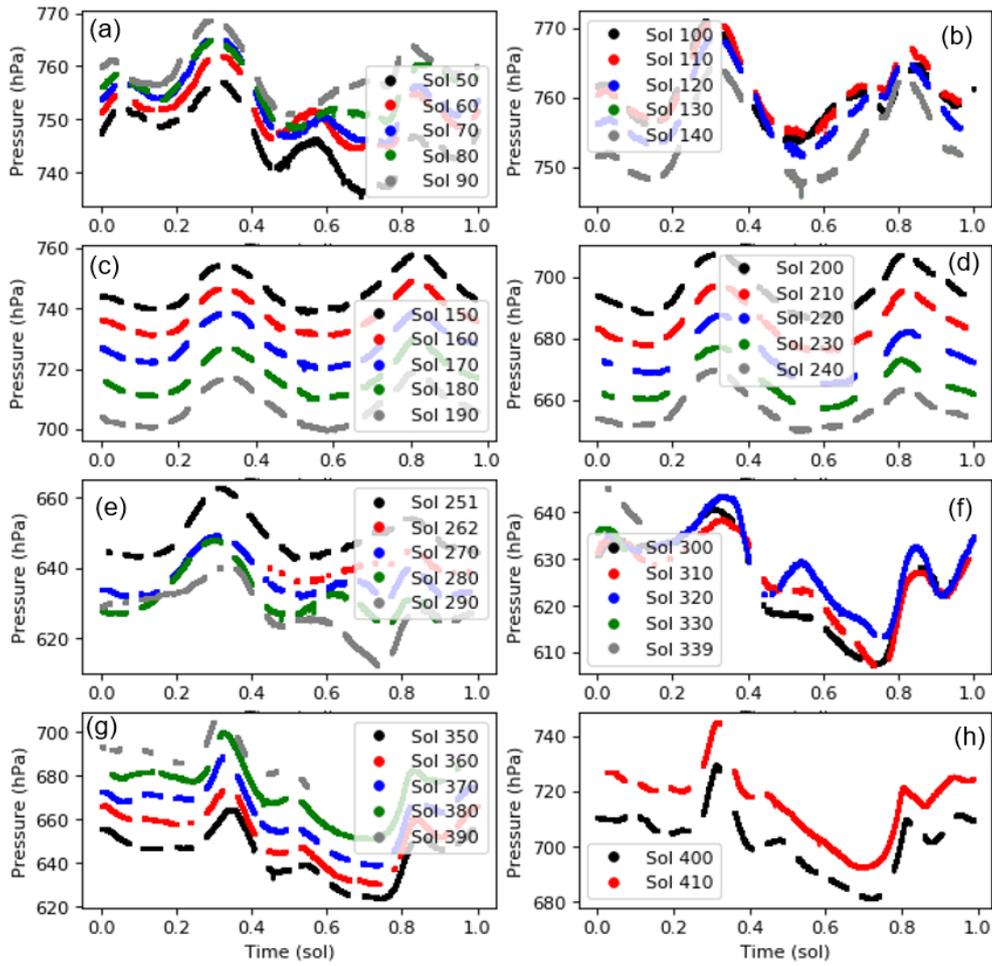


Figure 6. Evolution of diurnal pressure variation in steps of 10 sols covering the first 414 Perseverance sols during the advancing season. Each figure shows data averaged over five sols centered on the sol number shown, except the last on the bottom right (pane h).

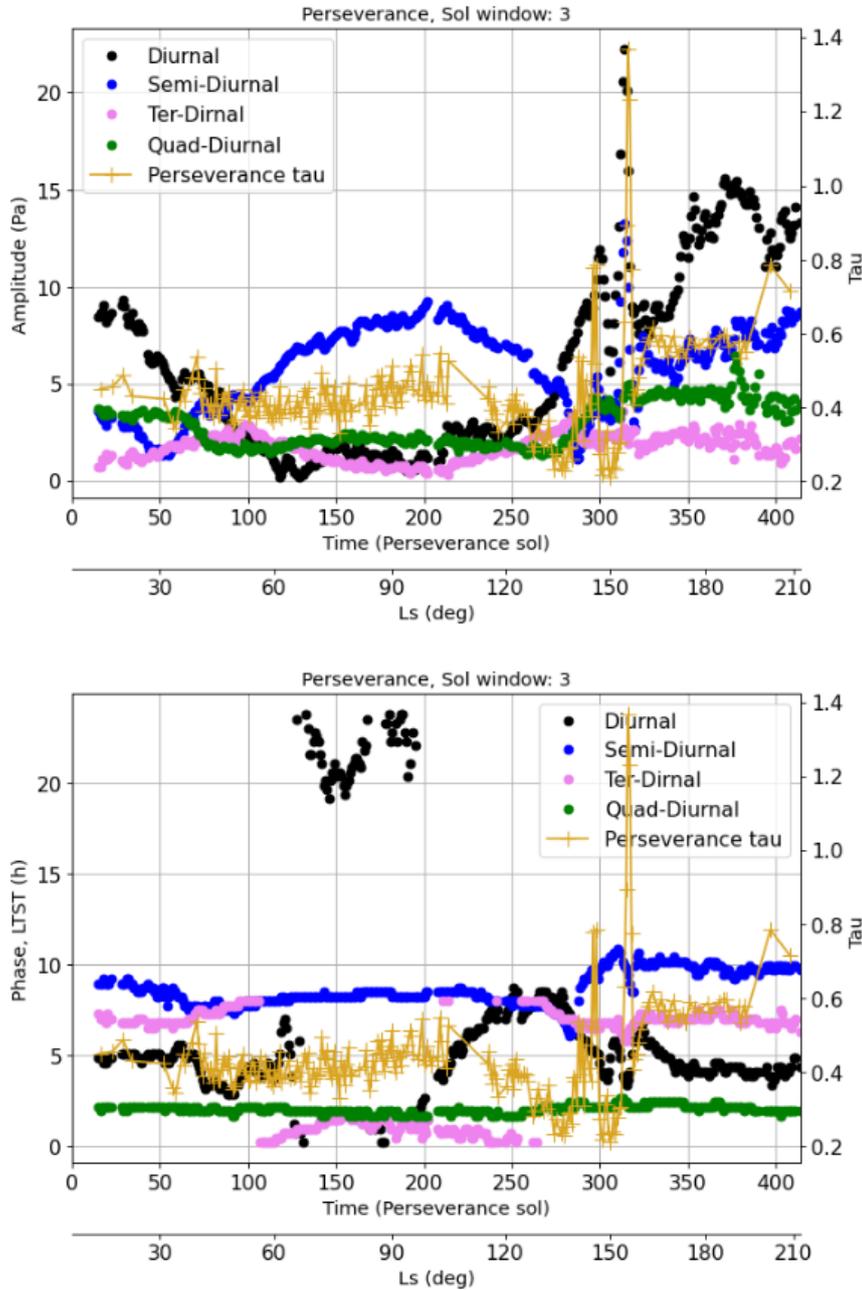


Figure 7. The amplitude and phase of the first four harmonic components of diurnal pressure calculated using FFT for all Perseverance sols. A running averaging window of three sols was used in the calculations. The amplitudes (top pane) and phases (lower pane) are illustrated in different colors (left axis). On the amplitude plot also the optical thickness observed by Perseverance is also shown (right axis).

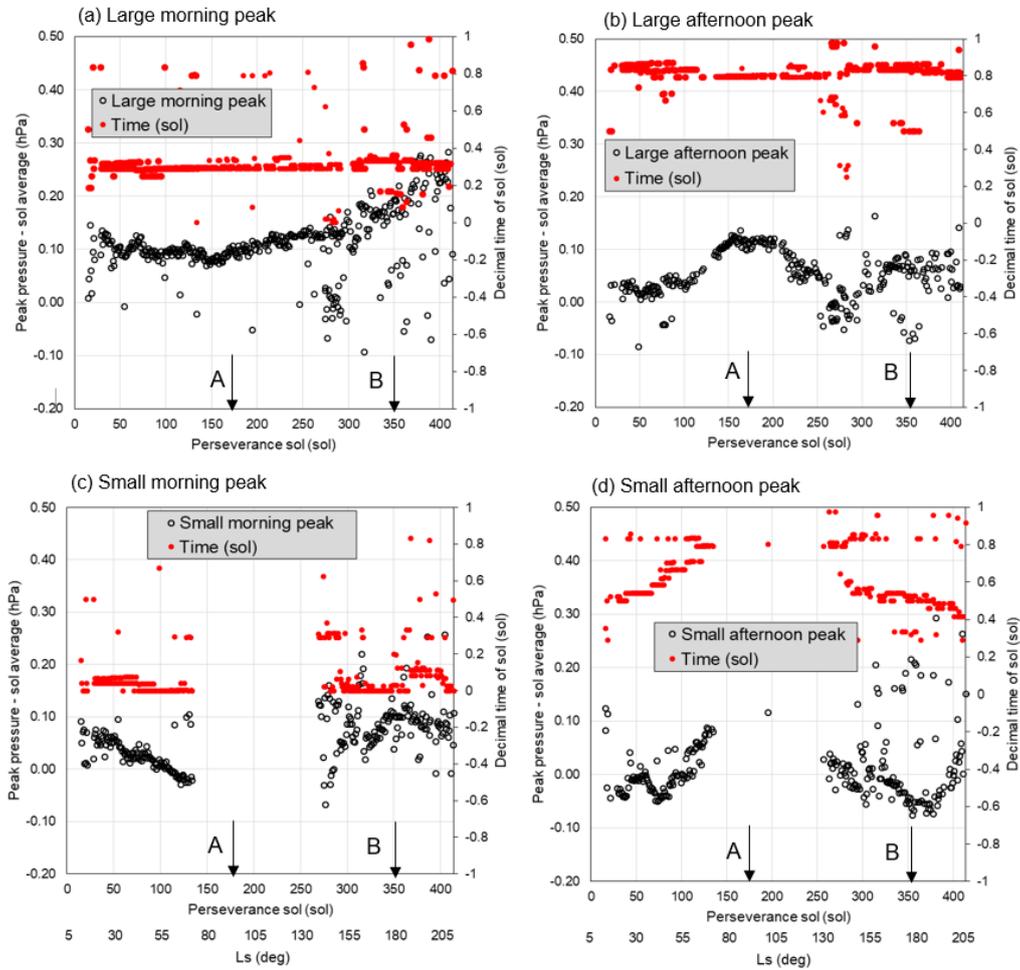


Figure 8. Black circles show the peak pressure minus sol averaged pressure. The time of occurrence of the peaks is also shown in red. The time has an uncertainty on it of plus or minus half an hour. The scatter in the points arises from relatively small fluctuations in flat regions of the data, *e.g.* in the dips between the peaks. The letters 'A' and 'B' point to midsummer (L_s 90°) and fall L_s 180°, respectively.

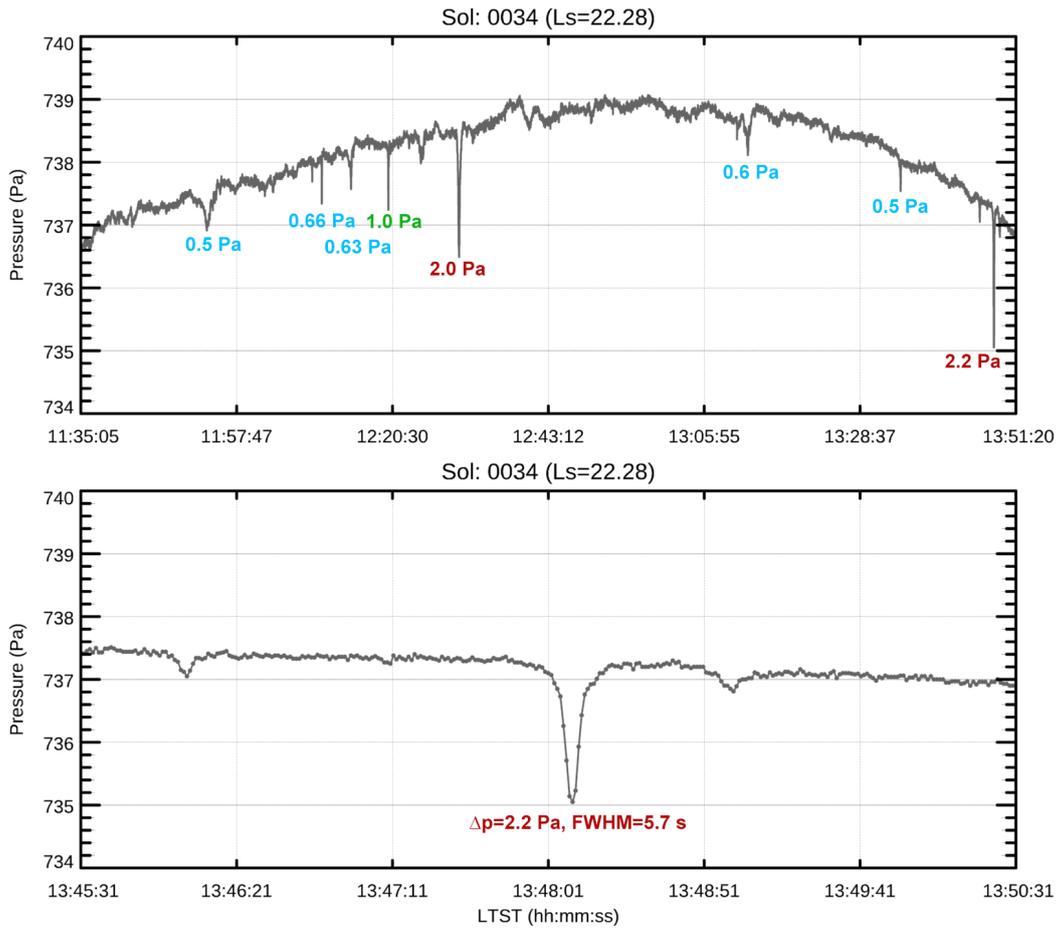


Figure 9. An example of vortex activity detected in pressure data over a 1.5 hour period around noon during the Perseverance mission sol 34. The upper pane displays vortex activity that can be seen as downward spikes in pressure with the depth of some spikes indicated. The lower pane zooms in on the deepest spike (2.2 Pa) to show a more detailed spike structure indicating also the full width at half maximum (FWHM) of the spike.

396 pressure has two distinct peaks, too – one in the morning and one in the evening.
 397 In the terrestrial tropics this is due to high-altitude ozone, whereas in northern late
 398 spring and early summer on Mars this may be due to the ever-present airborne dust
 399 getting heated by solar irradiation (Read and Lewis, 2001).

400 The semidiurnal tidal component at Jezero crater seems to be strong during
 401 Perseverance’s Northern summer. This may be due to the fact that regional atmo-
 402 spheric dust load is relatively high at that time, which would amplify the semid-
 403 iurnal component - assisted by the strong solar forcing at the Northern summer.
 404 Optical depth maps retrieved from the Mars Climate Database, based on data sets
 405 generated by Montabone et al. (2015), seem to support our inference. The maps
 406 from the MCD suggest that during the summer Perseverance is on the western
 407 edge of a patch of elevated optical depth that stretches over several 10s of degrees
 408 of longitude to the west. Later on in the year the optical depth at the latitude of
 409 Perseverance is more homogeneous.

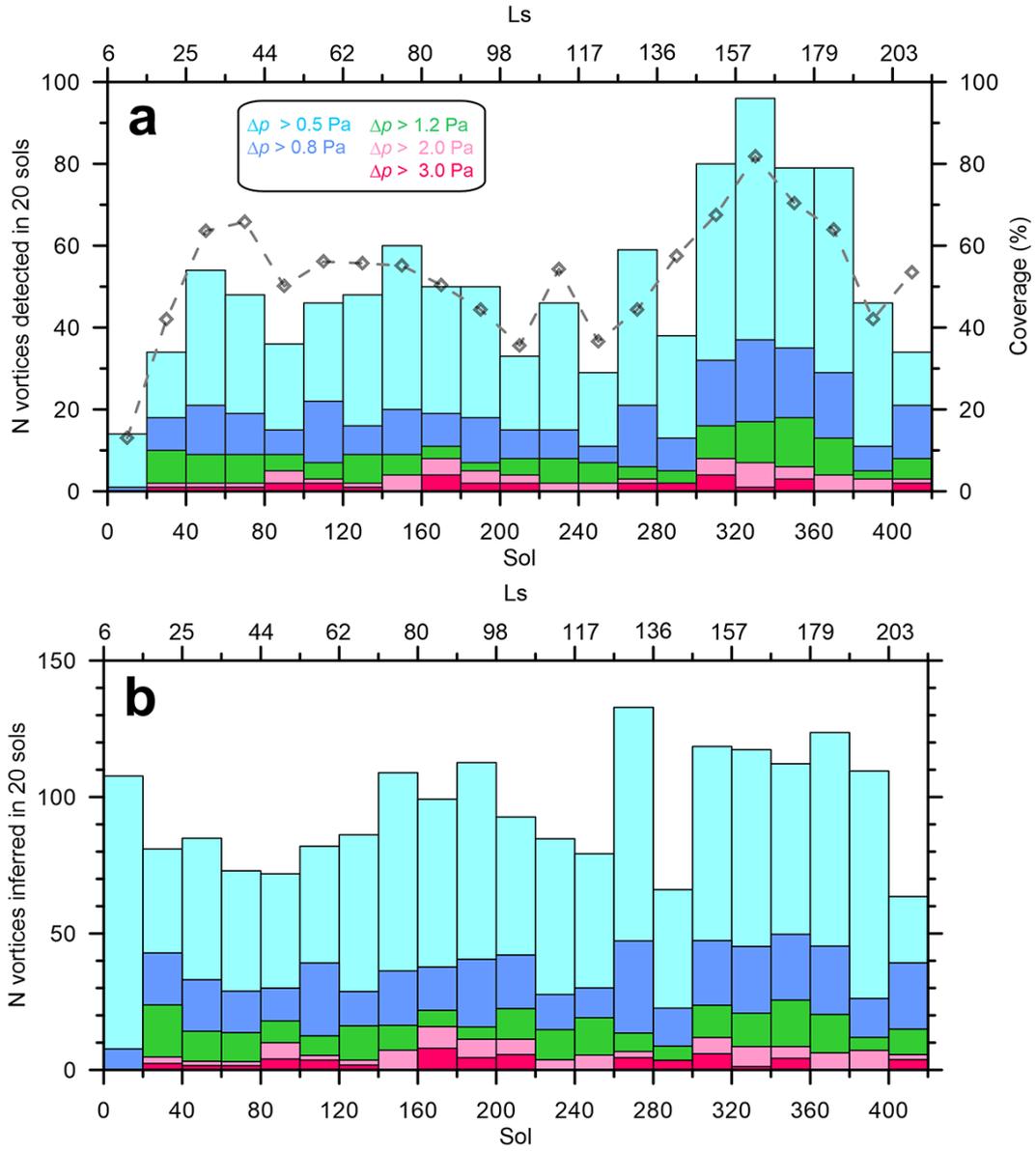


Figure 10. Assessment of the number of vortices by Perceverance through atmospheric pressure drops as a function of sol. (a) Number of vortices actually detected in intervals of 20 sols (left axis). The rhombs show the coverage of MEDA pressure data in each time interval (right axis). (b) Number of vortices that would have been detected if MEDA data would have been measured continuously. In both panes the intensity of the pressure drops is indicated by color coding as explained in the legend.

410 The seasonal evolution of diurnal pressure and its pattern of variation is shown
 411 in Figure 6. We found that during the Northern summertime a fairly stable pattern
 412 of two peaks was prevailing in diurnal pressure variation, but that was broken into
 413 four peaks during the spring and fall. Now, we can study further the evolution of
 414 the daily pressure pattern by analyzing the peaks and their evolution with the ad-
 415 vancing season (Figure 8). This is done by subtracting the average pressure of the
 416 sol of interest from maximum pressure to get the peak amplitude and also noting the
 417 local time of occurrence.

418 Figure 8 shows the peak pressures relative to the daily-averaged sol pressure
 419 and the time that the peaks occur. As can be seen in Figures 6 and 8 there is one
 420 large peak both in the morning and in the afternoon that persist in the daily pres-
 421 sure data. These are clearly illustrated in the top row of Figure 8. The time these
 422 peaks occur remains steady throughout sols 50 to 400 in the data. Their magni-
 423 tude varies with the large morning peak increasing after about sol 150. The large
 424 afternoon peak reaches a maximum around sol 150.

425 Figure 6 shows small morning and afternoon peaks prevailing during North-
 426 ern springtime and fall. They are also depicted in Figure 8, where it can be seen
 427 (bottom row) that the small morning peak occurs at the same time each sol but the
 428 magnitude decreases until about sol 140 and then the peaks disappear. They reap-
 429 pear around sol 270 but appear to fluctuate in magnitude before settling down to
 430 a near constant value around sol 360. In Figure 8 (lower right) the small afternoon
 431 peaks appear to increase in magnitude before disappearing around sol 140. They
 432 then reappear around sol 260 and decrease in magnitude with the advancing sols.

433 These interesting morning and afternoon peak variations illustrated by Fig-
 434 ures 6 and 8 could be a manifestation of local circulation phenomena causing pres-
 435 sure variation, which is then superposed with the strong semidiurnal pressure mode.
 436 During the Northern summer the semi-diurnal thermal tide (as shown by the semi-
 437 diurnal pressure variation) is at its strongest, which creates a stable diurnal pressure
 438 variation with one distinct large peak in the morning and another one in the af-
 439 ternoon. During the Northern spring and fall the semidiurnal mode of the thermal
 440 tide is weaker than in summer. Hence the stable situation is broken resulting in the
 441 creation of two additional small peaks, one preceding the large morning peak and
 442 another preceding the large afternoon peak.

443 This kind of pressure peak structure riding on top of the diurnal pressure
 444 variation is possibly caused by local effects due to the more complex topography
 445 of Jezero crater as compared, *e.g.*, to the topographically more simple and flat re-
 446 gion of the Pathfinder and Viking Lander sites (Soffen, 1976; Schofield et al., 1997),
 447 where such peaks are not so clearly visible. On the other hand, at the Curiosity
 448 rover site additional peaks are also seen in the diurnal pressure variation, which is
 449 likely due to the fact that Gale crater is also a topographically complex site (Harri
 450 et al., 2014; Haberle et al., 2014). Variations in the thermal tide could also intro-
 451 duce multiple oscillations into the observed surface pressure. Schofield et al. (1997)
 452 suggest interference effects between the westward tide and the eastern travelling to-
 453 pographically induced Kelvin mode could produce surface pressure observations with
 454 two minima and two maxima per sol.

455 A highly interesting atmospheric phenomenon regularly observed in pressure
 456 data are convective vortices - called dust devils when raising surface dust in the
 457 atmosphere (Zurek, 1982; Ferri et al., 2003, *e.g.*). These rotating small scale atmo-
 458 spheric phenomena are investigated in this journal issue by (Hueso et al., 2023) us-
 459 ing Perseverance pressure observations. Vortices appear as pressure drops in MEDA
 460 data, some times in bursts of activity as displayed by Figure 9 and 10 based on the
 461 investigations by Hueso et al. (2023). These pressure drops are most likely caused

462 by passages of thermal vortices. Some of these events can be identified as dust devils
 463 when observing with additional MEDA radiative sensors able to infer the presence
 464 of dust, and by other instruments onboard Perseverance such as rover cameras. In
 465 the context of the Aeolian environment of Jezero, thermal vortices were discussed
 466 by Newman et al. (2022). These studies provide the overall abundance of vortices
 467 at Jezero, their daily cycle of activity, which peaks roughly at local noon, with some
 468 seasonal variation in the transition from summer to fall, the frequency of vortices
 469 that carry dust and are therefore dust devils, and establish the link between vortex
 470 activity and the thermal gradient of the near surface atmosphere.

471 An interesting aspect of vortex activity at Jezero revealed originally by the
 472 work of Hueso et al. (2023)) is the nearly constant activity with little seasonal varia-
 473 tion during the period of observation of this investigation. This is demonstrated by
 474 Figure 10 showing the statistics of detected and estimated amount of vortices during
 475 the period of the first 414 Perseverance sols. This allows us to estimate (Figure 10)
 476 that about 100 thermal vortices with pressure drops exceeding 0.5 Pa during a 20
 477 sol period are dwelling in the Perseverance neighbourhood throughout the first 414
 478 Perseverance sols. Thus the vortex activity at Jezero seems to be nearly constant
 479 through the first 414 Perseverance sols. Apparently solar forcing varying consider-
 480 ably from springtime to fall has not significantly affected the generation of vortices.
 481 It is interesting to see whether this pattern will hold through the upcoming North-
 482 ern wintertime with decreasing thermal forcing.

483 Martian atmospheric small scale turbulence and dynamics can be investigated
 484 using Perseverance observations accompanied by additional Perseverance measure-
 485 ments. These phenomena are studied in an accompanying paper in this journal issue
 486 by Sánchez-Lavega et al. (2023).

487 **6 Perseverance diurnal pressure compared with other landing sites** 488 **and modeling results**

489 Atmospheric diurnal pressure variation is affected by *e.g.* the strength of ther-
 490 mal tide, regional and local geography and amount of airborne dust and hence some
 491 local atmospheric phenomena can be partially explained by studying diurnal pres-
 492 sure variation (Zurek, 1982; Zurek et al., 1992b; Haberle et al., 2014; Harri et al.,
 493 2014, *e.g.*). The diurnal pressure amplitude – minimum to maximum range – as a
 494 function of solar longitude for both Perseverance and Curiosity rovers is depicted
 495 in Figure 11 including the measured optical depth. Additionally results by regional
 496 models MWRP (squares) and MRAMS (plus-signs), as well as values by Mars Cli-
 497 mate Database (diamonds) are shown. Furthermore, an uncertainty corridor of two
 498 standard deviations is drawn on the pressure amplitude by smoothing over a few
 499 sols. The standard deviation of the diurnal pressure range is calculated over 10 sols
 500 and it is then drawn on both sides of the curve. Thus the width of the uncertainty
 501 shown is thus twice the standard deviation.

502 The diurnal pressure variation exhibits a clear amplitude increase with the
 503 increasing amount of the atmospheric dust, which was reported by Curiosity pres-
 504 sure observations (Haberle et al., 2013; Harri et al., 2014). This phenomenon has
 505 been discovered also earlier by, *e.g.* Zurek (1978, 1982); Tillman (1988); Kahre and
 506 Haberle (2010). Actually, this is considered as a manifestation of how the Martian
 507 atmospheric conditions are intertwined with the airborne dust to such extent that
 508 atmospheric diurnal pressure observations could even be used to infer the amount of
 509 dust afloat *e.g.* (Zurek, 1981; Guzewich et al., 2016).

510 Figure 11 shows that the observed daily amplitudes in pressure are similar to
 511 those predicted by two atmospheric models that cover Jezero crater at km scale

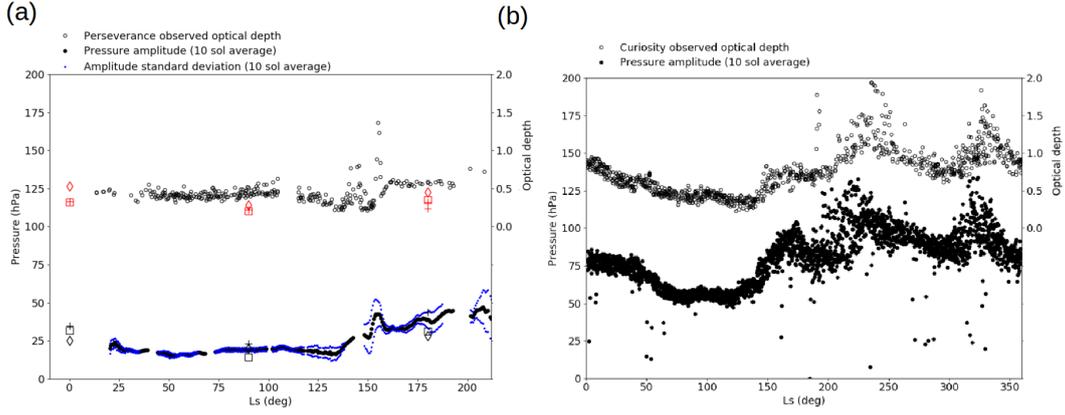


Figure 11. Diurnal pressure amplitude – minimum to maximum range – as a function of solar longitude (black dots, left axis) and the optical depth (small black spheres, right axis). The plots in (a) includes Perseverance pressure (MEDA PS) and optical thickness (M2020 Mastcam-Z) data during the first 414 Perseverance sols and in (b) all Curiosity pressure (REMS-P) and optical thickness (MSL Mastcam) data until Perseverance mission time. The depicted diurnal pressure range is a 10-sol moving average in both plots. The Perseverance plot also includes a 2-sigma belt around the diurnal pressure with the standard deviation (sigma) calculated from the 10 sols for each average point. Additionally results by regional models MWRF (squares) and MRAMS (plus-signs), as well as values by Mars Climate Database (diamonds) are shown.

512 resolution (MRAMS and MarsWRF). The amplitude predicted by MRAMS is usu-
 513 ally slightly higher and MarsWRF slightly lower, for the Ls with data available. The
 514 models use TES optical depth zonally averaged over previous non dust storm years
 515 (Pla-Garcia et al., 2020) (Newman et al., 2021). As to the MCD values for the loca-
 516 tion of Perseverance (18°N, 77°E) the optical depth used in these models is similar
 517 to those observed by Perseverance. Note that the pressure amplitude in the MCD,
 518 which has a resolution of order several hundred km, is also similar to that observed
 519 by Perseverance.

520 It is interesting to compare the average amplitude of diurnal pressure varia-
 521 tion – minimum to maximum value – at different locations and for varying Martian
 522 altitudes and terrain. The Martian atmospheric pressure has some interannual varia-
 523 tion, but it appears to be sufficiently small to the extent that the atmospheric pres-
 524 sure at each landing site seems to be behaving largely in a similar fashion from year
 525 to year as shown by, *e.g.*, Tillman (1988); Tillman et al. (1994). This interannual
 526 similarity justifies qualitative and also somewhat quantitative comparison of pres-
 527 sure by different landing missions even if they are not observed at the same time,
 528 but rather in different Martian years. This applies especially to diurnal pressure
 529 variation that is being largely driven by thermal tide, local geography and regional
 530 atmospheric flows.

531 Figure 12 depicts the daily pressure amplitude during the first 414 sols of the
 532 Perseverance mission with concurrently observed daily pressure amplitudes of the In-
 533 sight and Curiosity missions, as well as that of historical Viking Landers, Pathfinder
 534 and Phoenix mission data at matching solar longitudes. Basic characteristics of
 535 those seven Martian missions are shown in Table 1 including the climate zones and
 536 geographical locations (also in Figure 1) of those missions.

537 It can be readily seen in Figure 12 that the daily pressure amplitude of Per-
 538 severance, Viking Lander 1 and Pathfinder are quite similar, which is likely caused
 539 by the fact that they are at similar latitudes and experience similar thermal tides.
 540 The tides also have a distinct pattern in longitude too, though, due to interference
 541 by the large-scale topography although this does not seem to be a factor here. A
 542 regional dust storm like in the case of Viking Lander 1 starting on around L_s 200°
 543 increases the amplitude. In the case of Pathfinder the amplitude variation increases
 544 considerably as a function of the Martian season (Schofield et al., 1997). The diurnal
 545 pressure amplitude seems to be highest at the Curiosity and Insight landing areas,
 546 which are located close to the equator and hence have the strongest thermal tides.
 547 On the other hand, Phoenix observations have the lowest diurnal pressure amplitude
 548 as expected due to the weaker thermal tide occurring at such high latitudes.

549 Basic characteristics of those seven Martian missions are shown in Table 1
 550 including the climate zones and geographical locations (also in Figure 1) of those
 551 missions. It is to be noted that similarities on some of those characteristics allow
 552 interesting considerations to be made. Insight and Perseverance have a very sim-
 553 ilar altitude above the Martian geoid, which allows for direct comparison of the
 554 sol-averaged pressure data including the pressure variation with advancing Martian
 555 season. This is the most direct possibility for comparisons. As to the longitudinal
 556 location, Perseverance seems to be relatively isolated from the other landed missions.
 557 When inspecting the latitudinal location, Perseverance shares the same climate zone
 558 – North subtropics – with the Pathfinder and Viking 1 landers and is similarly able
 559 to feel the additional effects of baroclinic disturbances through the mesoscale small
 560 pressure variations that these disturbances cause at the surface. The same applies
 561 also to the traveling low- and high-pressure systems – typical both on Mars and
 562 the Earth - causing pressure variations in a 2–5 sols time range especially in the
 563 wintertime subtropics and low midlatitudes (James et al., 1992).

564 The shape of diurnal pressure variation at different Martian landing sites in
 565 four periods evenly separated over the first 414 Perseverance sols are shown in Fig-
 566 ure 13. In each case, two sols of data are shown figure 13 (top left) shows clearly
 567 that the diurnal pressure amplitude observed by Curiosity in Gale crater is larger by
 568 a factor of 2-3 than for Perseverance in Jezero crater. The diurnal pressure ampli-
 569 tude observed by some other landing missions (Figure 13, top right) – Pathfinder,
 570 Viking Landers, Insight - is also smaller than what Curiosity has observed. The
 571 large amplitude of pressures observed by Curiosity has been shown by using atmo-
 572 spheric models to arise from the influence of a daily cycle of heating on the large
 573 slopes of Gale crater, such that warming of air causes mass to flow out of the crater
 574 in order to maintain hydrostatic balance along the slopes (Richardson and New-
 575 man, 2018). Perseverance observations indicate that the diurnal pressure range at
 576 the Jezero crater is smaller by a factor of 2-3, somewhat smaller amplitude than
 577 measured by Insight, about the same amplitude than calculated from historical ob-
 578 servations of Viking lander 1 and 2 and, however, somewhat larger than diurnal
 579 pressure range measured by the Phoenix mission.

580 In the two lower rows of Figure 13 (panes c-f), approximately two sols for each
 581 lander at four solar longitude values marked in panes a-b are shown. Perseverance
 582 can be seen to have a similar mean pressure to InSight. This is likely due the similar
 583 elevations of around -2.6 km. The diurnal pressure patterns are similar in amplitude
 584 but slightly out of phase between Perseverance and InSight, most likely due to the
 585 59° difference in longitude, i.e. the thermal tide will pass over Insight and then over
 586 Perseverance four hours later. Also note that the diurnal patterns for Curiosity and
 587 InSight, separated by only one degree of longitude, are similar except that Curiosity
 588 has a greater diurnal amplitude.

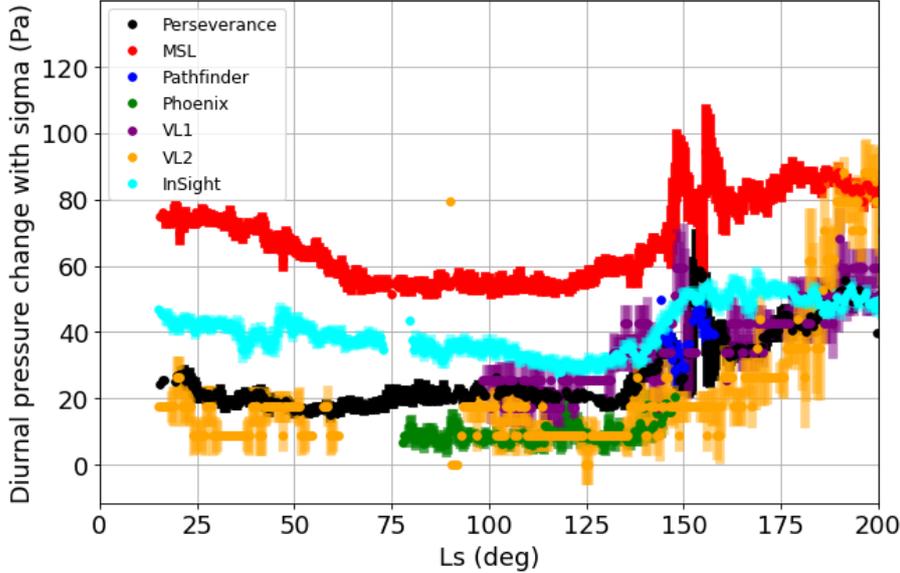


Figure 12. Diurnal pressure amplitude – minimum to maximum value – during the first 414 sols of the Perseverance mission with concurrently observed diurnal pressure amplitude of InSight and Curiosity missions, as well as that of historical Viking Landers, Pathfinder and Phoenix mission data on matching solar longitude range. Each diurnal pressure point is a moving 3-sol central average. The thickness of the curves represent the value of 2 standard deviations calculated over seven sols around each average diurnal pressure point.

589 At the Viking lander 2 site the daily pressure amplitude approaches similar
 590 levels to those observed by Curiosity only in the second half of the year, i.e. in the
 591 winter, as can be seen in figure 13 (b). The diurnal pressure amplitudes for the
 592 landers at high latitudes, i.e. Phoenix and Viking lander 2, during the northern
 593 hemisphere summer are small because of the weak thermal tide (Zhao et al., 2015).
 594 Curiosity and InSight latitudes (Table 1) are close to the equator and both have
 595 consistent daily pressures amplitudes throughout the year suggesting little variation
 596 in the thermal tide conditions at these latitudes.

597 Regional atmospheric modeling efforts are needed to expand the value of the
 598 *in situ* observations. This was done by running MarsWRF and MRAM models (Pla-
 599 Garcia et al., 2021) at the Perseverance site on solar longitude values of L_s 270°,
 600 90°, 180° and 270°. Figure 14 illustrates these results together with *in situ* Persever-
 601 ance observations at L_s 0°, 90°, 180° as well as data points acquired from the Mars
 602 Climate Database MCD (LMD-Jussieu, 2021).

603 MarsWRF and MRAMS simulate Jezero crater at high resolution. Mar-
 604 sWRF is a mesoscale nest embedded inside a global model model and MRAMS is
 605 a mesoscale model. Overall, MarsWRF and MRAMS as well as the lower-resolution
 606 MCD do fairly well compared to the actual *in situ* pressure observations. MarsWRF
 607 seems to reproduce the dip at 1700 better than MRAMS in Figure 14. MarsWRF
 608 reproduces the main features quite well except the small peaks at noon in the North-
 609 ern springtime (L_s 0°, Figure 14a) and fall (L_s 180°, Figure 14c) where it generates
 610 a shoulder-like feature instead. The average pressure in Figure 14a for MarsWRF
 611 is generally good but in the Northern summertime (L_s 90°, Figure 14b) and fall
 612 (Figure 14c) the average pressure is too low. The height of the peaks in Figure 14b

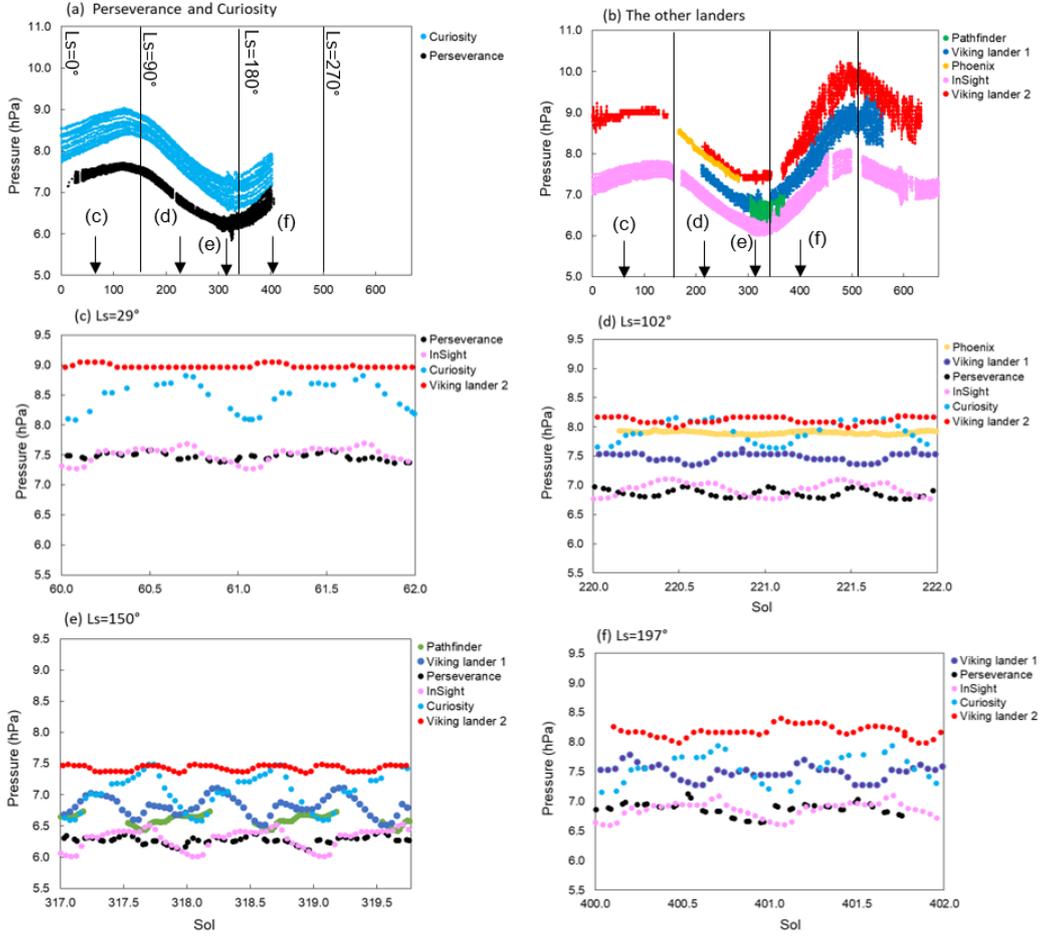


Figure 13. Diurnal pressure range of the Perseverance Rover compared over seasons with the diurnal pressure ranges observed by the Curiosity Rover, Insight Lander, Viking Lander 2 and Pathfinder (top row). Detailed diurnal pressure variation over 2-sol periods on these five surface missions is depicted at four solar longitudes evenly covering the first 414 sols of Perseverance operations. The lander data is plotted against the yearly sol, i.e. midnight on sol 1 corresponds to $L_s=0^\circ$ at the prime meridian, with midnight offset at each landing site depending on their longitude. The 2-sol periods were chosen in (c) to (f) over periods that avoided gaps in the lander data.

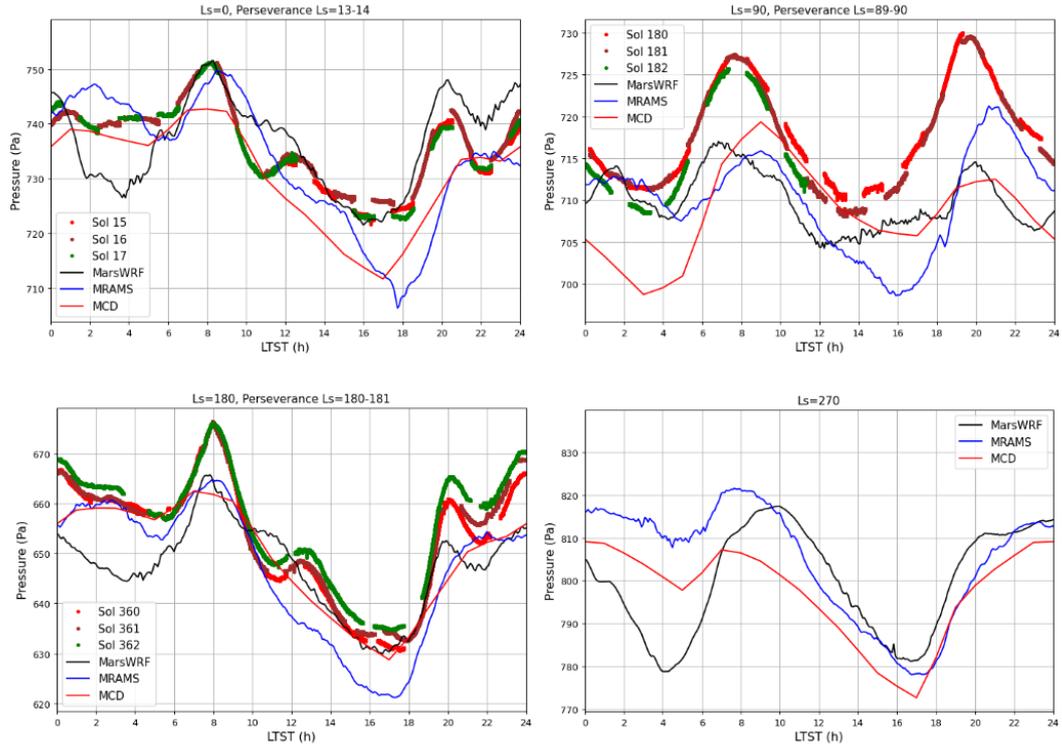


Figure 14. Diurnal pressure variation modeled by atmospheric models that simulate Jezero at km grid spacing MarsWRF, MRAMS and also the same data points from Mars Climate Database at solar longitude L_s 0° , 90° , 180° and 270° , which are depicted in panes a) to d). Around the solar longitude 0, 90 and 180 Perseverance pressure observations from three sols are added (Perseverance has no data as yet at L_s 270°).

613 are too low in the MarsWRF data. MCD is roughly producing in the average similar
614 results to Mars WRF and MRAMS.

615 MRAMS matches the average pressure level quite well in Figure 14a if it was
616 not for the big dip at 1700. It is not clear if it reproduces the peaks at 2200 and
617 midnight. The occurrence of the peaks in the MRAMS data seems to be delayed
618 by about 2 hours. Like MarsWRF MRAM does not reproduce the small peak at
619 noon. MRAMS reproduces the height of the two big peaks in Figure 14b but they
620 are on average too low. The timing of the peaks seems to be delayed by about 2
621 hours in Figure 14b. Overall, it seems to be the case that state-of-the-art regional
622 atmospheric models succeed fairly well in producing diurnal pressure variation at
623 the Jezero crater region. Then, understandably, reproducing through modeling the
624 small peaks in diurnal pressure variation caused largely by the local geography and
625 atmospheric flow conditions proves to be challenging.

626 The distinct oscillations in the observed surface pressure are expected to be
627 primarily due to the thermal tides and their interactions with the Martian topogra-
628 phy, e.g. Wilson and Hamilton (1996). Oscillations in the pressure could also include
629 contributions of the local crater circulations that are especially important for deep
630 craters like Gale crater (Tyler and Barnes, 2015; Wilson, 2017). In addition hydro-
631 static adjustment has been shown to be important in amplification of the amplitude
632 of the diurnal pressure variation (Richardson and Newman, 2018).

633 This complex structure in the pressure signal was anticipated by Pla-Garcia
634 et al. (2020). This is demonstrated in a distinct fashion in figure 14. A more com-
635 prehensive modeling study is needed, but the Perseverance pressure observations
636 support the initial regional atmospheric modeling results at the Perseverance site
637 made with the Mars WRF and MRAMS models as well as the data provided by
638 MCD.

639 Jezero crater does not seem to have a similarly strong amplification from hy-
640 drostatic adjustment as is the case at the Gale crater based on the observations by
641 the Curiosity rover (Harri et al., 2014; Newman et al., 2021). A plausible reason for
642 this is the fact that compared to the Gale crater, the Jezero crater is shallow and
643 wide resulting in relatively weaker amplification effect on the diurnal pressure vari-
644 ation amplitude. In addition the thermal tide at the Gale crater is stronger at most
645 times of year than at Jezero crater because it is closer to the subsolar point for most
646 of the year.

647 Combining the atmospheric regional modeling with *in situ* pressure observa-
648 tions proves to be highly useful – it adds the value of the observations by expanding
649 their effect beyond the actual point of observation and sheds more light on the phys-
650 ical and meteorological processes behind the Martian atmospheric phenomena. The
651 physics and implementation of the models themselves can also be modified to better
652 address the actual atmosphere.

653 **7 Summary and discussion**

654 The Mars2020 Perseverance Rover landed successfully onto the Martian sur-
655 face on the Jezero Crater floor (18°N, 77°E) at the Martian solar longitude L_s 5° in
656 February 2021. Since then it has produced highly valuable environmental measure-
657 ments with a versatile scientific payload including a suite of environmental sensors
658 MEDA (Mars Environmental Dynamics Analyzer). One of the MEDA sensor sys-
659 tems is MEDA PS pressure device weighing 40 grams.

660 The Martian atmospheric pressure observations by MEDA PS have proved to
661 be of excellent quality fulfilling expectations with the estimated overall uncertainty

662 being equal or better than 3.5 Pa and the resolution about 0.13 Pa. The system
 663 resources required by the whole MEDA PS package are dimensions being $62 \times 50 \times 17$
 664 mm, mass 40g and power consumption less than 15 mW.

665 This paper presents initial results of the first 414 sols of Martian atmospheric
 666 surface pressure observations by the MEDA PS device whose performance was found
 667 to fulfill the specification. Observations controlled by the Perseverance resources
 668 allocation schedule cover approximately 50 – 70 % of the Perseverance operational
 669 time.

670 The atmospheric pressure measurement device (MEDA PS) is based on the
 671 silicon-micro-machined pressure sensor head (Barocap®) and transducer technology
 672 developed by Vaisala Inc. The Barocap® version used by MEDA PS is optimized
 673 for the Martian near-surface atmospheric pressure. The transducer electronics and
 674 required electromagnetic shielding and mechanical support structures were developed
 675 by Finnish Meteorological Institute (FMI).

676 The MEDA PS pressure device is making measurements continuously with 1
 677 Hz frequency in average for every other hour according to the operational schedule
 678 by the Perseverance Rover. That enables us to generate data sets with averaged
 679 pressure measurements approximately at 1-hour intervals, as well as data sets with
 680 pressure observations at 1 second intervals for one or a few hours in a row for short
 681 time scale studies. In this work we use data sets with 1-hour intervals. The 1-hour
 682 data sets are not complete but they do have some gaps due to scheduling of Perse-
 683 verance and MEDA operations. However, the available data coverage allows good
 684 characterisation of both the diurnal and seasonal variations in the pressure.

685 The seasonal-to-annual time scales the CO₂ condensation-sublimation cycle
 686 of the Martian atmosphere is nicely demonstrated at the Jezero crater site by the
 687 Perseverance Rover measurements. The observed sol-averaged atmospheric pres-
 688 sure during the 414 first Perseverance sols from the landing time at early Northern
 689 springtime to Northern fall follow an anticipated pattern of total pressure varia-
 690 tion in the course of the advancing season. The data has the first maximum in late
 691 spring roughly on the Perseverance sol 110 and minimum on sol 310, whereas by
 692 the Perseverance sol 414 corresponding to approximately L_s 212° the atmospheric
 693 pressure is climbing higher than the first maximum toward the seasonal maximum.
 694 When comparing Perseverance with concurrent observations by the Curiosity Rover
 695 and the Insight lander as well as with the historical Viking Landers data, we can see
 696 distinct differences with the amplitude of the seasonal pressure variation that are
 697 due to different surface elevations.

698 When comparing pressure observations of the seven Martian landing missions
 699 on different locations on Mars the first part of seasonal atmospheric pressure cycle
 700 measured by Perseverance seems to follow the seasonal increase and decrease in the
 701 atmospheric pressure as expected. The visible bias between the landers' pressure ob-
 702 servations is largely due to different landing elevations. Detailed investigation reveals
 703 that during L_s 0 – 170° the Perseverance pressure looks to be decreasing somewhat
 704 more slowly than the pressure measured by the historical Viking landers. However,
 705 Insight exhibits similar kind of slow pressure decrease and hence this could be due to
 706 a regional occurrence possibly related with the regional topography or variability in
 707 large scale atmospheric flows.

708 The observed diurnal pressure amplitude is ranging roughly within 2 -5 % of
 709 the sol-averaged pressure with the absolute amplitude (10 – 35 hPa) not having a
 710 direct relationship with the sol-averaged pressure. The optical thickness varying
 711 with the amount of airborne dust seems to affect considerably the diurnal pressure
 712 amplitude. The increase of optical thickness from 0.5 to 0.8 around sols 130-160

713 seems to raise the diurnal pressure amplitude from approximately 20 hPa to 35 hPa.
 714 Regional atmospheric models seem to give roughly similar results on the average
 715 diurnal pressure amplitude, when Perseverance -like airborne dust conditions are
 716 assumed.

717 It appears to be evident that the range of diurnal atmospheric pressure varies
 718 considerably with location on Mars. The Perseverance diurnal pressure variation
 719 seem to be smaller than those measured by the Curiosity rover at Gale crater where
 720 tidal forcing is stronger due to the location close to the equator and also due to the
 721 fact that at Curiosity's longitude sector eastward and westward modes are expected
 722 to interact constructively. Comparison with pressure observations at other Martian
 723 sites it looks that also regional and local geography also play a role in the range of
 724 observed diurnal pressure variation.

725 When inspecting the structure of diurnal pressure, 2-4 small peaks appear
 726 in the data on each sol (Figure 6). A clear evolution of the peaks can be seen in
 727 the stacked diurnal pressure data. During Northern summer (Figure 6, second row
 728 from top) diurnal pressure exhibits two distinct and regular peaks, one in the morn-
 729 ing around 6-7 AM and the other one around 8-9 PM LTST. During the Northern
 730 spring (Figure 6, top row) and fall (Figure 6, lowest rows) this summertime regular
 731 pattern is broken into more like four separate peaks whose amplitudes vary along
 732 with advancing season.

733 During Northern springtime - at the start of the mission, Perseverance sols
 734 0-150 - it appears that smaller peaks are superimposed on the larger peaks. These
 735 smaller peaks disappear between about sols 150 and 250 (Northern summertime)
 736 and return around sol 300 in early fall. The wintertime has not yet come during the
 737 first 414 Perseverance sols. The features in the plots give clues on the behaviour of
 738 regional atmospheric dynamics and circulation patterns in the Martian atmosphere

739 The daily surface pressure profile seems to exhibit a largely repeatable two-
 740 peak shape during the Northern summertime (Figure 6). This is probably mostly
 741 due to the strong semi-diurnal thermal tidal component, which seems to be the case
 742 as illustrated in Figure 7.

743 MEDA PS observations allow us to estimate that about 100 thermal vor-
 744 tices with ≈ 0.5 Pa pressure drops during a 20 sol period throughout the first 414
 745 Perseverance sols. Based on this analysis, the vortex activity at Jezero crater in
 746 the vicinity of Perseverance seems to be nearly constant with little seasonal vari-
 747 ation. Apparently solar forcing varying considerably from springtime to fall has
 748 not affected the frequency of occurrence of thermal vortices. It is interesting to see
 749 whether this pattern will hold through the upcoming Northern wintertime.

750 Through *in situ* pressure observations and regional atmospheric modeling re-
 751 sults a distinct local circulation pattern including nighttime katabatic and daytime
 752 upslope flows over the boundary of the Jezero crater was discovered. This circulation
 753 amplifies the diurnal pressure variation.

754 For comparison, the Gale crater diurnal pressure amplitude measured by the
 755 Curiosity Rover is much larger (50 to 120 hPa) than at the Jezero crater. This
 756 may be due to the fact that Gale is smaller and deeper than Jezero resulting in a
 757 stronger diurnal pressure cycle due to hydrostatic adjustment. On the plateaus with
 758 more gentle local circulation the diurnal pressure variation based on Viking Lander
 759 observations is weaker than at the Gale crater and about the same as given by Per-
 760 severance observations. On the other hand Insight diurnal pressure is higher than
 761 that of Perseverance during Northern springtime and summer but assumes roughly
 762 the same level during fall. Apparently the behavior of local diurnal pressure is af-

763 fected by a mixture of solar forcing on the surface, airborne dust, regional geography
764 and atmospheric wave activity.

765 The observed diurnal pressure variation seems to have a significant seasonal
766 dependence. During Northern summer diurnal pressure displays two distinct and
767 regular peaks, one in the morning around 6-7 AM and the other one around 8-9 PM
768 LTST. This regular pattern is likely caused by the interaction of strong thermal tide
769 and the seasonally varying airborne dust causing an amplified semi-diurnal compo-
770 nent. During the Northern fall and spring this summertime regular pattern is broken
771 into four separate peaks whose amplitudes vary along with advancing season.

772 The seasonal form of the diurnal pressure variation was investigated through
773 regional atmospheric modeling by Mars WRF and MRAMS limited area models us-
774 ing the modeling results described in Pla-Garcia et al. (2020). The modeling results
775 were compared with actual MEDA PS observations at solar longitude values L_s 0° ,
776 90° and 180° , as well as with the MCD data. In the summertime (midsummer
777 L_s 90°) the modeling results match very well with the shape and two-peak pattern
778 of diurnal pressure cycle, but they underestimate the average pressure level. These
779 modeling results showed the importance of the boundary fields for the regional mod-
780 els in getting pressure levels correct. Also the complexity of the diurnal pressure
781 signal especially during the springtime and fall was revealed.

782 Overall, the modeling data seems to fit surprisingly well with the Perseverance
783 pressure observations. Mars WRF and MRAMS have higher resolution than the
784 relatively coarse MCD and hence these models pick up the local daily pressure vari-
785 ation better than MCD. But even the MCD seems to work surprisingly well, which
786 is an excellent indication of the capabilities of current Martian atmospheric modeling
787 tools. The modelling data indicates that they are correctly modelling the large-scale
788 forcing of the main components of the daily pressure curves.

789 These modeling efforts underlined the clear need to investigate more in detail
790 the diurnal pressure cycle as a superposition of the thermal tide, regional and local
791 crater circulations and of various barotropic and baroclinic wave forms with seasonal
792 dependence. These differences between the models and the observations inform us
793 about the needs and areas to focus on in improving atmospheric models.

794 8 Open Research

795 The observational data used for this work is available in Planetary Data Sys-
796 tem (PDS) at the web site <https://pds.nasa.gov/>. MEDA instrument data is avail-
797 able in the PDS Atmospheres node in <https://doi.org/10.17189/1522849> (Rodriguez-
798 Manfredi & de la Torre Juarez, 2021).

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Perseverance MEDA Atmospheric Pressure Observations - Initial Results

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Key Points:

- The atmospheric pressure observations by Perseverance Rover have proved to be of excellent quality fulfilling expectations
- Jezero crater pressure exhibits significant differences to other Martian areas likely due to varying regional geography and solar forcing
- Overall, the diurnal and seasonal atmospheric pressure cycles at Jezero Crater follow an anticipated pattern of pressure variation

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Abstract

The Mars2020 Perseverance Rover landed successfully on the Martian surface on the Jezero Crater floor (18.44°N, 77.45°E) at Martian solar longitude, L_s , ~ 5 in February 2021. Since then it has produced highly valuable environmental measurements with a versatile scientific payload including the MEDA (Mars Environmental Dynamics Analyzer) suite of environmental sensors. One of the MEDA systems is the PS pressure sensor system which weighs 40 grams and has an estimated absolute accuracy of better than 3.5 Pa and a resolution of 0.13 Pa. We present initial results from the first 414 sols of Martian atmospheric surface pressure observations by the PS whose performance was found to meet its specifications. Observed sol-averaged atmospheric pressures follow an anticipated pattern of pressure variation in the course of the advancing season and are consistent with data from other landing missions. The observed diurnal pressure amplitude varies by ~ 2 -5 % of the sol-averaged pressure, with absolute amplitude 10-35 Pa in an approximately direct relationship with airborne dust. During a regional dust storm, which began at L_s 135° the diurnal pressure amplitude roughly doubles. The diurnal pressure variations were found to be remarkably sensitive to the seasonal evolution of the atmosphere. In particular analysis of the diurnal pressure signature revealed diagnostic information likely related to the regional scale structure of the atmosphere. Comparison of Perseverance pressure observations to data from other landers reveals the global scale seasonal behaviour of Mars' atmosphere.

Plain Language Summary

The Mars2020 Perseverance Rover successfully arrived at Mars in February 2021. It landed during an early Martian spring afternoon in a crater north of Mars' equator called Jezero crater. The rover is equipped with meteorological instruments that have so far produced extensive and valuable data for understanding the Martian atmosphere. One of the meteorological instruments is an accurate and precise pressure sensor. The pressure sensor has revealed large changes in the pressure over the seasons that are related to large changes in the actual mass of the Martian atmosphere. This is in line with seasonal pressure changes measured during previous Mars missions and can be explained as the freezing of the atmosphere onto the Martian poles and its subsequent thaw. On a shorter time scale the pressure sensor revealed complex pressure changes over a Martian day. These variations are thought to be related to atmospheric dust whose ubiquitous nature is known to have a strong influence on the Martian climate. As the seasons progressed the daily pressure variations morphed to exhibit different patterns likely related to the large-scale regional changes in the atmosphere. Comparison of Perseverance pressure observations to other landers revealed the global nature of the atmosphere.

1 Introduction

The Mars2020 Perseverance Rover landed successfully on the Martian surface on the Jezero Crater floor (18.44°N, 77.45°E) at the Martian solar longitude, L_s , 5° in February 2021. Since then, it has produced highly valuable environmental measurements with a versatile scientific payload including the MEDA (Mars Environmental Dynamics Analyzer) suite of environmental sensors (? , ?). One of the MEDA sensor systems is the pressure sensor (PS) whose observations and initial results utilizing the data acquired during the first 414 sols of the mission ($L_s 5 - 212^\circ$) will be addressed in this manuscript.

Martian atmospheric investigations through spacecraft observations began in the early to middle 1960s as reported by, *e.g.*, ? (? , ?) and later by ? (? , ? , ? , ? , ?).

73 Surface pressure of the atmosphere was firstly estimated using remote sensing meth-
 74 ods, both ground based by *e.g.* (? , ?) and from spacecraft starting from Mariner as
 75 reported by, *e.g.* (? , ?). The Viking landers in 1974-77 provided the first time series
 76 of *in situ* atmospheric observations that turned out to be a treasure trove of data
 77 covering multiple Martian years (? , ? , ? , ? , ?). Thereafter Mars Pathfinder (? , ? , ?),
 78 the Phoenix lander (? , ? , ?), the Mars Science Laboratory aka Curiosity Rover (? , ?),
 79 the InSight lander (? , ?) and the Perseverance Rover (? , ?) have continued *in situ*
 80 investigations of the Martian atmosphere including accurate atmospheric pressure
 81 observations.

82 During the years of *in situ* and remote observations, Martian atmospheric ob-
 83 servations have been accompanied and supplemented by increasingly sophisticated
 84 and varied modeling efforts in a range of spatial and temporal scales already since
 85 late 1960s (? , ? , ? , ? , ? , ? , ? , ? , ? , ? , ?). Pressure observations from surface sta-
 86 tions have prompted investigations of the CO₂ cycle and its connection to the poles,
 87 ice and dust *e.g.* ? (? , ?). The characterisation of pressure changes due to large
 88 scale circulations (? , ? , ?) and local meteorology (? , ? , ?) have been predicted and
 89 characterised using computer models.

90 Data assimilation using orbital data is an important activity to enable realistic
 91 predictions using atmospheric models and verifying the physics (? , ? , ? , ?). Better
 92 understanding of the behaviour of the Martian atmosphere can help develop better
 93 predictions *e.g.* ? (?). A network of surface pressure stations could be key
 94 to characterising fast evolving weather systems and dust lifting events (? , ?). Our
 95 current understanding of the Martian atmosphere and its processes is still under-
 96 standably far less detailed than our understanding of our own terrestrial atmosphere,
 97 but the Martian atmospheric phenomena are presently clearly much better under-
 98 stood than those of any other solar system atmospheres.

99 Some of the earlier Martian landing vehicles have operated at similar latitudes
 100 or elevations to Perseverance, resulting in similarities in terms of climate zone or
 101 annual mean atmospheric pressure. Figure 1 shows the locations of Martian land-
 102 ing vehicles with Martian topography, giving a clear idea of the differences in the
 103 altitude and type of terrain of the landing sites. In terms of longitude, however, Per-
 104 severance seems to be relatively isolated, which has implications when comparing
 105 to data from other landed missions. Perseverance observations also have particular
 106 significance because they mean that for the first time, we have four *in situ* sets of
 107 meteorological observations being carried out at the same time at different locations
 108 on the Martian surface (including observations by MSL, InSight, Perseverance, and
 109 also China’s Zhurong rover, data from which are not currently publicly available).
 110 We will present several interesting initial discoveries based on these facts, in addition
 111 to the independent Perseverance pressure observations.

112 In addition to this article there are two companion articles in this journal uti-
 113 lizing the pressure data focusing on atmospheric dynamics (? , ?) and small-scale
 114 thermal vortices (? , ?).

115 2 Brief MEDA PS device specification and performance

116 **Instrument description.** The Perseverance pressure measurement device
 117 (MEDA PS) is based on the silicon-micro-machined pressure sensor head (Baro-
 118 cap®) and transducer technology developed by Vaisala Inc. The Barocap® version
 119 used by MEDA PS is optimized for the Martian near-surface atmospheric pressure.
 120 Changing ambient pressure is changing the sensor head capacitance by varying the
 121 distance of the sensor head capacitor plates. Besides being pressure dependent, the
 122 Barocap® capacitance is also sensitive to temperature, and thus accurate temper-

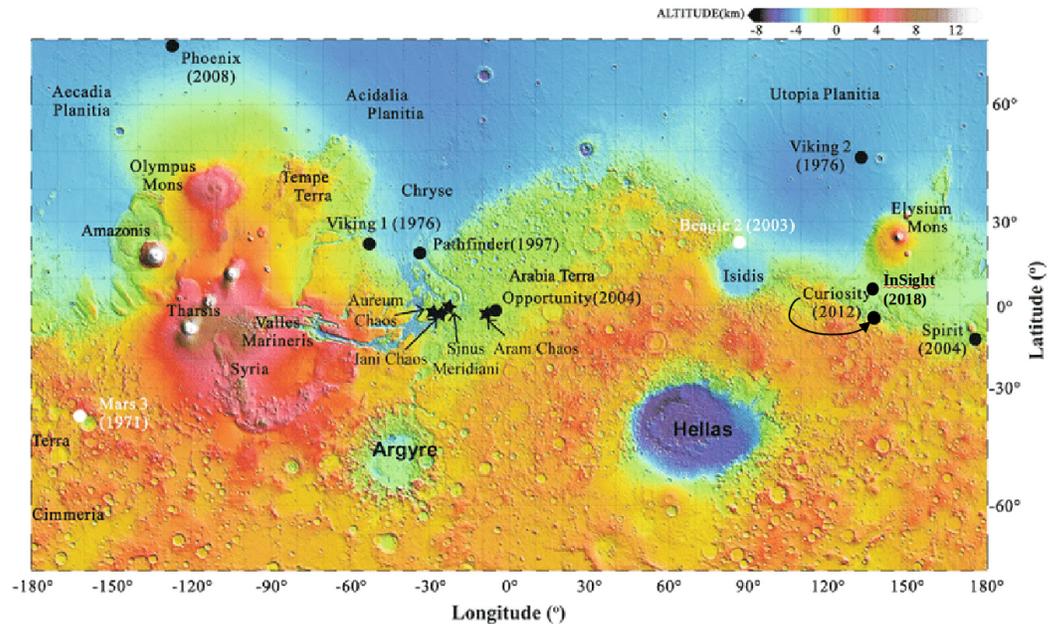


Figure 1. Landing sites of the seven spacecraft having provided *in situ* atmospheric data depicted on a topographic map of Mars (NASA JPL, 2021).

123 ature measurements close to the sensor head are necessary. The supporting house-
 124 keeping temperature measurements are provided by Vaisala’s Thermocap® sensor
 125 heads.

126 MEDA PS consists of two transducers, each having its controlling ASIC (ap-
 127 plication specific integrated circuit) and 8 channels containing the Barocap sensor
 128 heads, Thermocap sensor heads and constant reference capacitors. Two types of
 129 Barocap sensors are used: the NGM type with high stability and relatively long
 130 warm-up time and the less stable but faster RSP2M type as a backup. Hence, the
 131 primary sensor for scientific investigations is the NGM type Barocap on transducer
 132 1 channel 8 and the secondary sensor the RSP2M Barocap on transducer 1 chan-
 133 nel 6. We provide a calibrated pressure reading for both sensor heads in the DER
 134 and CAL type data products in the PDS archive (?, ?) that are optimal for most
 135 investigations.

136 **Calibration and performance.** MEDA PS has been calibrated at the
 137 Finnish Meteorological Institute (FMI) laboratories over the expected operational
 138 pressure and temperature ranges. The calibration has been performed in stable tem-
 139 peratures from -45°C to $+55^{\circ}\text{C}$ and stable pressure points ranging from 0 hPa to
 140 14 hPa, which extend well beyond the pressure and temperature ranges prevailing
 141 within the electronics compartment housing the MEDA PS on Mars itself. Cali-
 142 bration measurements were also performed in changing pressure and temperature
 143 conditions. The Barocap sensors are known to have small changes in the tempera-
 144 ture dependence or sensor offset when introduced to a new electrical and thermal
 145 environment, and thus calibration checks were performed at all stages after the
 146 sensor-level calibration. The calibration checks were performed after integration
 147 to the MEDA electronics compartment (MEDA ICU), during the final rover-level
 148 thermal vacuum test, during the interplanetary cruise and soon after landing on
 149 Mars. The RSP2M Barocaps are also periodically cross-checked against the primary
 150 Barocap for possible drift compensation.

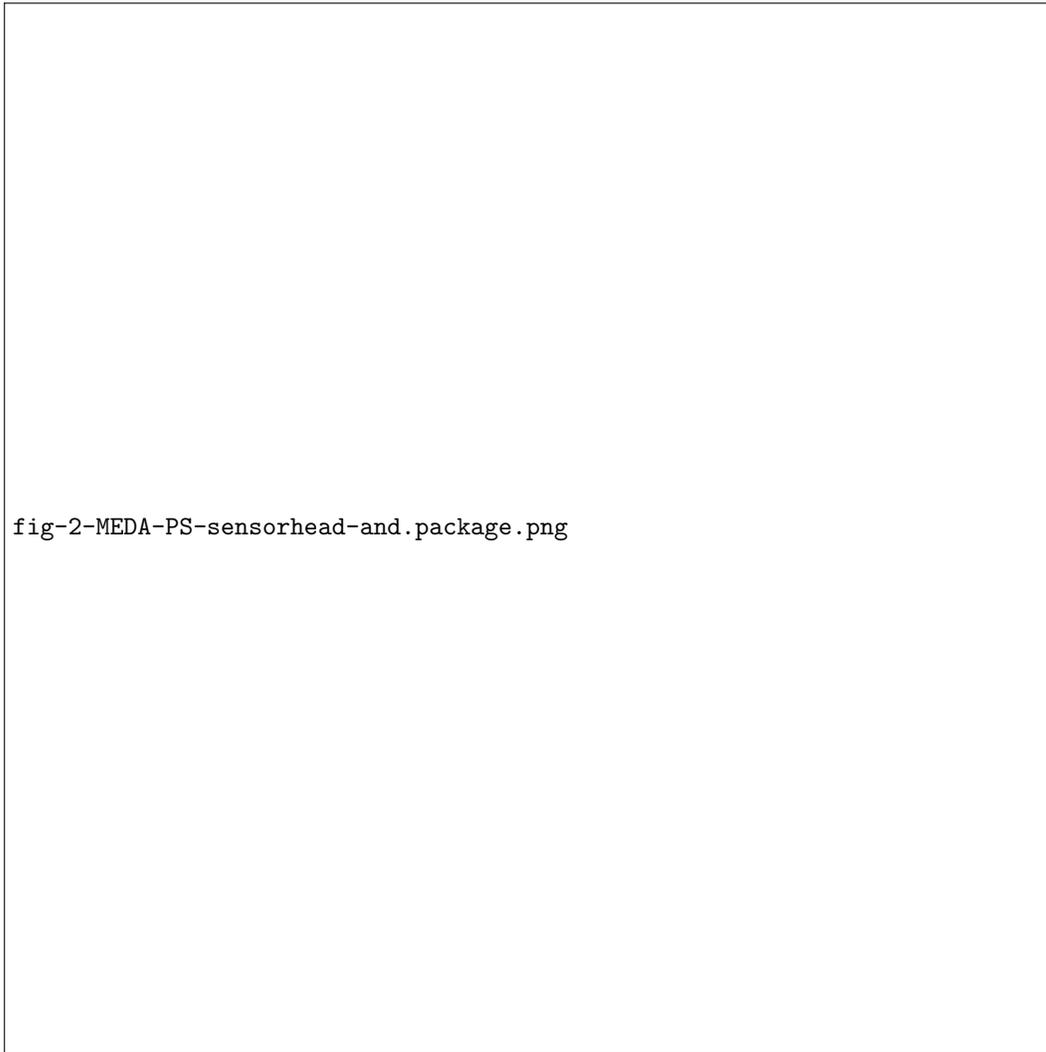


Figure 2. MEDA PS device within its Faraday cage made out of thin conductive foil (left pane) and the instrument with its pressure sensor heads and part of the electronics visible without the Faraday cover (right pane). The structure of the silicon micromachined sensor head is shown on the lower row.

151 The estimated MEDA PS uncertainty based on the sensor- and rover-level
 152 measurements was analyzed to be better than 3.5 Pa. This includes the effects of
 153 the short-term repeatability, environmental effects and the pressure reference accu-
 154 racy. The resolution of the primary Barocap, restricted mostly by the electronics
 155 noise, is 0.13 Pa in nominal measurement mode, and 0.1 Pa in high-resolution mode,
 156 as determined in sensor-level measurements. According to the test data, the time
 157 response of MEDA PS is equal to or less than 1 s, having almost no effect on the
 158 measurements at the nominal sampling rate of 1 Hz. The effect of the warm-up time
 159 of the NGM Barocaps has been removed by the calibration.

160 The system resources required by the whole MEDA PS package are dimensions
 161 $62\times 50\times 17$ mm, mass 43 g and power consumption less than 15 mW. The MEDA
 162 PS detailed specification available before the launch of the Perseverance Rover is
 163 described in detail by (? , ?). The MEDA PS is located inside the MEDA Instru-
 164 ment Control Unit (ICU) in the rover body, with a filter-protected tube connecting
 165 it to the outside environment and conveying ambient pressure to be measured. The
 166 MEDA PS device is depicted in Figure 2 illustrating the pressure sensor head
 167 and its encapsulation of the full pressure device in a Faraday cage giving shielding
 168 against electromagnetic interference.

169 During the first 414 Martian sols of Perseverance operations MEDA PS has
 170 been functioning as expected. The temperature dependence of the Barocap sensors
 171 was checked and corrected at the beginning of the operations against the primary
 172 Barocap, which is known to be very stable based on the test data. In the first drift
 173 offset check performed after 150 sols, the drift of the secondary Barocap was less
 174 than 0.3 Pa and slightly larger for the other RSP2M Barocaps.

175 **3 MEDA PS observation strategy and pressure data coverage**

176 MEDA has been designed for flexible operations that are being conducted
 177 according to the scheduling by the Perseverance rover. MEDA measures for five
 178 minutes at the top of each hour in local mean solar time (LMST) in every mission
 179 sol, other than during exceptional circumstances. In addition, on average, MEDA is
 180 operating continuously for every other hour. That enables us to generate data sets
 181 with averaged pressure measurements approximately at 1-hour intervals, as well as
 182 data sets with pressure observations at 1 second intervals for a period of one hour
 183 or a few hours in a row for *e.g.* turbulence-related studies. There are also periods,
 184 when MEDA is only able to measure for five minutes per hour (or sometimes fifteen
 185 or twenty minutes per hour) or is doing no measurements at all for a few hours, due
 186 to Perseverance resource allocation reasons.

187 In the present investigations we use data sets with 1-hour intervals. The 1-hour
 188 data sets are not complete but they do have gaps due to scheduling of Persever-
 189 ance and MEDA operations. Figure 3 illustrates how well the observed data sets
 190 cover each Perseverance sol. in the average about 50-70 % of the 24 hour of a sol
 191 throughout the season with some periods having 100 % coverage and few sols have
 192 no pressure data at all. The gaps in the 1-hour data set take place more or less ran-
 193 domly around the 24 hour Martian sol. The data coverage of this level allows good
 194 characterisation of both the diurnal and seasonal variations in the pressure.

195 **4 Changes in Jezero crater atmospheric pressure with seasonal** 196 **cycle**

197 The condensation and sublimation of CO₂ in the polar regions during winter
 198 and spring causes planetwide seasonal variations in the surface pressure, which were
 199 first detected by the Viking landers as reported by, *e.g.*, ? (? , ?). The seasonal CO₂

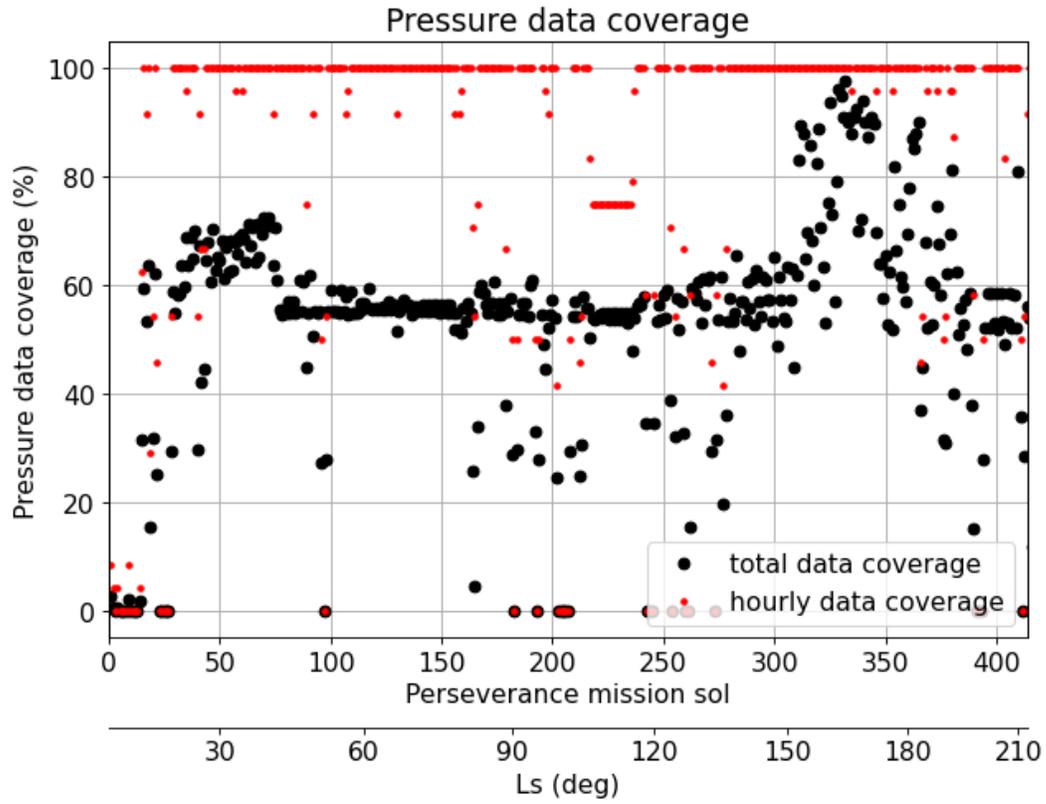


Figure 3. The coverage of atmospheric pressure observations made by the MEDA PS instrument. The black dots depict the overall percentage of pressure readings once per second in a sol, red dots the percentage of the pressure readings available at 1-hour intervals.

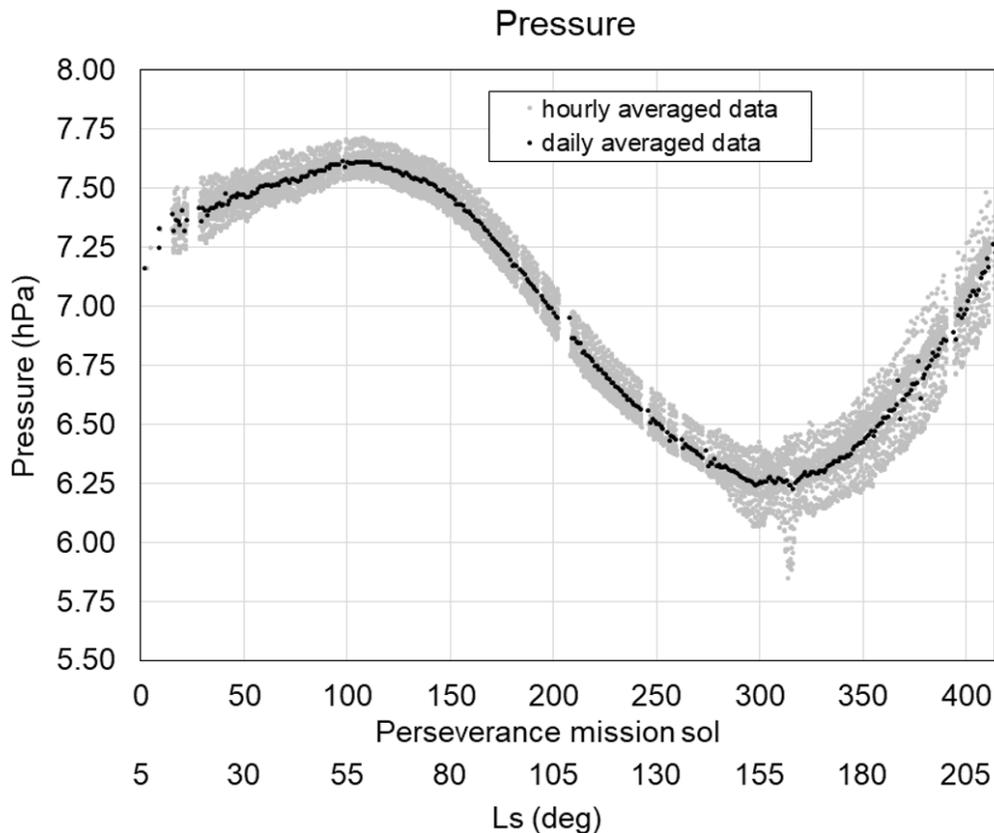


Figure 4. The sol averaged pressure data and the diurnal pressure amplitude (approximate total peak-to-peak range based on observations once per hour) for Perseverance during the period of the first 414 sols corresponding to approximately solar longitude range of L_s 5 – 212°.

200 cycle, which is largely controlled by the polar heat balance (?, ?, e.g.), can clearly
 201 be seen in the seasonal variation of daily average surface pressure.

202 This is nicely demonstrated at the Jezero crater site by the Perseverance Rover
 203 measurements. The daily averaged atmospheric surface pressure during the first 414
 204 sols of the Perseverance mission is depicted in Figure 4. The figure also includes the
 205 range of diurnal pressure variation plotted on both sides of the average pressure line
 206 with a gray color. Hence the gray area illustrates the approximate total range of di-
 207 urnal pressure variation around the average pressure of a sol. The minimum pressure
 208 peak at around Ls 153 shown in Figure 4 was likely caused by a regional dust storm
 209 (?, ?).

210 In seasonal-to-annual time scales the CO₂ condensation-sublimation cycle at
 211 the polar regions gives rise to a seasonal pressure variation on the order of as much
 212 as 30 % of the local surface pressure (?, ?, ?, e.g.). The observed sol-averaged at-
 213 mospheric pressure during the 414 first Perseverance sols, from the landing time
 214 at early Northern springtime to Northern fall, follows an anticipated pattern of to-
 215 tal pressure variation in the course of the advancing season. The data has the first
 216 maximum in late spring roughly on Perseverance sol 110 and a minimum on sol
 217 310, whereas by the Perseverance sol 414 (corresponding to approximately L_s 212°)
 218 the atmospheric pressure is climbing higher than the first maximum toward the an-
 219 nual maximum. When comparing Perseverance with concurrent observations by the

Table 1. Essential characteristics of seven Martian lander missions performing atmospheric observations. The elevations are based on MOLA data (?, ?)

Vehicle	Lat (°N)	Lon (°E)	Elevation (km)	Climate Zone	Operational (years)	Platform Type
Viking lander 1	22	-48	-3.6	North sub-tropics	1976-82	Stationary
Viking lander 2	48	134	-4.4	North mid-latitudes	1976-80	Stationary
Mars Pathfinder	19	-34	-3.7	North sub-tropics	1997	Stationary
Phoenix	68	-126	-4.1	North polar regions	2008	Stationary
Curiosity	-4.6	137	-4.5	Equatorial regions	2012-	Mobile
InSight	4.5	136	-2.6	Equatorial regions	2020-	Stationary
Perseverance	18	77	-2.6	North sub-tropics	2021-	Mobile

220 Curiosity Rover and the Insight lander as well as with the historical Viking Lan-
 221 ders data, we can see distinct differences in the amplitude of the seasonal pressure
 222 variations that are due to different surface elevations.

223 The sol-averaged MEDA PS atmospheric pressure data together with the
 224 hourly-averaged pressure depicted in Figure 4 is nicely showing the evolution of
 225 the atmospheric pressure over first 414 Perseverance sols at the Jezero crater site.
 226 In the beginning of the data set the pressure is going down during the Northern
 227 spring and summer seasons and turning to an increasing leg during the late sum-
 228 mer. The diurnal amplitude, shown approximately by the gray area in Figure 4,
 229 shows a clear increase during periods with increased amounts of airborne dust start-
 230 ing approximately from Perseverance sol 270 and staying high until sol 414 (when
 231 our investigation period ends). There seems to be a direct relationship between the
 232 range of diurnal pressure variation and the amount of airborne dust as has been
 233 earlier discovered by, *e.g.*, ? (? , ? , ?).

234 The seasonal dependence of the Martian atmospheric pressure drives the at-
 235 mosphere to the extent that about one third of the mass of the Martian atmosphere
 236 is deposited on the polar caps during Northern and Southern winters and evapo-
 237 rated back to the atmosphere during summertime. This results in the characteristic
 238 atmospheric pressure pattern having two local maxima and minima during a Mar-
 239 tian year, with the maxima occurring approximately at solar longitudes L_s 60°
 240 and L_s 260° . This pattern can clearly be seen in Figure 5, which compares the sol-
 241 averaged pressure of Perseverance with Curiosity Rover, Insight Lander, Viking
 242 Landers and the Pathfinder mission. Table 1 gives the basic characteristics of each
 243 mission.

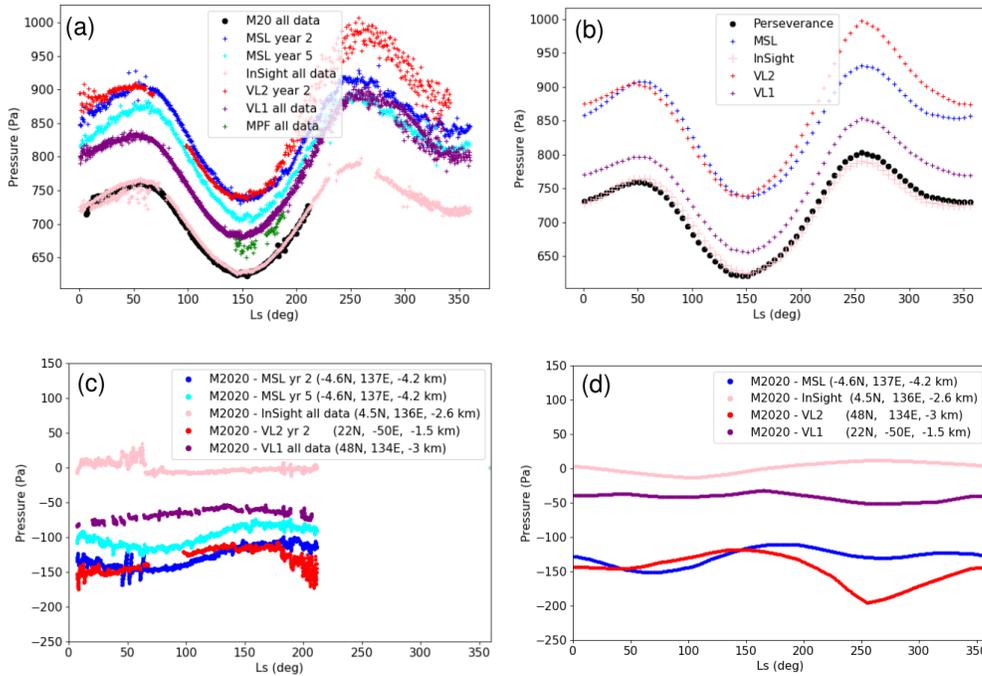


Figure 5. Comparisons of pressure between different lander missions. The top row shows the sol averaged observed pressure data, and the bottom row sol-averaged pressure data by different lander missions subtracted from Perseverance pressures. The left column shows results from the observations while on the right are the same results from the Mars Climate Database.

244 Investigations of the seasonal pressure cycle together with observations from
 245 other Martian landing missions enhance our understanding of the CO₂ cycle, the
 246 annual heat balance of the polar caps and the global scale atmospheric circulation of
 247 Mars (? , ? , ?). Major drivers behind the seasonal variation are solar radiation and
 248 surface and subsurface thermal properties (Wood and Paige, 1992). Atmospheric
 249 dust loading and regional circulation will influence short scale variations (? , ? , ?).
 250 The annually averaged atmospheric pressure is largely depending on the elevation of
 251 the site and hence the atmospheric pressures are differing between observation sites
 252 (? , ? , ?).

253 In order to investigate the relative evolution of the pressure cycle at different
 254 latitudes figures 5 (c) and 5 (d) show the differences in pressure between the Perseverance
 255 landing site and the other four landers, excluding Pathfinder. In figures 5
 256 (c) and (d) a more negative pressure signifies a higher pressure compared to Perseverance.
 257 The results from MCD data shown in figure 5 (d) tracks in the evolution of the results for the
 258 observational data shown in figure 5 (c). For Curiosity there are two sets of lines in figure 5 (c).
 259 These correspond to years 2 and 3 of the mission with year 3 being at a higher elevation which
 260 explain the difference in the mean pressure. There are a number of interesting dip or hump-like
 261 features over timescales of 100-200 sols in figure 5 (c) and (d) that need explaining.
 262

263 The dips and humps in the season pressures in figure 5 (c) and (d) are most
 264 likely connected to latitude dependant processes that include the orographic, i.e.

265 the large difference in elevation between the northern and southern hemisphere,
 266 and the dynamical effects on the pressure cycle (?). Regarding the orographic
 267 effect, during northern hemisphere winter a large mass of cool air is trapped in the
 268 low elevation of the northern hemisphere basin. In the winter a low atmospheric
 269 scale height traps a large portion of the atmosphere. The result is a higher winter
 270 maximum at higher latitudes in the northern hemisphere in winter. For example
 271 the heights of the winter and summer pressure peaks for Viking landers 1 is much
 272 more symmetric than for Viking lander 2. We will not cover dynamical effect here,
 273 which is related to the winds, as it apparently has little influence at the equatorial
 274 and middle latitudes considered here. An explanation of the dynamical effect can be
 275 found in ? (?).

276 The greatest dip seen is for the Viking lander 2 in 5 (d) which is at a lati-
 277 tude of 48°N. This results from the pressure observed by Viking lander 2 increasing
 278 more rapidly than the pressure observed by Perseverance most likely due to the oro-
 279 graphic effect. For the other landers the, except maybe for Curiosity, the pressure
 280 differences in figures 5 (c) and (d) are fairly level indicating the pressures at these
 281 landing site increase more or less at the same rate.

282 A shallow but distinct dip can be seen for Curiosity in figures 5 (c) and (d)
 283 over the spring-summer time period. A possible reason for a dip at this time of year
 284 is that the cold air trapped in the northern hemisphere trapped during the winter
 285 is now being released as it is the summer. This lowers the pressure faster at the
 286 Perseverance landing site than at the Curiosity landing site, which is located near
 287 the equator in the southern hemisphere. This would result a relative increase in the
 288 pressure between Curiosity and Perseverance as seen in figure 5 (c) and (d). Both
 289 plots for Curiosity exhibit a dip around the summer solstice indicating that the pro-
 290 cess driving the evolution of the pressure, i.e. the dip, is not related to the change in
 291 elevation.

292 There are shallow dips and and troughs in the data for other landers in figures
 293 5 (c) and (d) but these are less obvious and probably cannot be interpreted with
 294 much certainty. For example there appears to be a small dip in the MCD data for
 295 InSight in figure 5 (d). This might be expected because InSight is located at a more
 296 southerly latitude than Perseverance with InSight being less sensitive to the ejection
 297 of summer time air from the northern basin than Perseverance. Interestingly this dip
 298 cannot be seen in Figure 5 (c) perhaps suggesting some other process or mechanism
 299 is masking the effect in the observations or limits with the model.

300 5 Diurnal atmospheric pressure and small scale atmospheric phe- 301 nomena

302 *In situ* pressure observations by several landed missions have shown that the
 303 Martian atmospheric surface pressure is composed of variations over several time
 304 scales and amplitudes. They include, *e.g.*, the overarching seasonal CO₂ cycle,
 305 regional-scale perturbations caused by planetary waves and thermal tides, including
 306 their interactions with topography, hydrostatic adjustment flows, and baroclinic and
 307 barotropic disturbances. Small scale eddies and disturbances, *e.g.* convective vortices
 308 are a usual cause of the shortest pressure variations of the order of a few tens of sec-
 309 onds (?), (?), *e.g.*). If the vortices carry an optically distinguishable dust load they are
 310 called dust devils.

311 Thermal tides driven by solar irradiation cause distinct detectable diurnal pres-
 312 sure variations and are especially significant at low latitudes. In the Martian thin
 313 atmosphere the thermal tides - and hence the range of diurnal pressure variation

314 - are much larger than in Earth's atmosphere due to the relatively stronger solar
 315 forcing at the surface (? , ? , ?).

316 At the Jezero crater site measured by Perseverance rover the diurnal atmo-
 317 spheric pressure range seems to be approximately 20 Pa during the first 270 sols of
 318 the mission and thereafter during mission sols 270-414 extending to roughly 40 Pa.
 319 The wider range of diurnal pressure is likely due to increased amounts of airborne
 320 dust measured by Perseverance. Several earlier investigations have found the direct
 321 relationship between the amount of airborne dust and the range of diurnal pressure
 322 variation as shown by, *e.g.*, ? (? , ? , ?).

323 The Perseverance in situ pressure observations show variations ranging from
 324 microscale to seasonal scale as has been observed by earlier *in situ* pressure measure-
 325 ments of Viking (? , ? , ?), Pathfinder (? , ?), Phoenix (? , ?) and Curiosity missions
 326 (? , ? , ?). The advancing Martian season has a clear signature in the atmospheric
 327 pressure as clearly manifested by Figure 6 depicting the diurnal pressure variation
 328 by data stacked in steps of 10 sols. It shows the gradual increase of the observed
 329 Perseverance pressure levels during the Northern spring until approximately sol 110,
 330 then gradual decrease bypassing the Northern midsummer (Ls 90) until sol 320,
 331 and thereafter again showing increasing pressure until the last sol (414) of this in-
 332 vestigation when the season advances further into the Northern fall. The data of
 333 this investigation covers only 60 % of the Martian year, but this kind of seasonal
 334 dependence will be seen throughout the Martian year.

335 When inspecting the structure of diurnal pressure, 2-4 peaks appear in the
 336 data on each sol in Figure 6. A clear evolution of the peaks can be seen in the
 337 stacked diurnal pressure data. During Northern summer (Figure 6, second row
 338 from top) diurnal pressure exhibits two distinct and regular peaks, one in the morn-
 339 ing around 6-7 AM and the other one around 8-9 PM LTST. During the Northern
 340 spring (Figure 6, top row) and fall (Figure 6, lowest rows) this summertime regular
 341 pattern is broken into more like four separate peaks whose amplitudes vary along
 342 with advancing season.

343 It seems that during springtime - at the start of the mission, Perseverance sols
 344 0-150 - smaller peaks are superimposed on the larger peaks. These smaller peaks dis-
 345 appear between about sols 150 and 250 (Northern summertime) and return around
 346 sol 300 in early Northern fall. The wintertime has not yet come during the first 414
 347 Perseverance sols. The features in the plots give clues on the behaviour of regional
 348 atmospheric dynamics and circulation patterns in the Martian atmosphere (? , ? ,
 349 *e.g.*).

350 The largely repeatable two-peak shape of the daily surface pressure profile
 351 especially during the Northern summertime (Figure 6) is likely due to the strong
 352 semi-diurnal thermal tidal component as indicated in Figure 7. Abundant amount
 353 of airborne dust is one cause responsible for amplified semi-diurnal tidal component
 354 as shown by, *e.g.*, (? , ? , ?). Similar two-peak structure was also discovered during
 355 Pathfinder mission ? (?).

356 The harmonic components – principal components - of daily pressure variations
 357 sheds light on our understanding on the atmospheric phenomena behind the com-
 358 plex structure of daily pressure cycle. The principal components of the atmospheric
 359 diurnal pressure variation can be revealed by decomposing the pressure observations
 360 through Fourier transformation. The estimated diurnal, semi-, ter- and quad-diurnal
 361 amplitudes are represented by the first four components of the resulting series repre-
 362 sentation, respectively, as shown in Figure 7 together with the Perseverance optical
 363 thickness observations.

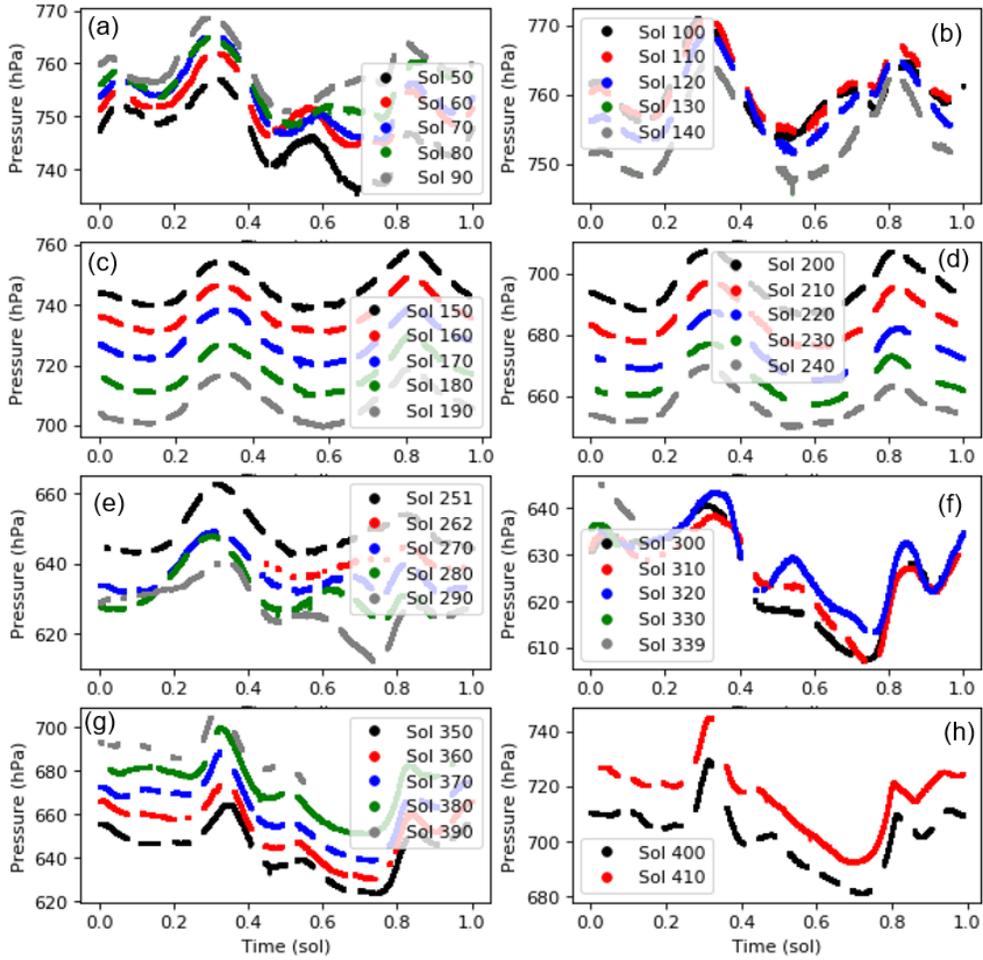


Figure 6. Evolution of diurnal pressure variation in steps of 10 sols covering the first 414 Perseverance sols during the advancing season. Each figure shows data averaged over five sols centered on the sol number shown, except the last on the bottom right (pane h).



Figure 7. The amplitude and phase of the first four harmonic components of diurnal pressure calculated using FFT for all Perseverance sols. A running averaging window of three sols was used in the calculations. The amplitudes (top pane) and phases (lower pane) are illustrated in different colors (left axis). On the amplitude plot also the optical thickness observed by Perseverance is also shown (right axis).

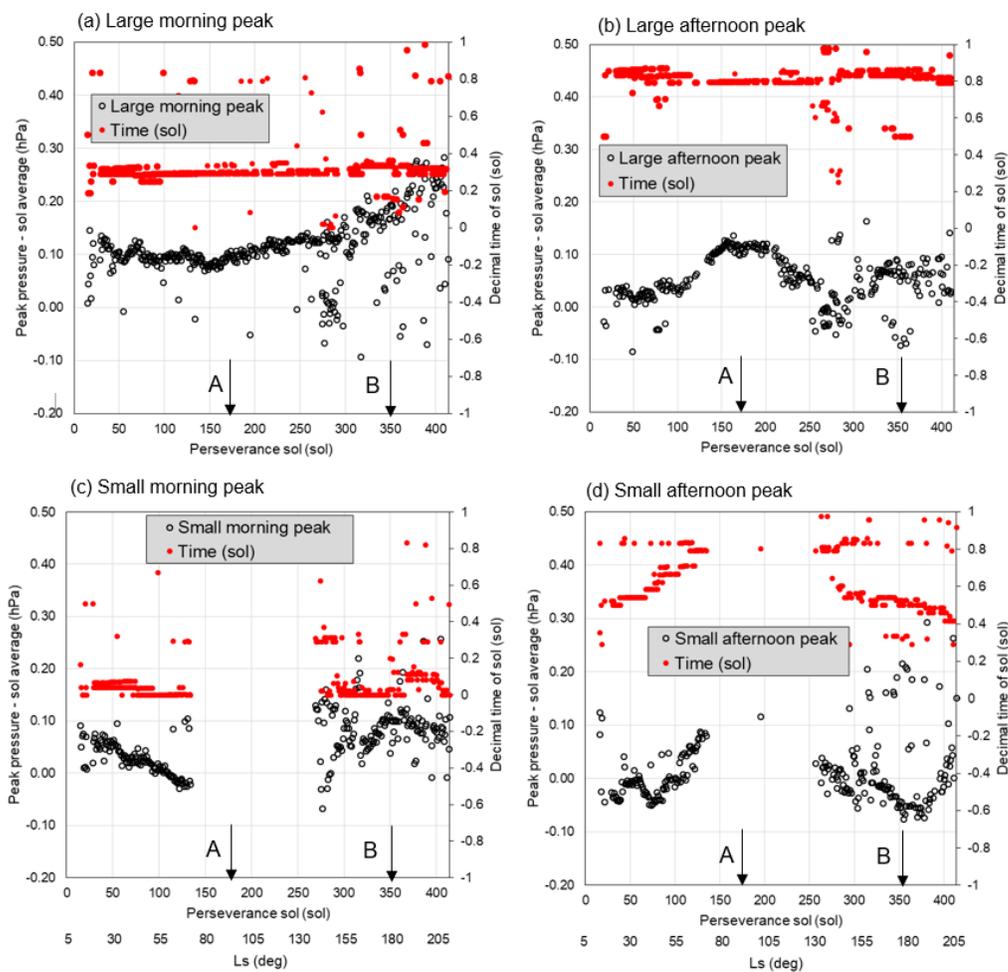


Figure 8. Black circles show the peak pressure minus sol averaged pressure. The time of occurrence of the peaks is also shown in red. The time has an uncertainty on it of plus or minus half an hour. The scatter in the points arises from relatively small fluctuations in flat regions of the data, *e.g.* in the dips between the peaks. The letters 'A' and 'B' point to midsummer (L_s 90°) and fall L_s 180° , respectively.

364 The Fourier transformations shown in Figure 7 were calculated using a fast
 365 Fourier transform (FFT) scheme. The input data series was created by generating
 366 hourly bins of observations from a window of three sols to get at least one observa-
 367 tion per hour. In case of multiple observations per hour the bin value was achieved
 368 by averaging. The middle sol of the three-sol window was the one that was assigned
 369 the calculated amplitudes and phases. When using this procedure it was assumed
 370 that the three consecutive sols were sufficiently similar for calculating the principal
 371 components. The analysis was performed by sliding the three-sol window over the
 372 first 414 sols of Perseverance observations.

373 The principal components of the Perseverance diurnal pressure variation seem
 374 to be smaller than those measured by the Curiosity rover at Gale crater where tidal
 375 forcing is stronger due to the location close to the equator and also due to the fact
 376 that, at Curiosity’s longitude sector, eastward and westward modes are expected to
 377 interact constructively (Wilson and Hamilton, 1996; Haberle et al., 2013; Harri et
 378 al., 2014).

379 In the light of the strong semi-diurnal component shown in Figure 7 during the
 380 Northern summer (sols 150-250), the prevailing stable 2-peak diurnal pressure cycle
 381 may be due to the strong summertime tidal forcing by relatively high amount of re-
 382 gional airborne dust creating a strong and stable semidiurnal component (Figure 7,
 383 top panel). This situation resembles that in the terrestrial tropics, where diurnal
 384 pressure has two distinct peaks, too – one in the morning and one in the evening.
 385 In the terrestrial tropics this is due to high-altitude ozone, whereas in northern late
 386 spring and early summer on Mars this may be due to the ever-present airborne dust
 387 getting heated by solar irradiation (Read and Lewis, 2001).

388 The semidiurnal tidal component at Jezero crater seems to be strong during
 389 Perseverance’s Northern summer. This may be due to the fact that regional atmo-
 390 spheric dust load is relatively high at that time, which would amplify the semid-
 391 iurnal component - assisted by the strong solar forcing at the Northern summer.
 392 Optical depth maps retrieved from the Mars Climate Database, based on data sets
 393 generated by ? (?), seem to support our inference. The maps from the MCD suggest
 394 that during the summer Perseverance is on the western edge of a patch of elevated
 395 optical depth that stretches over several 10s of degrees of longitude to the west.
 396 Later on in the year the optical depth at the latitude of Perseverance is more homo-
 397 geneous.

398 The seasonal evolution of diurnal pressure and its pattern of variation is shown
 399 in Figure 6. We found that during the Northern summertime a fairly stable pattern
 400 of two peaks was prevailing in diurnal pressure variation, but that was broken into
 401 four peaks during the spring and fall. Now, we can study further the evolution of
 402 the daily pressure pattern by analyzing the peaks and their evolution with the ad-
 403 vancing season (Figure 8). This is done by subtracting the average pressure of the
 404 sol of interest from maximum pressure to get the peak amplitude and also noting the
 405 local time of occurrence.

406 Figure 8 shows the peak pressures relative to the daily-averaged sol pressure
 407 and the time that the peaks occur. As can be seen in Figures 6 and 8 there is one
 408 large peak both in the morning and in the afternoon that persist in the daily pres-
 409 sure data. These are clearly illustrated in the top row of Figure 8. The time these
 410 peaks occur remains steady throughout sols 50 to 400 in the data. Their magni-
 411 tude varies with the large morning peak increasing after about sol 150. The large
 412 afternoon peak reaches a maximum around sol 150.

413 Figure 6 shows small morning and afternoon peaks prevailing during North-
 414 ern springtime and fall. They are also depicted in Figure 8, where it can be seen

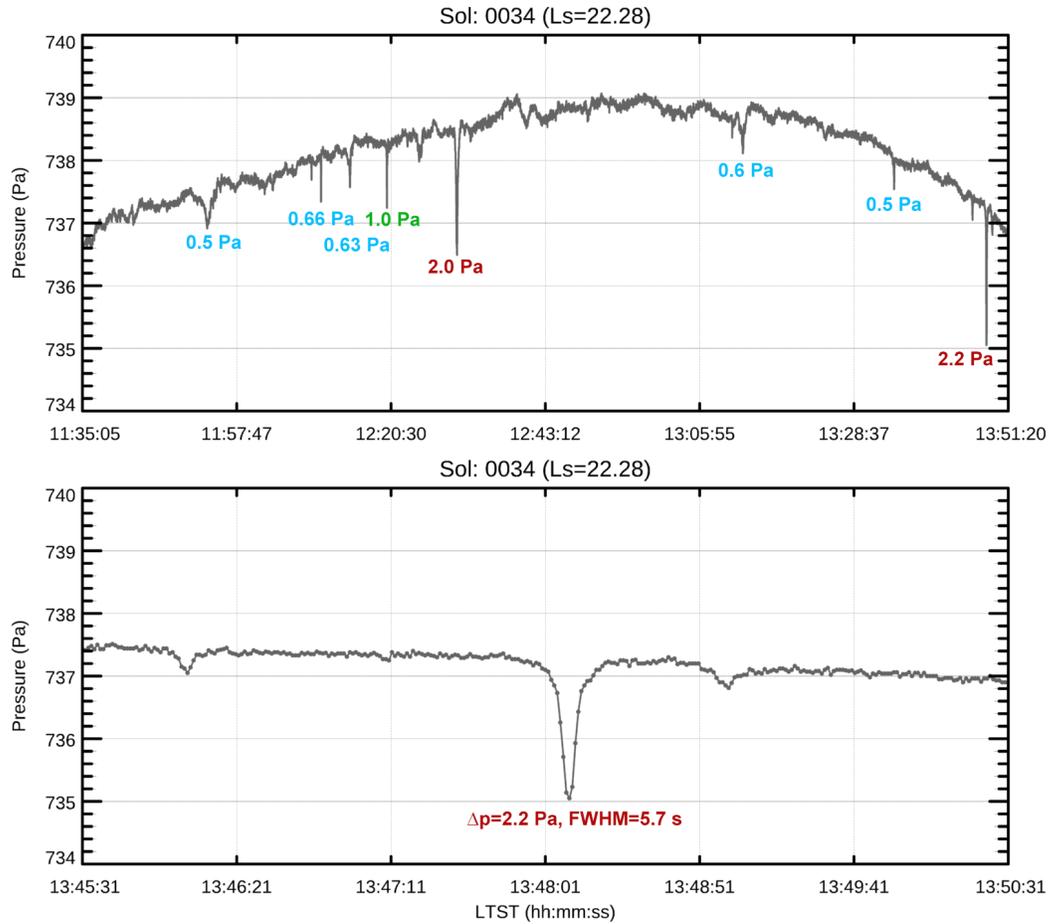


Figure 9. An example of vortex activity detected in pressure data over a 1.5 hour period around noon during the Perseverance mission sol 34. The upper pane displays vortex activity that can be seen as downward spikes in pressure with the depth of some spikes indicated. The lower pane zooms in on the deepest spike (2.2 Pa) to show a more detailed spike structure indicating also the full width at half maximum (FWHM) of the spike.

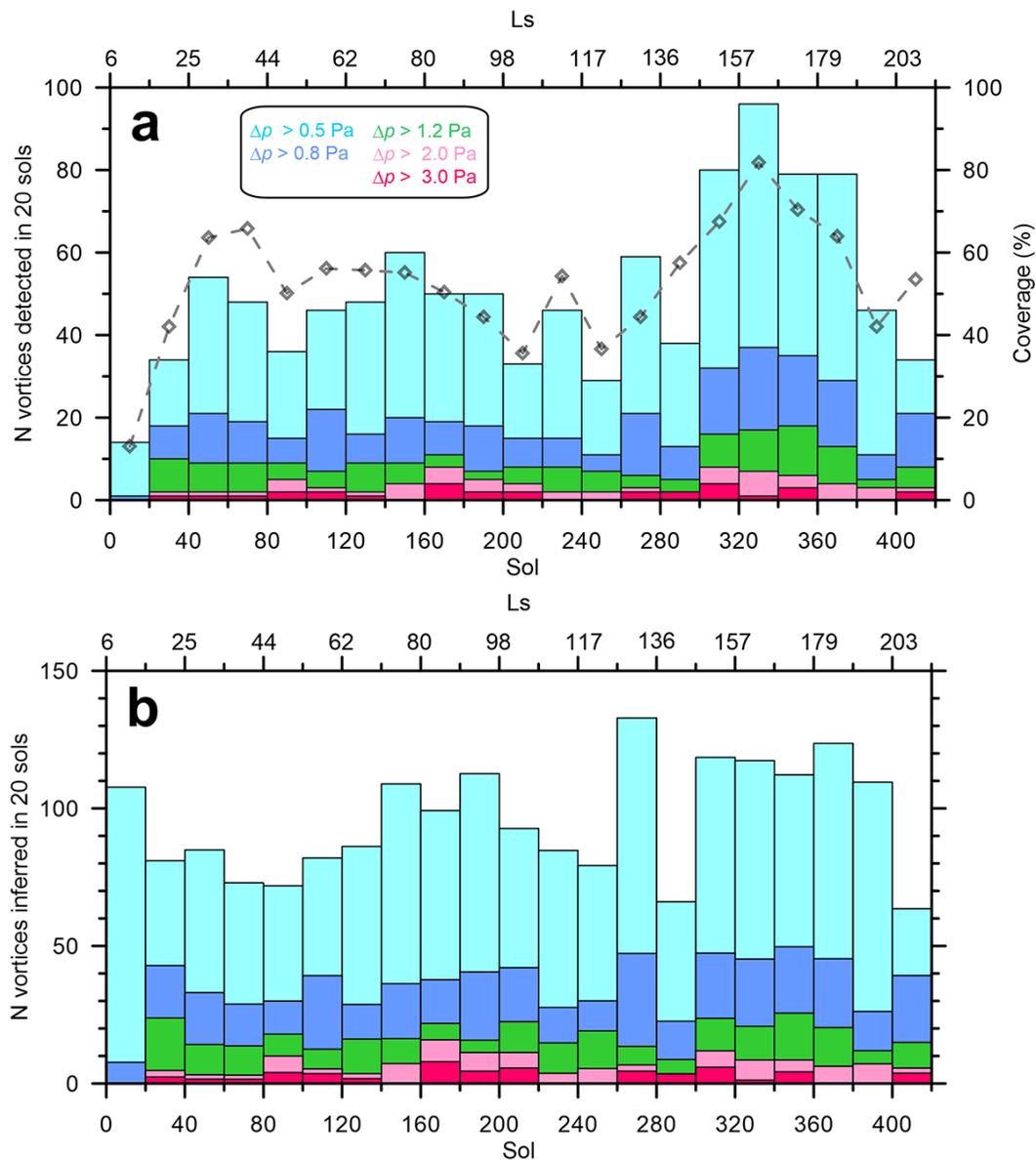


Figure 10. Assessment of the number of vortices by Perceverance through atmospheric pressure drops as a function of sol. (a) Number of vortices actually detected in intervals of 20 sols (left axis). The rhombs show the coverage of MEDA pressure data in each time interval (right axis). (b) Number of vortices that would have been detected if MEDA data would have been measured continuously. In both panes the intensity of the pressure drops is indicated by color coding as explained in the legend.

415 (bottom row) that the small morning peak occurs at the same time each sol but the
 416 magnitude decreases until about sol 140 and then the peaks disappear. They reap-
 417 pear around sol 270 but appear to fluctuate in magnitude before settling down to
 418 a near constant value around sol 360. In Figure 8 (lower right) the small afternoon
 419 peaks appear to increase in magnitude before disappearing around sol 140. They
 420 then reappear around sol 260 and decrease in magnitude with the advancing sols.

421 These interesting morning and afternoon peak variations illustrated by Fig-
 422 ures 6 and 8 could be a manifestation of local circulation phenomena causing pres-
 423 sure variation, which is then superposed with the strong semidiurnal pressure mode.
 424 During the Northern summer the semi-diurnal thermal tide (as shown by the semi-
 425 diurnal pressure variation) is at its strongest, which creates a stable diurnal pressure
 426 variation with one distinct large peak in the morning and another one in the af-
 427 ternoon. During the Northern spring and fall the semidiurnal mode of the thermal
 428 tide is weaker than in summer. Hence the stable situation is broken resulting in the
 429 creation of two additional small peaks, one preceding the large morning peak and
 430 another preceding the large afternoon peak.

431 This kind of pressure peak structure riding on top of the diurnal pressure
 432 variation is possibly caused by local effects due to the more complex topography
 433 of Jezero crater as compared, *e.g.*, to the topographically more simple and flat re-
 434 gion of the Pathfinder and Viking Lander sites (? , ? , ?), where such peaks are not
 435 so clearly visible. On the other hand, at the Curiosity rover site additional peaks
 436 are also seen in the diurnal pressure variation, which is likely due to the fact that
 437 Gale crater is also a topographically complex site (? , ? , ?). Variations in the thermal
 438 tide could also introduce multiple oscillations into the observed surface pressure. ?
 439 (?) suggest interference effects between the westward tide and the eastern travelling
 440 topographically induced Kelvin mode could produce surface pressure observations
 441 with two minima and two maxima per sol.

442 A highly interesting atmospheric phenomenon regularly observed in pressure
 443 data are convective vortices - called dust devils when raising surface dust in the
 444 atmosphere (? , ? , ? , *e.g.*). These rotating small scale atmospheric phenomena are
 445 investigated in this journal issue by (? , ?) using Perseverance pressure observations.
 446 Vortices appear as pressure drops in MEDA data, some times in bursts of activity
 447 as displayed by Figure 9 and 10 based on the investigations by ? (?). These pres-
 448 sure drops are most likely caused by passages of thermal vortices. Some of these
 449 events can be identified as dust devils when observing with additional MEDA ra-
 450 diative sensors able to infer the presence of dust, and by other instruments onboard
 451 Perseverance such as rover cameras. In the context of the Aeolian environment of
 452 Jezero, thermal vortices were discussed by ? (?). These studies provide the overall
 453 abundance of vortices at Jezero, their daily cycle of activity, which peaks roughly
 454 at local noon, with some seasonal variation in the transition from summer to fall,
 455 the frequency of vortices that carry dust and are therefore dust devils, and estab-
 456 lish the link between vortex activity and the thermal gradient of the near surface
 457 atmosphere.

458 An interesting aspect of vortex activity at Jezero revealed originally by the
 459 work of ? (?) is the nearly constant activity with little seasonal variation during the
 460 period of observation of this investigation. This is demonstrated by Figure 10 show-
 461 ing the statistics of detected and estimated amount of vortices during the period of
 462 the first 414 Perseverance sols. This allows us to estimate (Figure 10) that about
 463 100 thermal vortices with pressure drops exceeding 0.5 Pa during a 20 sol period are
 464 dwelling in the Perseverance neighbourhood throughout the first 414 Perseverance
 465 sols. Thus the vortex activity at Jezero seems to be nearly constant through the first
 466 414 Perseverance sols. Apparently solar forcing varying considerably from springtime
 467 to fall has not significantly affected the generation of vortices. It is interesting to

468 see whether this pattern will hold through the upcoming Northern wintertime with
 469 decreasing thermal forcing.

470 Martian atmospheric small scale turbulence and dynamics can be investigated
 471 using Perseverance observations accompanied by additional Perseverance measure-
 472 ments. These phenomena are studied in an accompanying paper in this journal issue
 473 by ? (?).

474 **6 Perseverance diurnal pressure compared with other landing sites** 475 **and modeling results**

476 Atmospheric diurnal pressure variation is affected by *e.g.* the strength of ther-
 477 mal tide, regional and local geography and amount of airborne dust and hence
 478 some local atmospheric phenomena can be partially explained by studying diurnal
 479 pressure variation (? , ? , ? , ? , ? , *e.g.*). The diurnal pressure amplitude – minimum
 480 to maximum range – as a function of solar longitude for both Perseverance and
 481 Curiosity rovers is depicted in Figure 11 including the measured optical depth. Ad-
 482 ditionally results by regional models MWRM (squares) and MRAMS (plus-signs),
 483 as well as values by Mars Climate Database (diamonds) are shown. Furthermore, an
 484 uncertainty corridor of two standard deviations is drawn on the pressure amplitude
 485 by smoothing over a few sols. The standard deviation of the diurnal pressure range
 486 is calculated over 10 sols and it is then drawn on both sides of the curve. Thus the
 487 width of the uncertainty shown is thus twice the standard deviation.

488 The diurnal pressure variation exhibits a clear amplitude increase with the
 489 increasing amount of the atmospheric dust, which was reported by Curiosity pres-
 490 sure observations (Haberle et al., 2013; Harri et al., 2014). This phenomenon has
 491 been discovered also earlier by, *e.g.* ? (? , ? , ? , ?). Actually, this is considered as a
 492 manifestation of how the Martian atmospheric conditions are intertwined with the
 493 airborne dust to such extent that atmospheric diurnal pressure observations could
 494 even be used to infer the amount of dust afloat *e.g.* (? , ? , ?).

495 Figure 11 shows that the observed daily amplitudes in pressure are similar to
 496 those predicted by two atmospheric models that cover Jezero crater at km scale
 497 resolution (MRAMS and MarsWRF). The amplitude predicted by MRAMS is usu-
 498 ally slightly higher and MarsWRF slightly lower, for the Ls with data available. The
 499 models use TES optical depth zonally averaged over previous non dust storm years
 500 (Pla-Garcia et al., 2020) (? , ?). As to the MCD values for the location of Persever-
 501 ance (18°N, 77°E) the optical depth used in these models is similar to those observed
 502 by Perseverance. Note that the pressure amplitude in the MCD, which has a resolu-
 503 tion of order several hundred km, is also similar to that observed by Perseverance.

504 It is interesting to compare the average amplitude of diurnal pressure varia-
 505 tion – minimum to maximum value – at different locations and for varying Martian
 506 altitudes and terrain. The Martian atmospheric pressure has some interannual vari-
 507 ation, but it appears to be sufficiently small to the extent that the atmospheric
 508 pressure at each landing site seems to be behaving largely in a similar fashion from
 509 year to year as shown by, *e.g.*, ? (? , ?). This interannual similarity justifies quali-
 510 tative and also somewhat quantitative comparison of pressure by different landing
 511 missions even if they are not observed at the same time, but rather in different Mar-
 512 tian years. This applies especially to diurnal pressure variation that is being largely
 513 driven by thermal tide, local geography and regional atmospheric flows.

514 Figure 12 depicts the daily pressure amplitude during the first 414 sols of the
 515 Perseverance mission with concurrently observed daily pressure amplitudes of the In-
 516 sight and Curiosity missions, as well as that of historical Viking Landers, Pathfinder
 517 and Phoenix mission data at matching solar longitudes. Basic characteristics of

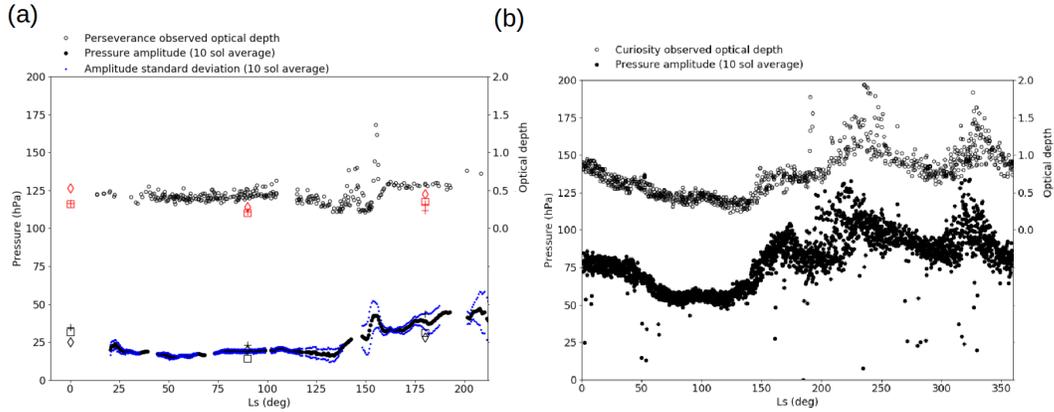


Figure 11. Diurnal pressure amplitude – minimum to maximum range – as a function of solar longitude (black dots, left axis) and the optical depth (small black spheres, right axis). The plots in (a) includes Perseverance pressure (MEDA PS) and optical thickness (M2020 Mastcam-Z) data during the first 414 Perseverance sols and in (b) all Curiosity pressure (REMS-P) and optical thickness (MSL Mastcam) data until Perseverance mission time. The depicted diurnal pressure range is a 10-sol moving average in both plots. The Perseverance plot also includes a 2-sigma belt around the diurnal pressure with the standard deviation (sigma) calculated from the 10 sols for each average point. Additionally results by regional models MWRF (squares) and MRAMS (plus-signs), as well as values by Mars Climate Database (diamonds) are shown.

518 those seven Martian missions are shown in Table 1 including the climate zones and
 519 geographical locations (also in Figure 1) of those missions.

520 It can be readily seen in Figure 12 that the daily pressure amplitude of Perse-
 521 verance, Viking Lander 1 and Pathfinder are quite similar, which is likely caused by
 522 the fact that they are at similar latitudes and experience similar thermal tides. The
 523 tides also have a distinct pattern in longitude too, though, due to interference by the
 524 large-scale topography although this does not seem to be a factor here. A regional
 525 dust storm like in the case of Viking Lander 1 starting on around L_s 200° increases
 526 the amplitude. In the case of Pathfinder the amplitude variation increases consid-
 527 erably as a function of the Martian season (?). The diurnal pressure amplitude
 528 seems to be highest at the Curiosity and Insight landing areas, which are located
 529 close to the equator and hence have the strongest thermal tides. On the other hand,
 530 Phoenix observations have the lowest diurnal pressure amplitude as expected due to
 531 the weaker thermal tide occurring at such high latitudes.

532 Basic characteristics of those seven Martian missions are shown in Table 1
 533 including the climate zones and geographical locations (also in Figure 1) of those
 534 missions. It is to be noted that similarities on some of those characteristics allow
 535 interesting considerations to be made. Insight and Perseverance have a very sim-
 536 ilar altitude above the Martian geoid, which allows for direct comparison of the
 537 sol-averaged pressure data including the pressure variation with advancing Martian
 538 season. This is the most direct possibility for comparisons. As to the longitudinal
 539 location, Perseverance seems to be relatively isolated from the other landed missions.
 540 When inspecting the latitudinal location, Perseverance shares the same climate zone
 541 – North subtropics – with the Pathfinder and Viking 1 landers and is similarly able
 542 to feel the additional effects of baroclinic disturbances through the mesoscale small
 543 pressure variations that these disturbances cause at the surface. The same applies

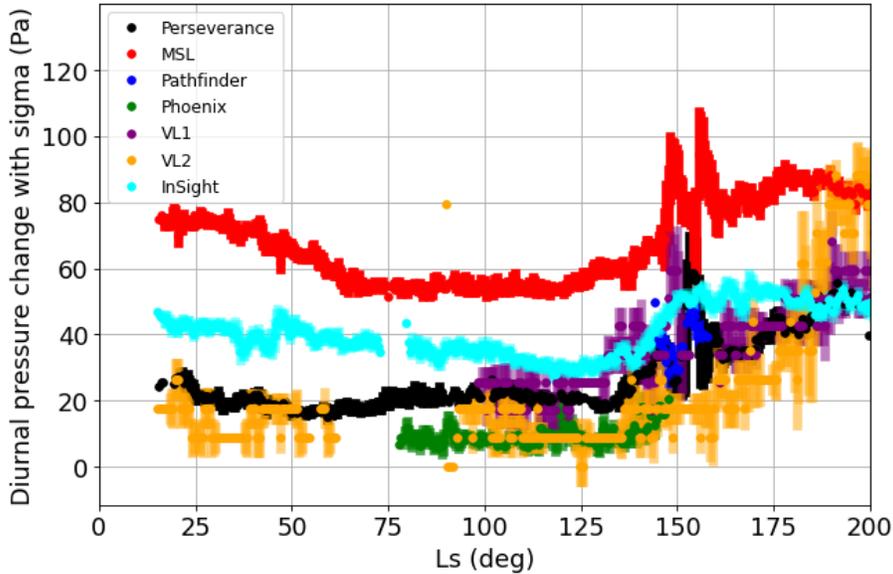


Figure 12. Diurnal pressure amplitude – minimum to maximum value – during the first 414 sols of the Perseverance mission with concurrently observed diurnal pressure amplitude of InSight and Curiosity missions, as well as that of historical Viking Landers, Pathfinder and Phoenix mission data on matching solar longitude range. Each diurnal pressure point is a moving 3-sol central average. The thickness of the curves represent the value of 2 standard deviations calculated over seven sols around each average diurnal pressure point.

544 also to the traveling low- and high-pressure systems – typical both on Mars and
 545 the Earth - causing pressure variations in a 2–5 sols time range especially in the
 546 wintertime subtropics and low midlatitudes (? , ?).

547 The shape of diurnal pressure variation at different Martian landing sites in
 548 four periods evenly separated over the first 414 Perseverance sols are shown in Fig-
 549 ure 13. In each case, two sols of data are shown figure 13 (top left) shows clearly
 550 that the diurnal pressure amplitude observed by Curiosity in Gale crater is larger by
 551 a factor of 2-3 than for Perseverance in Jezero crater. The diurnal pressure ampli-
 552 tude observed by some other landing missions (Figure 13, top right) – Pathfinder,
 553 Viking Landers, InSight - is also smaller than what Curiosity has observed. The
 554 large amplitude of pressures observed by Curiosity has been shown by using atmo-
 555 spheric models to arise from the influence of a daily cycle of heating on the large
 556 slopes of Gale crater, such that warming of air causes mass to flow out of the crater
 557 in order to maintain hydrostatic balance along the slopes (Richardson and New-
 558 man, 2018). Perseverance observations indicate that the diurnal pressure range at
 559 the Jezero crater is smaller by a factor of 2-3, somewhat smaller amplitude than
 560 measured by InSight, about the same amplitude than calculated from historical ob-
 561 servations of Viking lander 1 and 2 and, however, somewhat larger than diurnal
 562 pressure range measured by the Phoenix mission.

563 In the two lower rows of Figure 13 (panes c-f), approximately two sols for each
 564 lander at four solar longitude values marked in panes a-b are shown. Perseverance
 565 can be seen to have a similar mean pressure to InSight. This is likely due the similar
 566 elevations of around -2.6 km. The diurnal pressure patterns are similar in amplitude
 567 but slightly out of phase between Perseverance and InSight, most likely due to the
 568 59° difference in longitude, i.e. the thermal tide will pass over InSight and then over

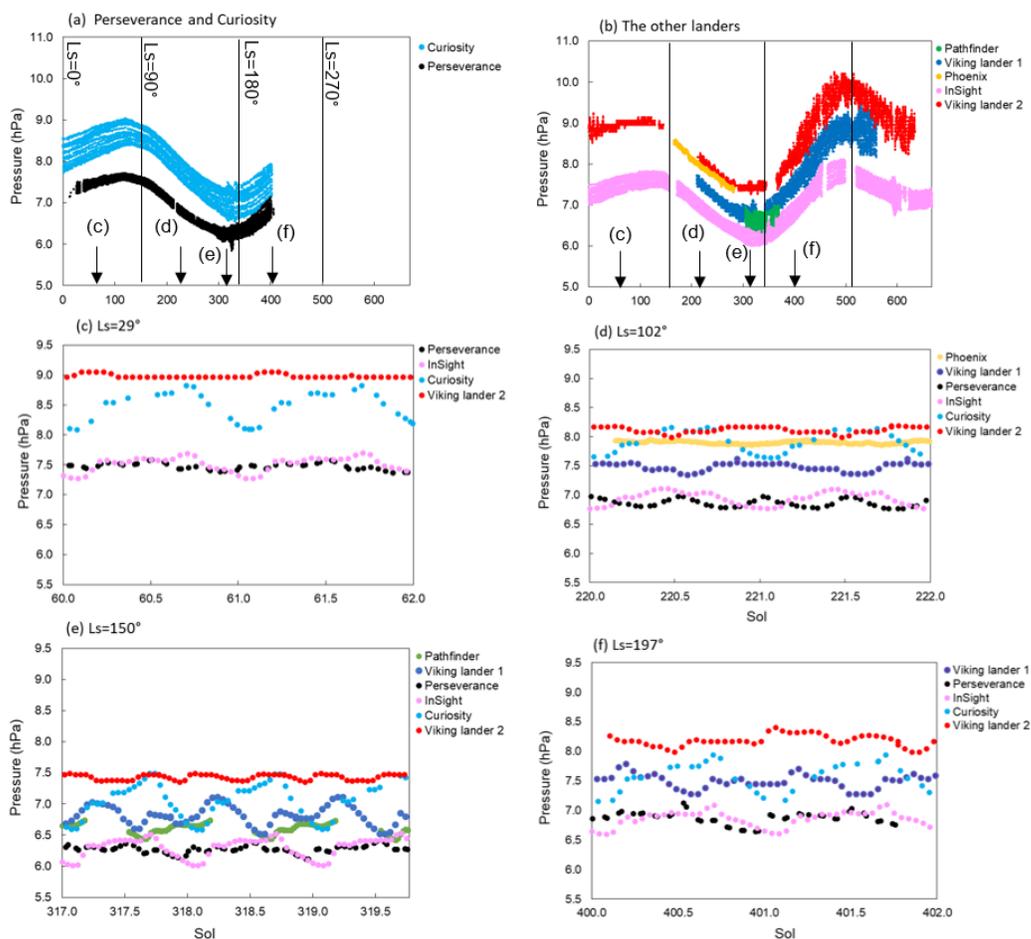


Figure 13. Diurnal pressure range of the Perseverance Rover compared over seasons with the diurnal pressure ranges observed by the Curiosity Rover, Insight Lander, Viking Lander 2 and Pathfinder (top row). Detailed diurnal pressure variation over 2-sol periods on these five surface missions is depicted at four solar longitudes evenly covering the first 414 sols of Perseverance operations. The lander data is plotted against the yearly sol, i.e. midnight on sol 1 corresponds to $L_s=0^\circ$ at the prime meridian, with midnight offset at each landing site depending on their longitude. The 2-sol periods were chosen in (c) to (f) over periods that avoided gaps in the lander data.

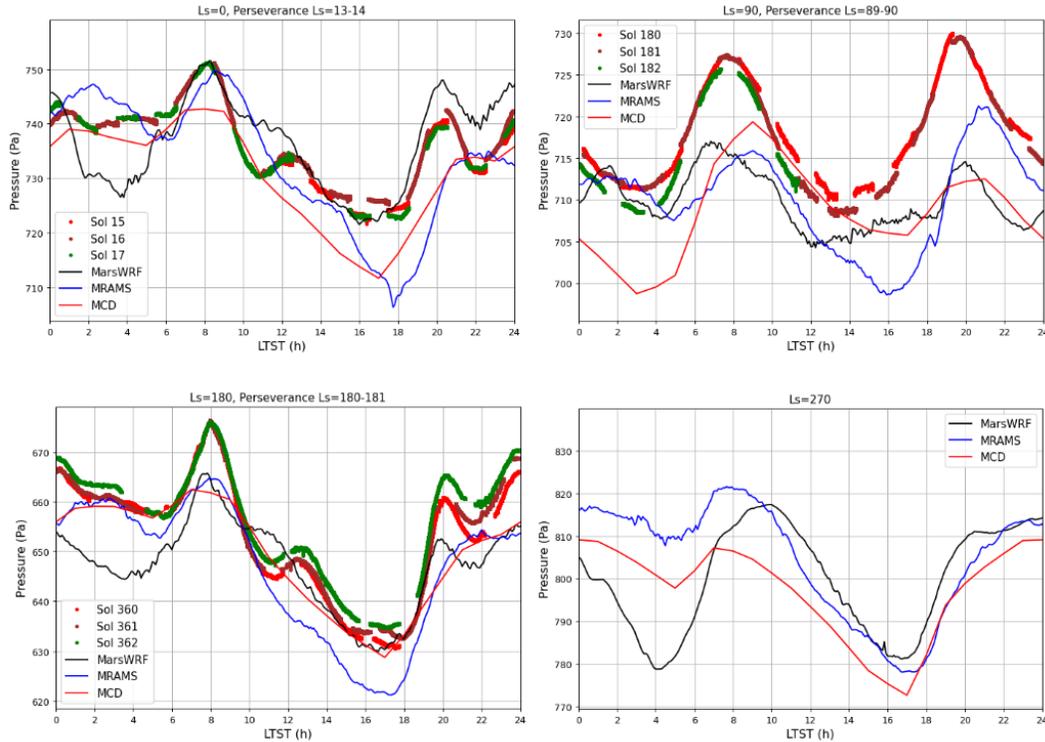


Figure 14. Diurnal pressure variation modeled by atmospheric models that simulate Jezero at km grid spacing MarsWRF, MRAMS and also the same data points from Mars Climate Database at solar longitude L_s 0° , 90° , 180° and 270° , which are depicted in panes a) to d). Around the solar longitude 0° , 90° and 180° Perseverance pressure observations from three sols are added (Perseverance has no data as yet at L_s 270°).

569 Perseverance four hours later. Also note that the diurnal patterns for Curiosity and
 570 InSight, separated by only one degree of longitude, are similar except that Curiosity
 571 has a greater diurnal amplitude.

572 At the Viking lander 2 site the daily pressure amplitude approaches similar
 573 levels to those observed by Curiosity only in the second half of the year, i.e. in the
 574 winter, as can be seen in figure 13 (b). The diurnal pressure amplitudes for the
 575 landers at high latitudes, i.e. Phoenix and Viking lander 2, during the northern
 576 hemisphere summer are small because of the weak thermal tide (Zhao et al., 2015).
 577 Curiosity and InSight latitudes (Table 1) are close to the equator and both have
 578 consistent daily pressures amplitudes throughout the year suggesting little variation
 579 in the thermal tide conditions at these latitudes.

580 Regional atmospheric modeling efforts are needed to expand the value of the
 581 *in situ* observations. This was done by running MarsWRF and MRAM models (Pla-
 582 Garcia et al., 2021) at the Perseverance site on solar longitude values of L_s 270° ,
 583 90° , 180° and 270° . Figure 14 illustrates these results together with *in situ* Perseverance
 584 observations at L_s 0° , 90° , 180° as well as data points acquired from the Mars
 585 Climate Database MCD (?, ?).

586 MarsWRF and MRAMS simulate Jezero crater at high resolution. Mar-
 587 sWRF is a mesoscale nest embedded inside a global model model and MRAMS is

588 a mesoscale model. Overall, MarsWRF and MRAMS as well as the lower-resolution
 589 MCD do fairly well compared to the actual *in situ* pressure observations. MarsWRF
 590 seems to reproduce the dip at 1700 better than MRAMS in Figure 14. MarsWRF
 591 reproduces the main features quite well except the small peaks at noon in the North-
 592 ern springtime (L_s 0°, Figure 14a) and fall (L_s 180°, Figure 14c) where it generates
 593 a shoulder-like feature instead. The average pressure in Figure 14a for MarsWRF
 594 is generally good but in the Northern summertime (L_s 90°, Figure 14b) and fall
 595 (Figure 14c) the average pressure is too low. The height of the peaks in Figure 14b
 596 are too low in the MarsWRF data. MCD is roughly producing in the average similar
 597 results to Mars WRF and MRAMS.

598 MRAMS matches the average pressure level quite well in Figure 14a if it was
 599 not for the big dip at 1700. It is not clear if it reproduces the peaks at 2200 and
 600 midnight. The occurrence of the peaks in the MRAMS data seems to be delayed
 601 by about 2 hours. Like MarsWRF MRAM does not reproduce the small peak at
 602 noon. MRAMS reproduces the height of the two big peaks in Figure 14b but they
 603 are on average too low. The timing of the peaks seems to be delayed by about 2
 604 hours in Figure 14b. Overall, it seems to be the case that state-of-the-art regional
 605 atmospheric models succeed fairly well in producing diurnal pressure variation at
 606 the Jezero crater region. Then, understandably, reproducing through modeling the
 607 small peaks in diurnal pressure variation caused largely by the local geography and
 608 atmospheric flow conditions proves to be challenging.

609 The distinct oscillations in the observed surface pressure are expected to be
 610 primarily due to the thermal tides and their interactions with the Martian topogra-
 611 phy, e.g. Wilson and Hamilton (1996). Oscillations in the pressure could also include
 612 contributions of the local crater circulations that are especially important for deep
 613 craters like Gale crater (Tyler and Barnes, 2015; Wilson, 2017). In addition hydro-
 614 static adjustment has been shown to be important in amplification of the amplitude
 615 of the diurnal pressure variation (Richardson and Newman, 2018).

616 This complex structure in the pressure signal was anticipated by Pla-Garcia
 617 et al. (2020). This is demonstrated in a distinct fashion in figure 14. A more com-
 618 prehensive modeling study is needed, but the Perseverance pressure observations
 619 support the initial regional atmospheric modeling results at the Perseverance site
 620 made with the Mars WRF and MRAMS models as well as the data provided by
 621 MCD.

622 Jezero crater does not seem to have a similarly strong amplification from hy-
 623 drostatic adjustment as is the case at the Gale crater based on the observations by
 624 the Curiosity rover (Harri et al., 2014; Newman et al., 2021). A plausible reason for
 625 this is the fact that compared to the Gale crater, the Jezero crater is shallow and
 626 wide resulting in relatively weaker amplification effect on the diurnal pressure vari-
 627 ation amplitude. In addition the thermal tide at the Gale crater is stronger at most
 628 times of year than at Jezero crater because it is closer to the subsolar point for most
 629 of the year.

630 Combining the atmospheric regional modeling with *in situ* pressure observa-
 631 tions proves to be highly useful – it adds the value of the observations by expanding
 632 their effect beyond the actual point of observation and sheds more light on the phys-
 633 ical and meteorological processes behind the Martian atmospheric phenomena. The
 634 physics and implementation of the models themselves can also be modified to better
 635 address the actual atmosphere.

7 Summary and discussion

The Mars2020 Perseverance Rover landed successfully onto the Martian surface on the Jezero Crater floor (18°N, 77°E) at the Martian solar longitude L_s 5° in February 2021. Since then it has produced highly valuable environmental measurements with a versatile scientific payload including a suite of environmental sensors MEDA (Mars Environmental Dynamics Analyzer). One of the MEDA sensor systems is MEDA PS pressure device weighing 40 grams.

The Martian atmospheric pressure observations by MEDA PS have proved to be of excellent quality fulfilling expectations with the estimated overall uncertainty being equal or better than 3.5 Pa and the resolution about 0.13 Pa. The system resources required by the whole MEDA PS package are dimensions being 62×50×17 mm, mass 40g and power consumption less than 15 mW.

This paper presents initial results of the first 414 sols of Martian atmospheric surface pressure observations by the MEDA PS device whose performance was found to fulfill the specification. Observations controlled by the Perseverance resources allocation schedule cover approximately 50 – 70 % of the Perseverance operational time.

The atmospheric pressure measurement device (MEDA PS) is based on the silicon-micro-machined pressure sensor head (Barocap®) and transducer technology developed by Vaisala Inc. The Barocap® version used by MEDA PS is optimized for the Martian near-surface atmospheric pressure. The transducer electronics and required electromagnetic shielding and mechanical support structures were developed by Finnish Meteorological Institute (FMI).

The MEDA PS pressure device is making measurements continuously with 1 Hz frequency in average for every other hour according to the operational schedule by the Perseverance Rover. That enables us to generate data sets with averaged pressure measurements approximately at 1-hour intervals, as well as data sets with pressure observations at 1 second intervals for one or a few hours in a row for short time scale studies. In this work we use data sets with 1-hour intervals. The 1-hour data sets are not complete but they do have some gaps due to scheduling of Perseverance and MEDA operations. However, the available data coverage allows good characterisation of both the diurnal and seasonal variations in the pressure.

The seasonal-to-annual time scales the CO₂ condensation-sublimation cycle of the Martian atmosphere is nicely demonstrated at the Jezero crater site by the Perseverance Rover measurements. The observed sol-averaged atmospheric pressure during the 414 first Perseverance sols from the landing time at early Northern springtime to Northern fall follow an anticipated pattern of total pressure variation in the course of the advancing season. The data has the first maximum in late spring roughly on the Perseverance sol 110 and minimum on sol 310, whereas by the Perseverance sol 414 corresponding to approximately L_s 212° the atmospheric pressure is climbing higher than the first maximum toward the seasonal maximum. When comparing Perseverance with concurrent observations by the Curiosity Rover and the Insight lander as well as with the historical Viking Landers data, we can see distinct differences with the amplitude of the seasonal pressure variation that are due to different surface elevations.

When comparing pressure observations of the seven Martian landing missions on different locations on Mars the first part of seasonal atmospheric pressure cycle measured by Perseverance seems to follow the seasonal increase and decrease in the atmospheric pressure as expected. The visible bias between the landers' pressure observations is largely due to different landing elevations. Detailed investigation reveals that during L_s 0 – 170° the Perseverance pressure looks to be decreasing somewhat

687 more slowly than the pressure measured by the historical Viking landers. However,
 688 Insight exhibits similar kind of slow pressure decrease and hence this could be due to
 689 a regional occurrence possibly related with the regional topography or variability in
 690 large scale atmospheric flows.

691 The observed diurnal pressure amplitude is ranging roughly within 2 -5 % of
 692 the sol-averaged pressure with the absolute amplitude (10 – 35 hPa) not having a
 693 direct relationship with the sol-averaged pressure. The optical thickness varying
 694 with the amount of airborne dust seems to affect considerably the diurnal pressure
 695 amplitude. The increase of optical thickness from 0.5 to 0.8 around sols 130-160
 696 seems to raise the diurnal pressure amplitude from approximately 20 hPa to 35 hPa.
 697 Regional atmospheric models seem to give roughly similar results on the average
 698 diurnal pressure amplitude, when Perseverance -like airborne dust conditions are
 699 assumed.

700 It appears to be evident that the range of diurnal atmospheric pressure varies
 701 considerably with location on Mars. The Perseverance diurnal pressure variation
 702 seem to be smaller than those measured by the Curiosity rover at Gale crater where
 703 tidal forcing is stronger due to the location close to the equator and also due to the
 704 fact that at Curiosity's longitude sector eastward and westward modes are expected
 705 to interact constructively. Comparison with pressure observations at other Martian
 706 sites it looks that also regional and local geography also play a role in the range of
 707 observed diurnal pressure variation.

708 When inspecting the structure of diurnal pressure, 2-4 small peaks appear
 709 in the data on each sol (Figure 6). A clear evolution of the peaks can be seen in
 710 the stacked diurnal pressure data. During Northern summer (Figure 6, second row
 711 from top) diurnal pressure exhibits two distinct and regular peaks, one in the morn-
 712 ing around 6-7 AM and the other one around 8-9 PM LTST. During the Northern
 713 spring (Figure 6, top row) and fall (Figure 6, lowest rows) this summertime regular
 714 pattern is broken into more like four separate peaks whose amplitudes vary along
 715 with advancing season.

716 During Northern springtime - at the start of the mission, Perseverance sols
 717 0-150 - it appears that smaller peaks are superimposed on the larger peaks. These
 718 smaller peaks disappear between about sols 150 and 250 (Northern summertime)
 719 and return around sol 300 in early fall. The wintertime has not yet come during the
 720 first 414 Perseverance sols. The features in the plots give clues on the behaviour of
 721 regional atmospheric dynamics and circulation patterns in the Martian atmosphere

722 The daily surface pressure profile seems to exhibit a largely repeatable two-
 723 peak shape during the Northern summertime (Figure 6). This is probably mostly
 724 due to the strong semi-diurnal thermal tidal component, which seems to be the case
 725 as illustrated in Figure 7.

726 MEDA PS observations allow us to estimate that about 100 thermal vor-
 727 tices with $\dot{\gamma}$ 0.5 Pa pressure drops during a 20 sol period throughout the first 414
 728 Perseverance sols. Based on this analysis, the vortex activity at Jezero crater in
 729 the vicinity of Perseverance seems to be nearly constant with little seasonal vari-
 730 ation. Apparently solar forcing varying considerably from springtime to fall has
 731 not affected the frequency of occurrence of thermal vortices. It is interesting to see
 732 whether this pattern will hold through the upcoming Northern wintertime.

733 Through *in situ* pressure observations and regional atmospheric modeling re-
 734 sults a distinct local circulation pattern including nighttime katabatic and daytime
 735 upslope flows over the boundary of the Jezero crater was discovered. This circulation
 736 amplifies the diurnal pressure variation.

737 For comparison, the Gale crater diurnal pressure amplitude measured by the
 738 Curiosity Rover is much larger (50 to 120 hPa) than at the Jezero crater. This
 739 may be due to the fact that Gale is smaller and deeper than Jezero resulting in a
 740 stronger diurnal pressure cycle due to hydrostatic adjustment. On the plateaus with
 741 more gentle local circulation the diurnal pressure variation based on Viking Lander
 742 observations is weaker than at the Gale crater and about the same as given by Per-
 743 severance observations. On the other hand Insight diurnal pressure is higher than
 744 that of Perseverance during Northern springtime and summer but assumes roughly
 745 the same level during fall. Apparently the behavior of local diurnal pressure is af-
 746 fected by a mixture of solar forcing on the surface, airborne dust, regional geography
 747 and atmospheric wave activity.

748 The observed diurnal pressure variation seems to have a significant seasonal
 749 dependence. During Northern summer diurnal pressure displays two distinct and
 750 regular peaks, one in the morning around 6-7 AM and the other one around 8-9 PM
 751 LTST. This regular pattern is likely caused by the interaction of strong thermal tide
 752 and the seasonally varying airborne dust causing an amplified semi-diurnal compo-
 753 nent. During the Northern fall and spring this summertime regular pattern is broken
 754 into four separate peaks whose amplitudes vary along with advancing season.

755 The seasonal form of the diurnal pressure variation was investigated through
 756 regional atmospheric modeling by Mars WRF and MRAMS limited area models us-
 757 ing the modeling results described in Pla-Garcia et al. (2020). The modeling results
 758 were compared with actual MEDA PS observations at solar longitude values L_s 0° ,
 759 90° and 180° , as well as with the MCD data. In the summertime (midsummer
 760 L_s 90°) the modeling results match very well with the shape and two-peak pattern
 761 of diurnal pressure cycle, but they underestimate the average pressure level. These
 762 modeling results showed the importance of the boundary fields for the regional mod-
 763 els in getting pressure levels correct. Also the complexity of the diurnal pressure
 764 signal especially during the springtime and fall was revealed.

765 Overall, the modeling data seems to fit surprisingly well with the Perseverance
 766 pressure observations. Mars WRF and MRAMS have higher resolution than the
 767 relatively coarse MCD and hence these models pick up the local daily pressure vari-
 768 ation better than MCD. But even the MCD seems to work surprisingly well, which
 769 is an excellent indication of the capabilities of current Martian atmospheric modeling
 770 tools. The modelling data indicates that they are correctly modelling the large-scale
 771 forcing of the main components of the daily pressure curves.

772 These modeling efforts underlined the clear need to investigate more in detail
 773 the diurnal pressure cycle as a superposition of the thermal tide, regional and local
 774 crater circulations and of various barotropic and baroclinic wave forms with seasonal
 775 dependence. These differences between the models and the observations inform us
 776 about the needs and areas to focus on in improving atmospheric models.

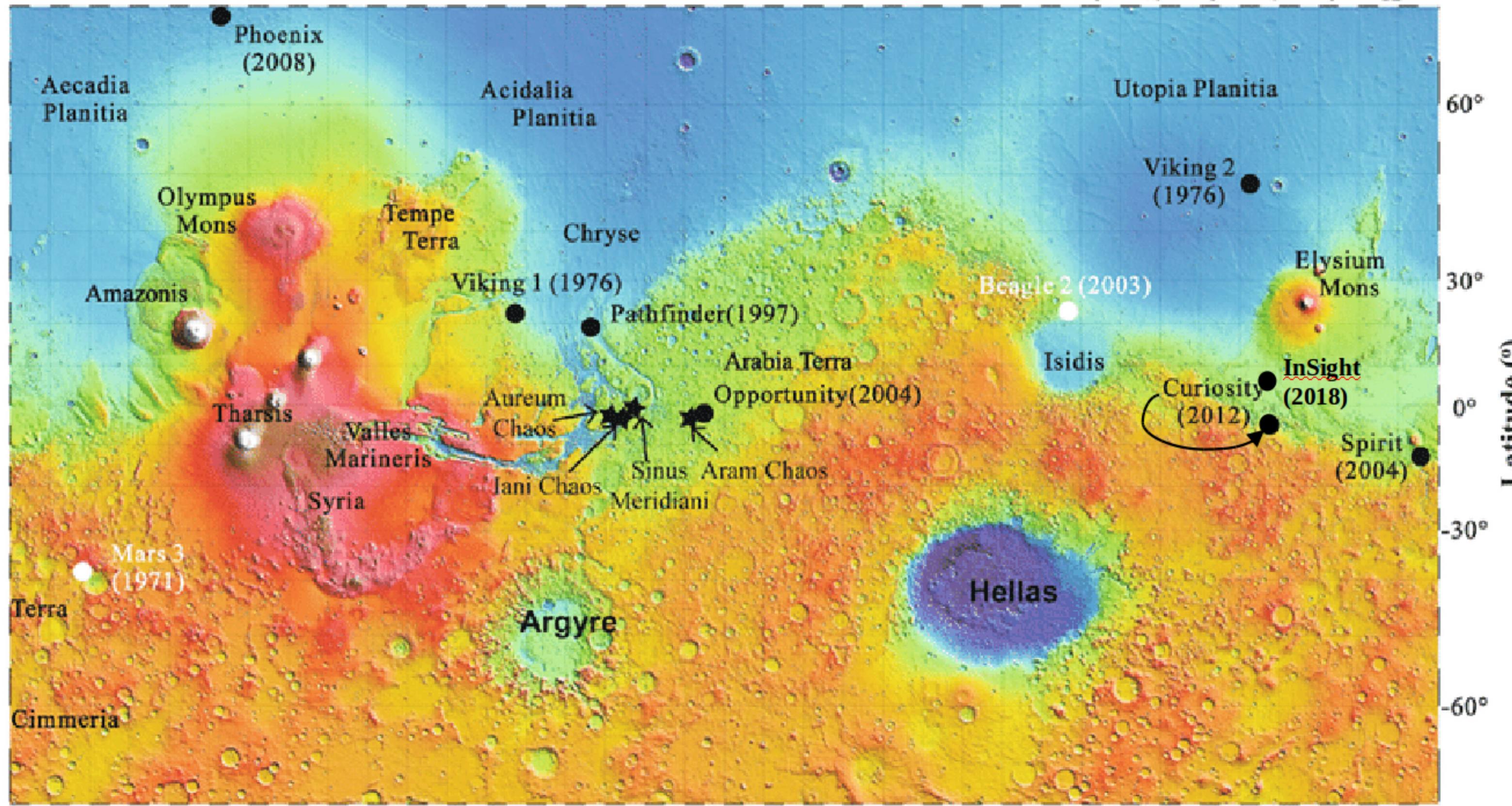
777 8 Open Research

778 The observational data used for this work is available in Planetary Data Sys-
 779 tem (PDS) at the web site <https://pds.nasa.gov/>. MEDA instrument data is avail-
 780 able in the PDS Atmospheres node in <https://doi.org/10.17189/1522849> (?, ?).

781 Acknowledgments

782 Ari-Matti Harri, Mark Paton, Maria Hieta and Jouni Polkko are thankful
 783 for the Finnish Academy grant number 310509. Agustín Sánchez-Lavega and
 784 Ricardo Hueso were supported by Grant PID2019-109467GB-I00 funded by
 785 MCIN/AEI/10.13039/501100011033/ and by Grupos Gobierno Vasco IT1742-22.

Figure 1.



Phoenix
(2008)

Aecadia
Planitia

Acidalia
Planitia

Utopia Planitia

60°

Olympus
Mons

Tempe
Terra

Chryse

Viking 2
(1976)

Amazonis

Viking 1 (1976)

Pathfinder(1997)

Beagle 2 (2003)

30°

Elysium
Mons

Tharsis

Valles
Marineris

Aureum
Chaos

Arabia Terra

Opportunity(2004)

Isidis

Curiosity
(2012)

InSight
(2018)

Spirit
(2004)

Latitude (°)

Syria

Jani Chaos

Sinus Aram Chaos
Meridiani

0°

Mars 3
(1971)

Terra

Argyre

Hellas

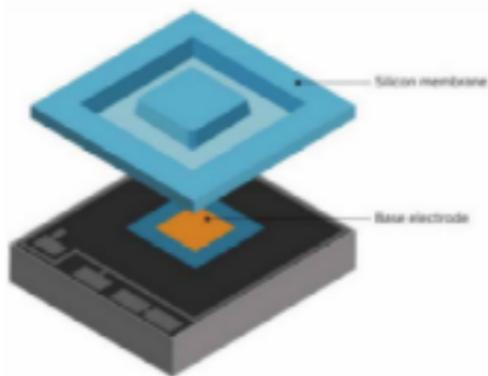
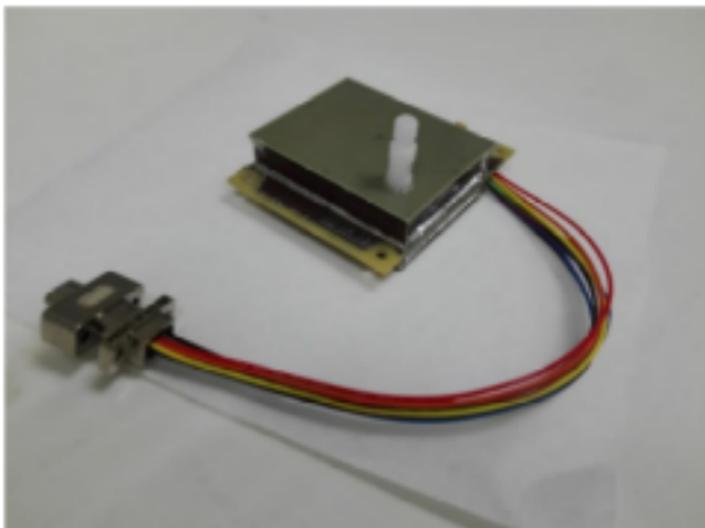
-30°

Cimmeria

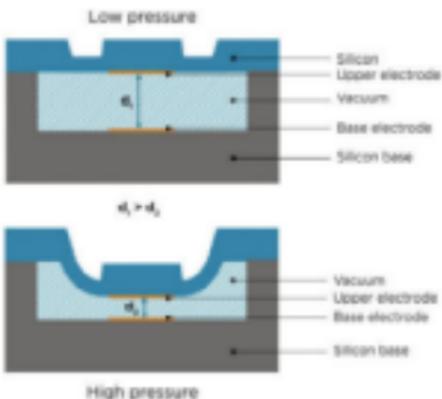
-180° -150° -120° -90° -60° -30° 0° 30° 60° 90° 120° 150° 180°

Longitude (°)

Figure 2.



BAROCAP sensor



Cross-section of the BAROCAP sensor

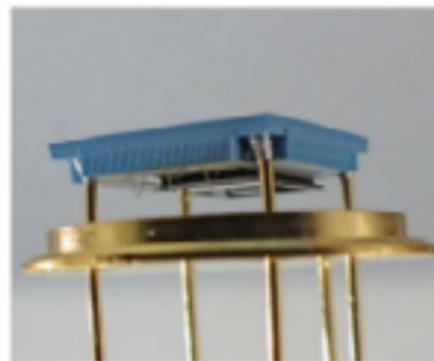


Figure 3.

Pressure data coverage

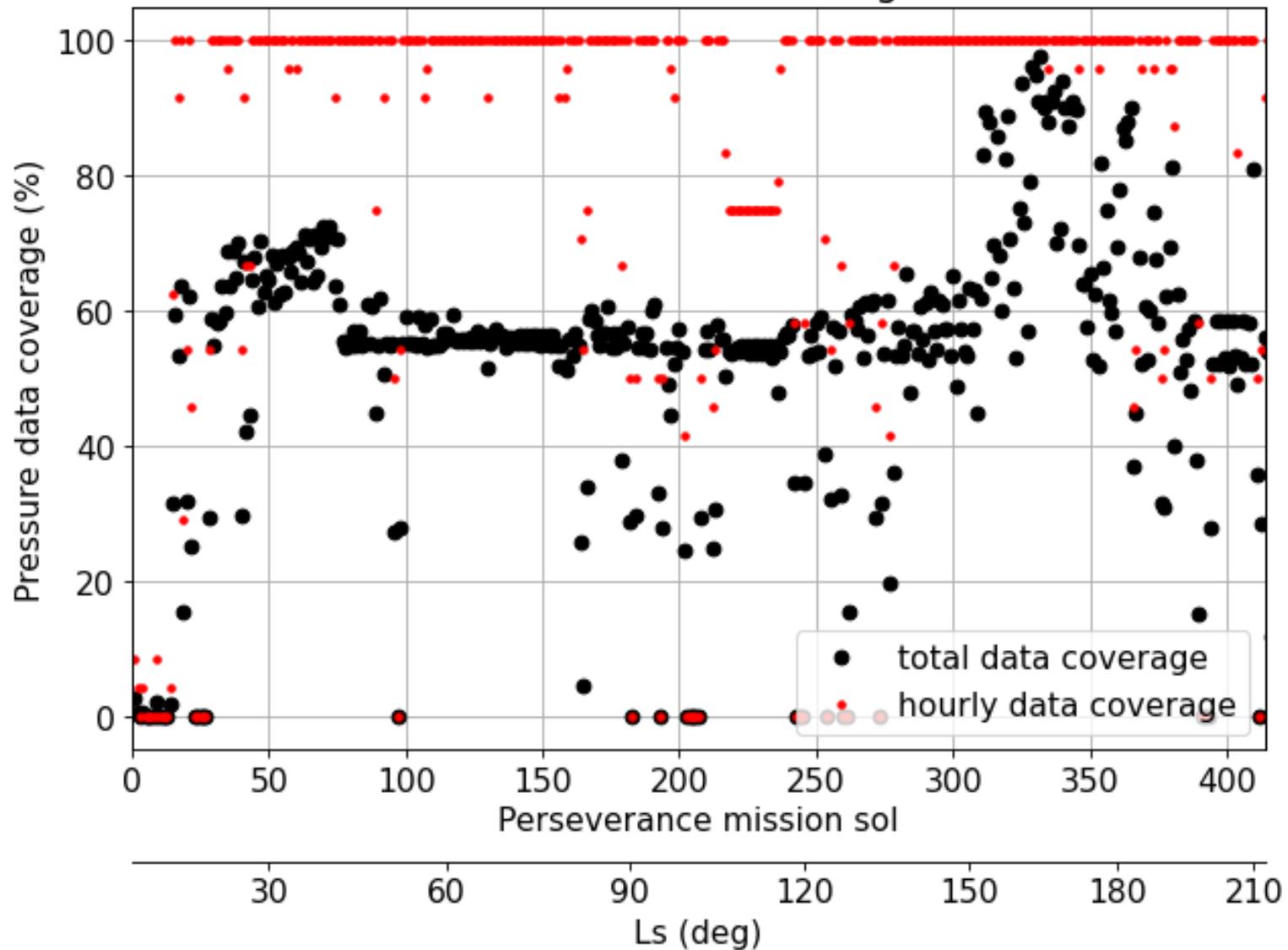


Figure 4.

Pressure

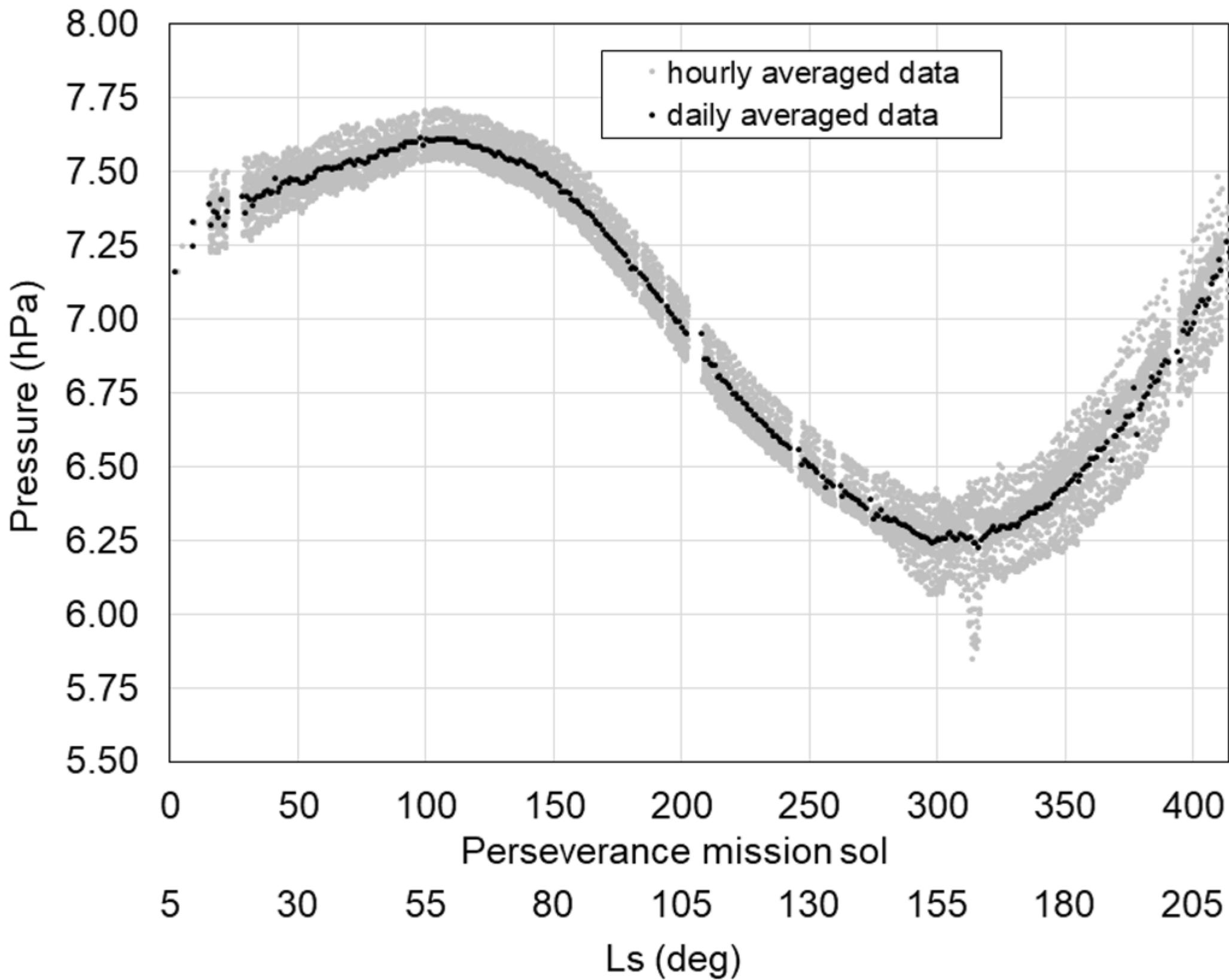


Figure 5.

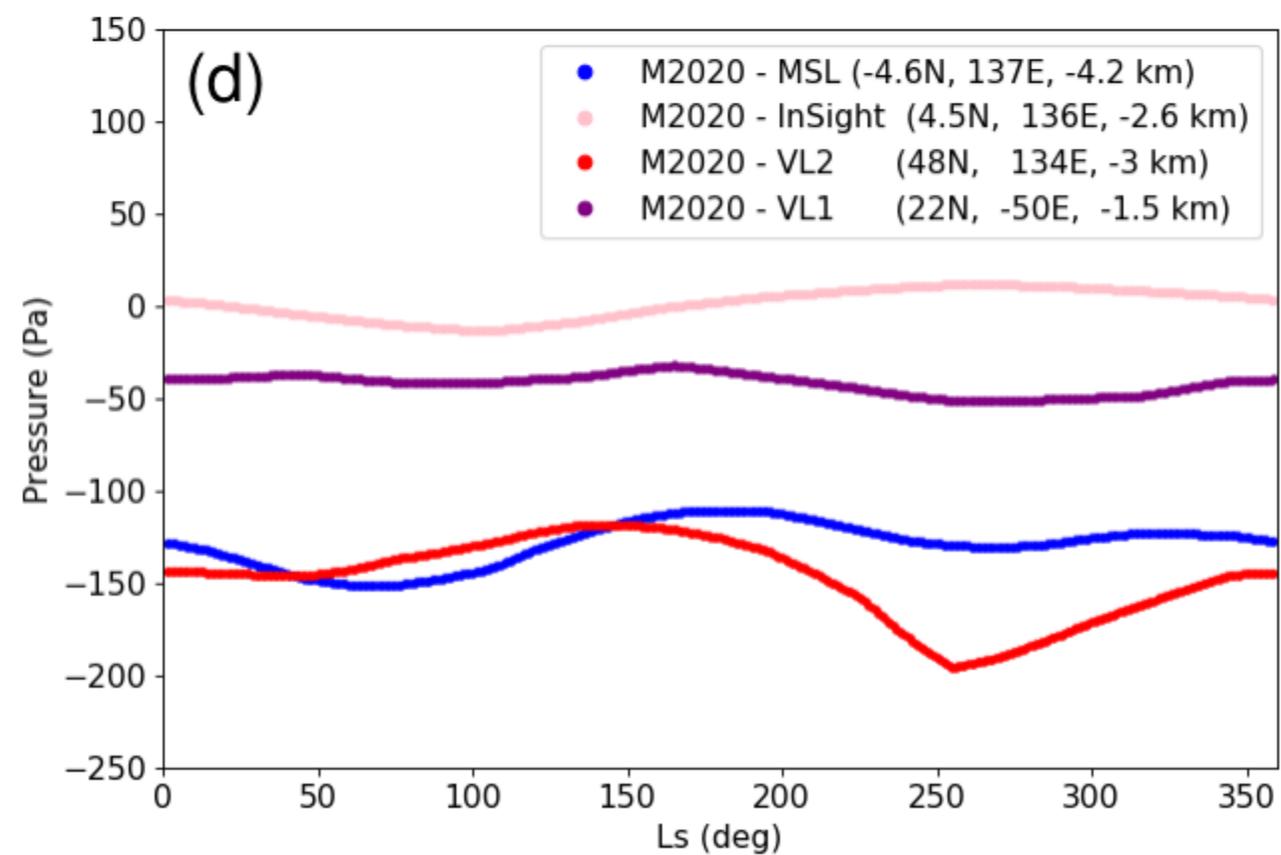
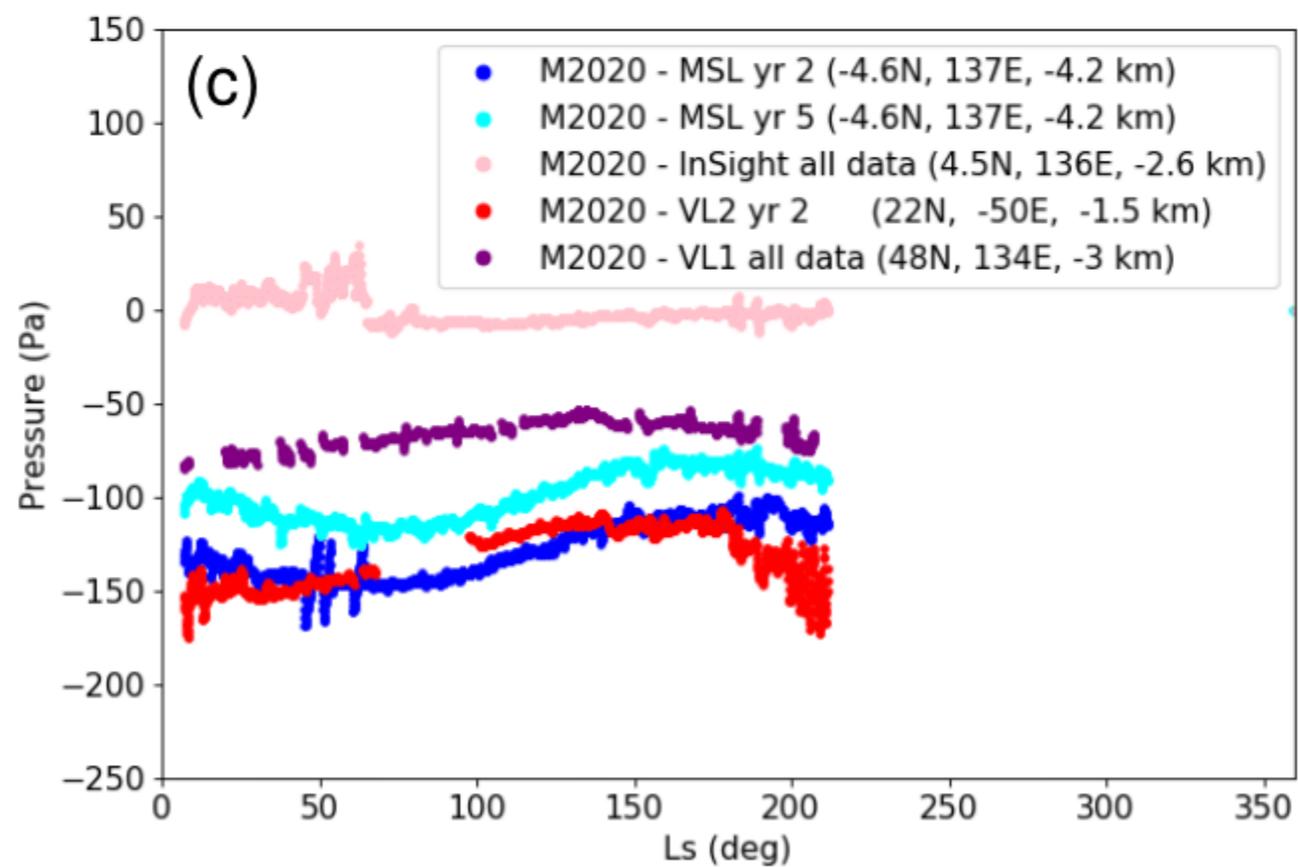
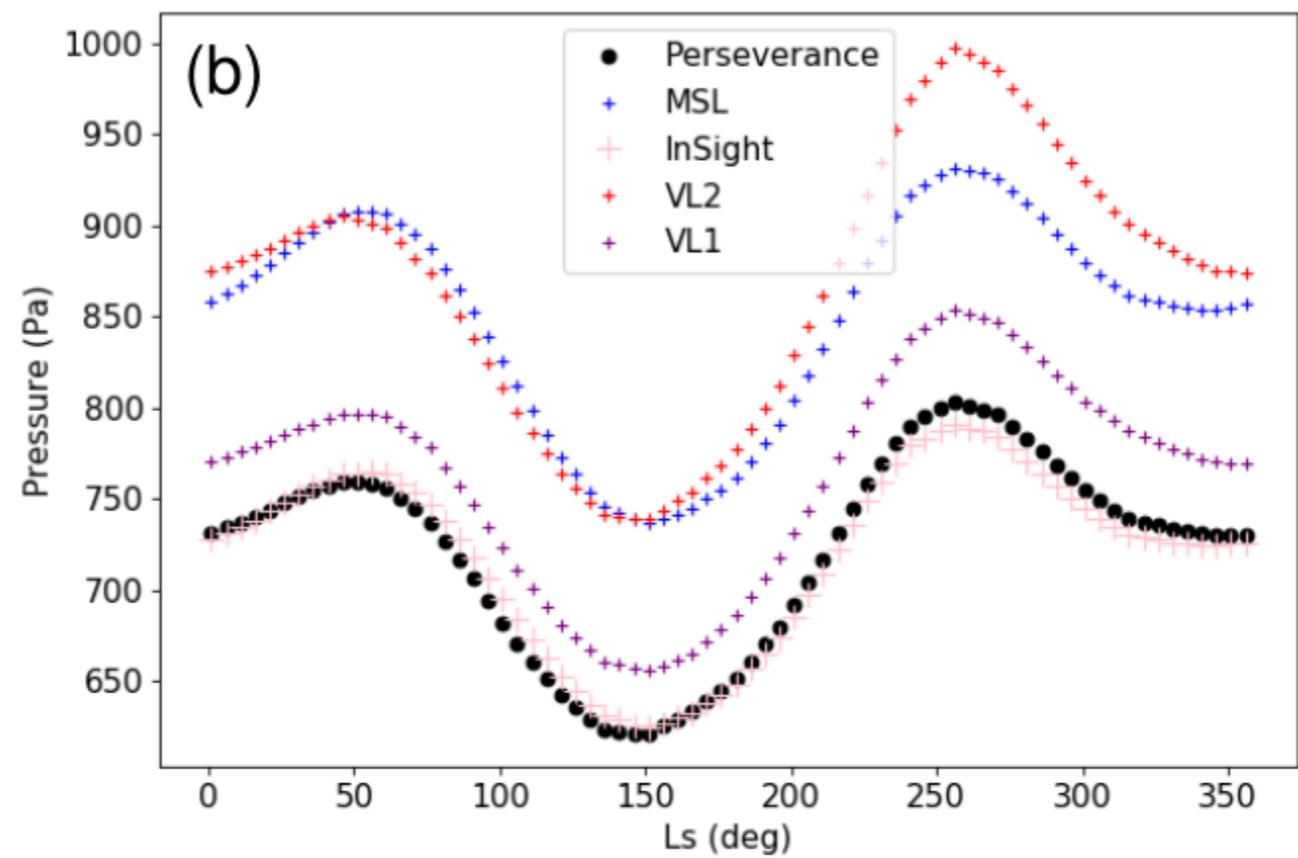
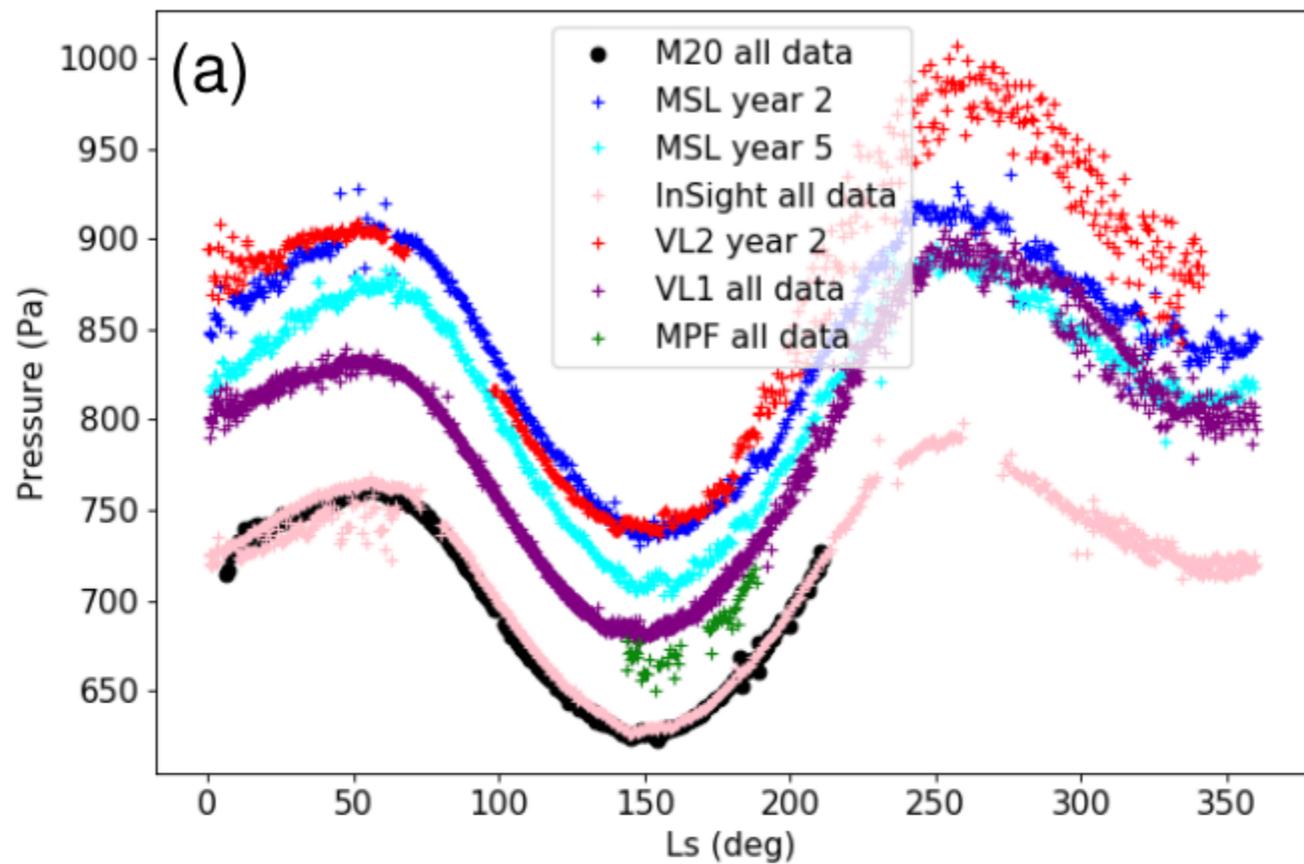


Figure 6.

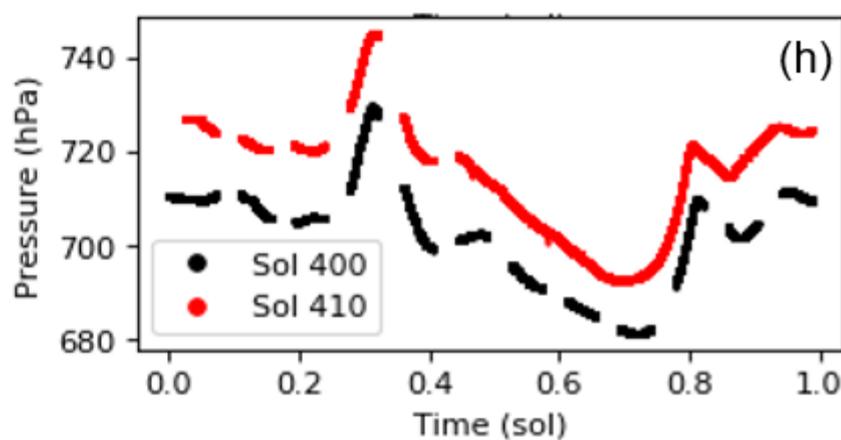
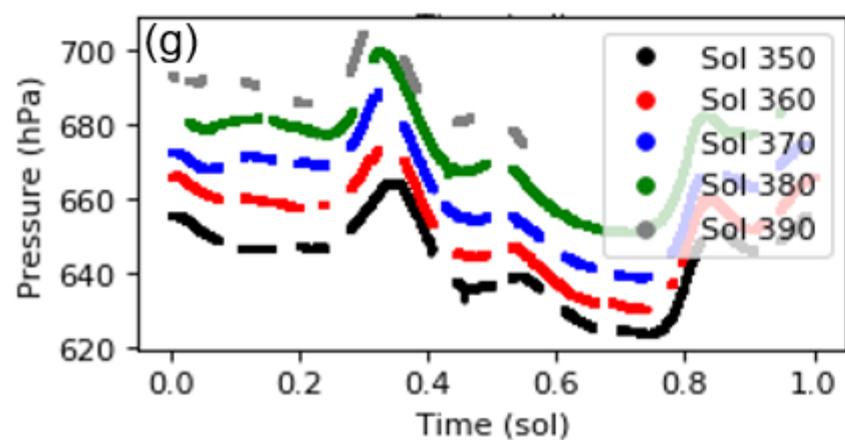
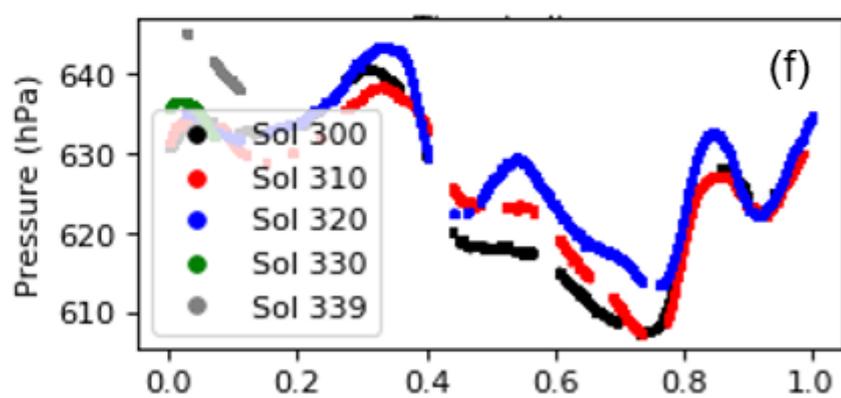
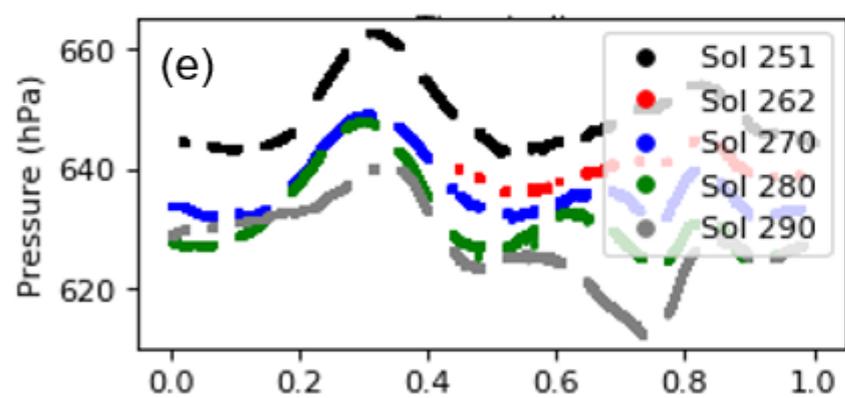
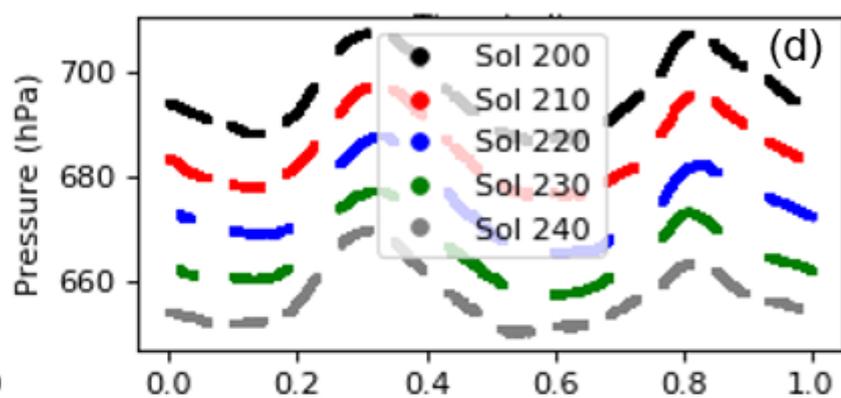
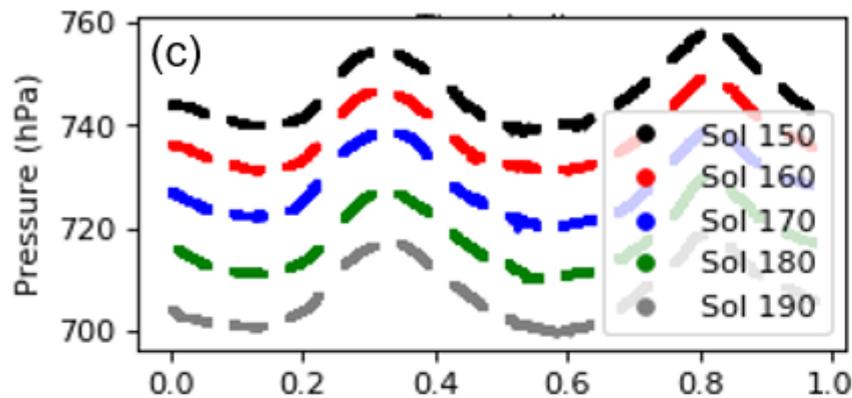
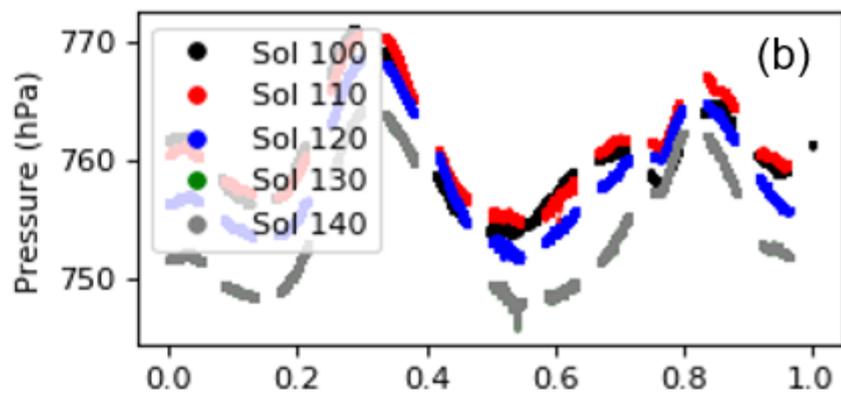
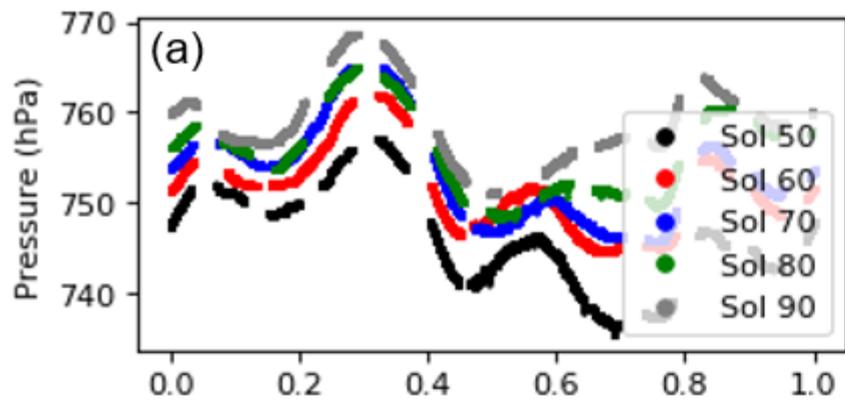
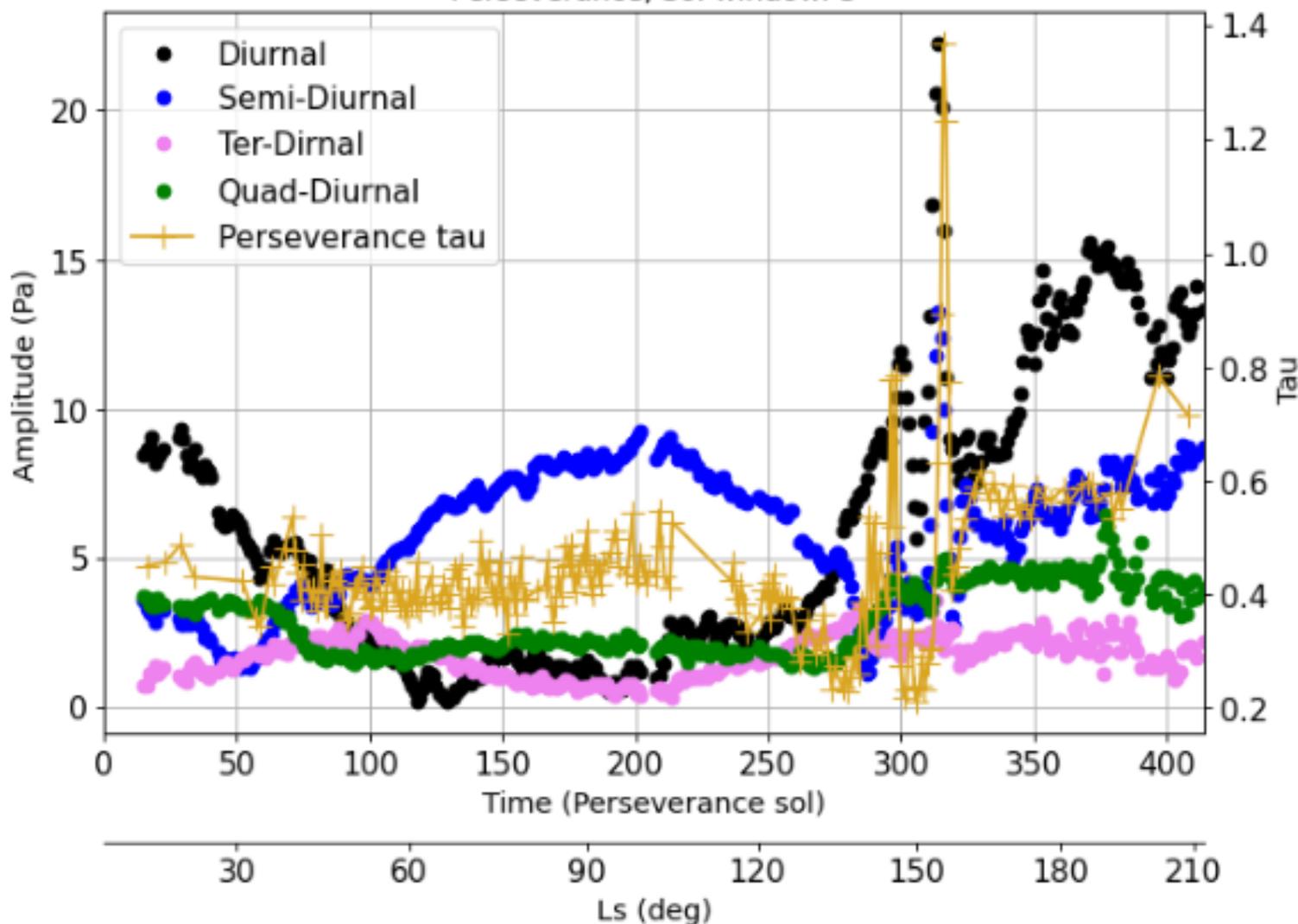


Figure 7.

Perseverance, Sol window: 3



Perseverance, Sol window: 3

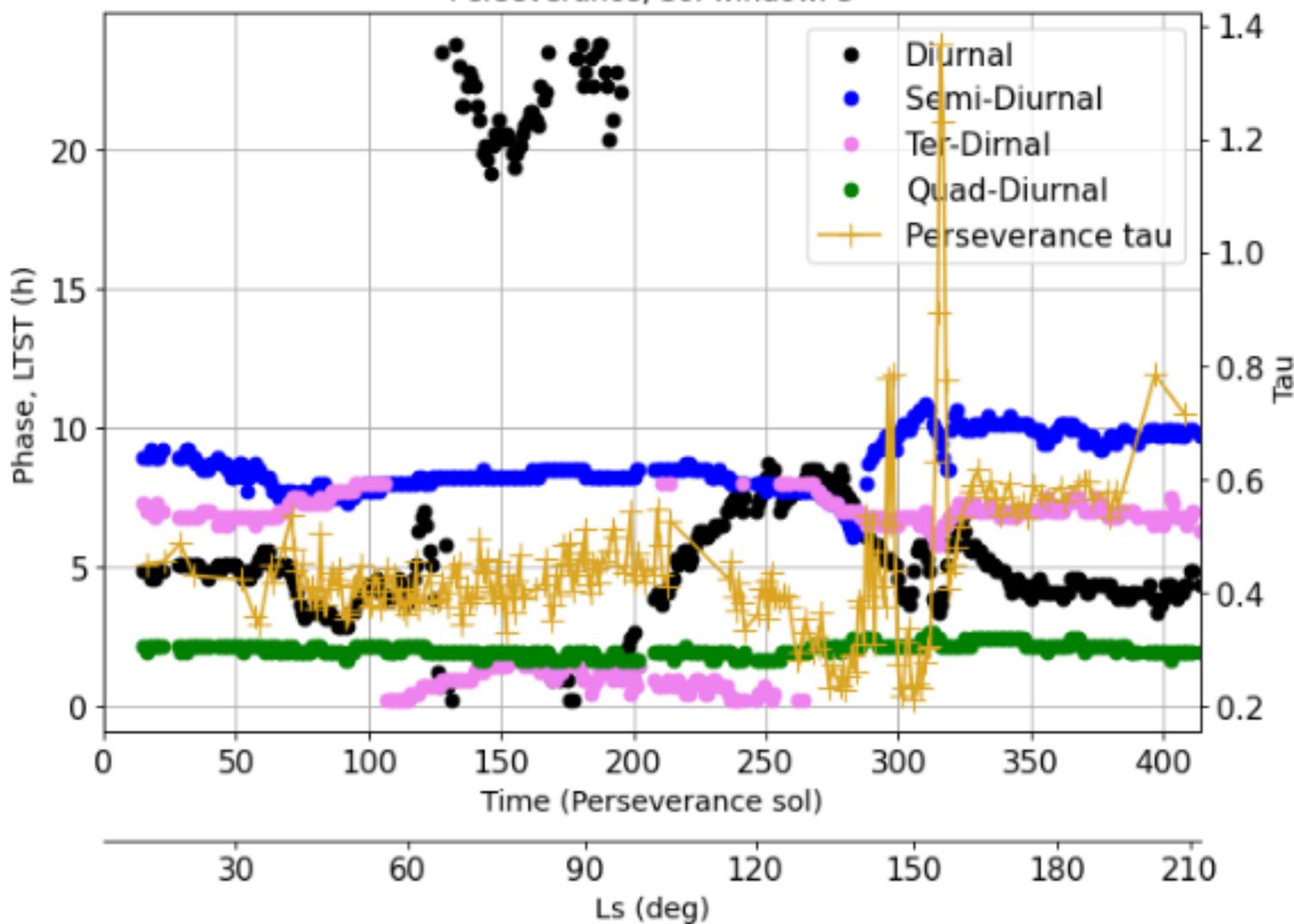
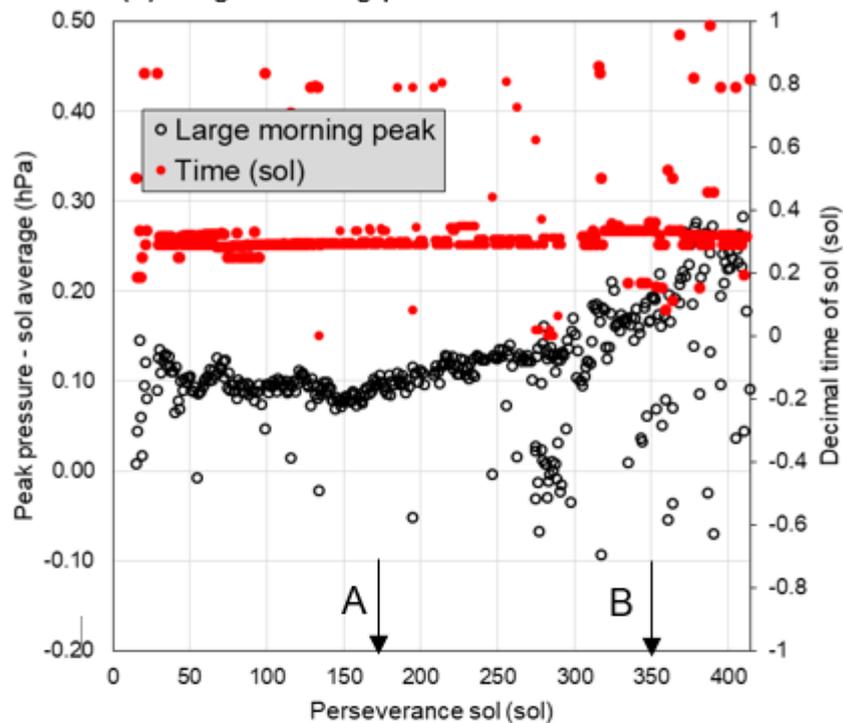
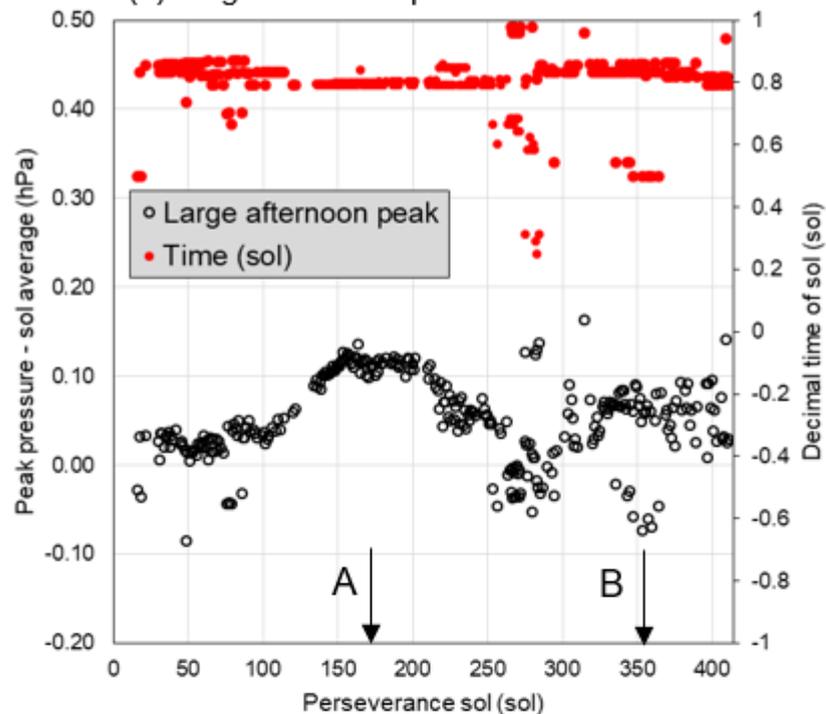


Figure 8.

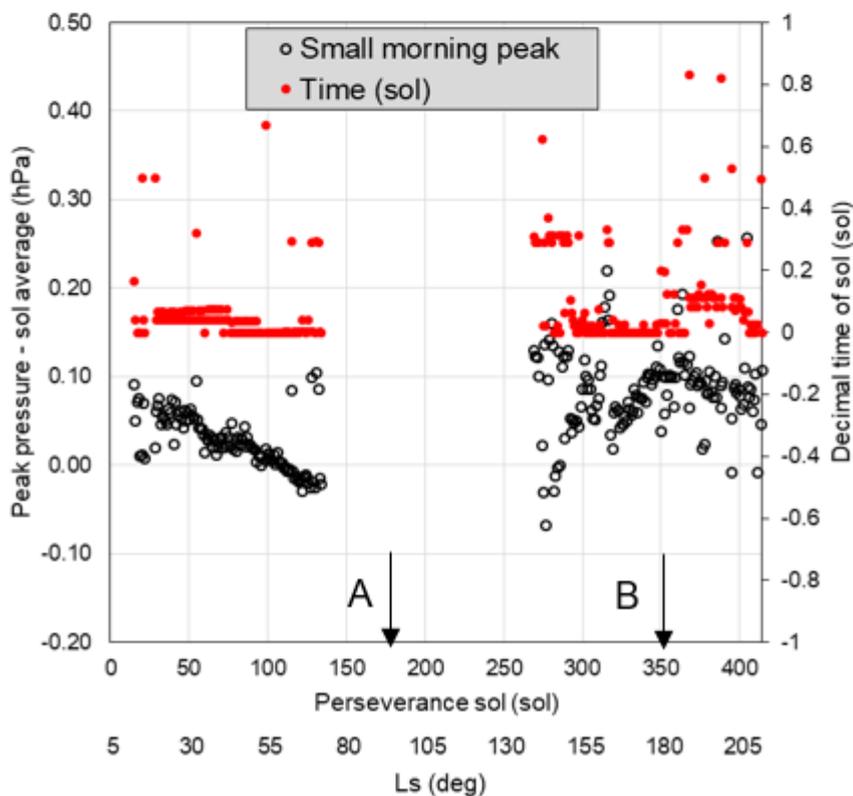
(a) Large morning peak



(b) Large afternoon peak



(c) Small morning peak



(d) Small afternoon peak

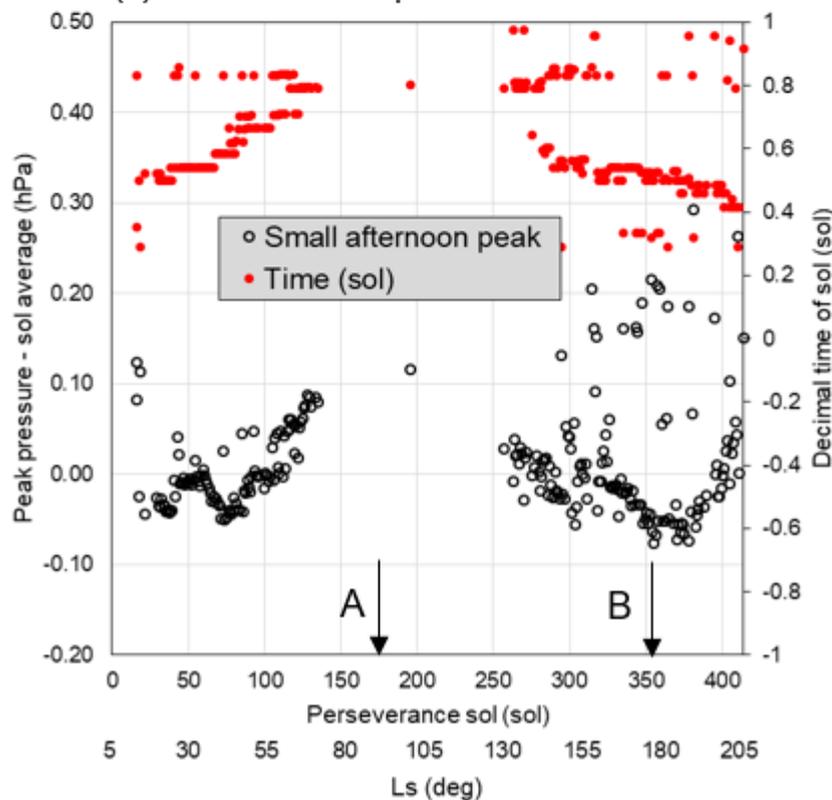
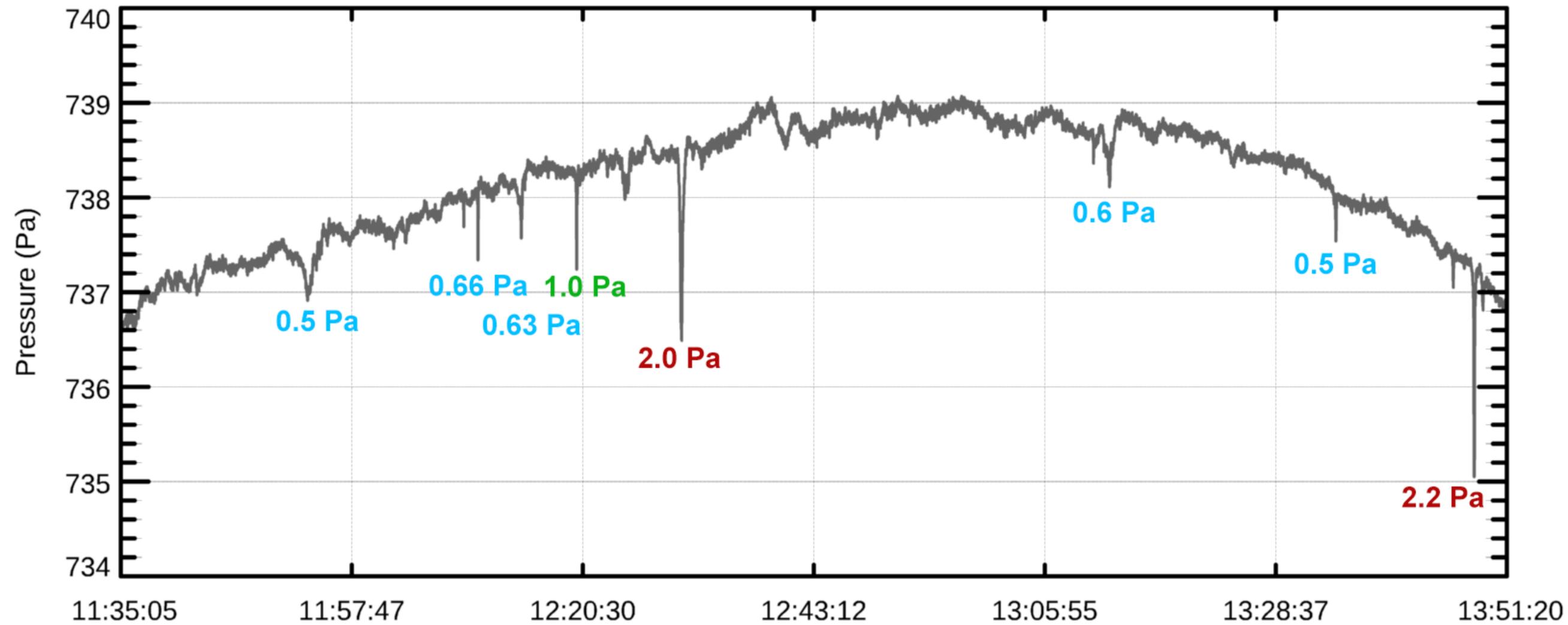


Figure 9.

Sol: 0034 (Ls=22.28)



Sol: 0034 (Ls=22.28)

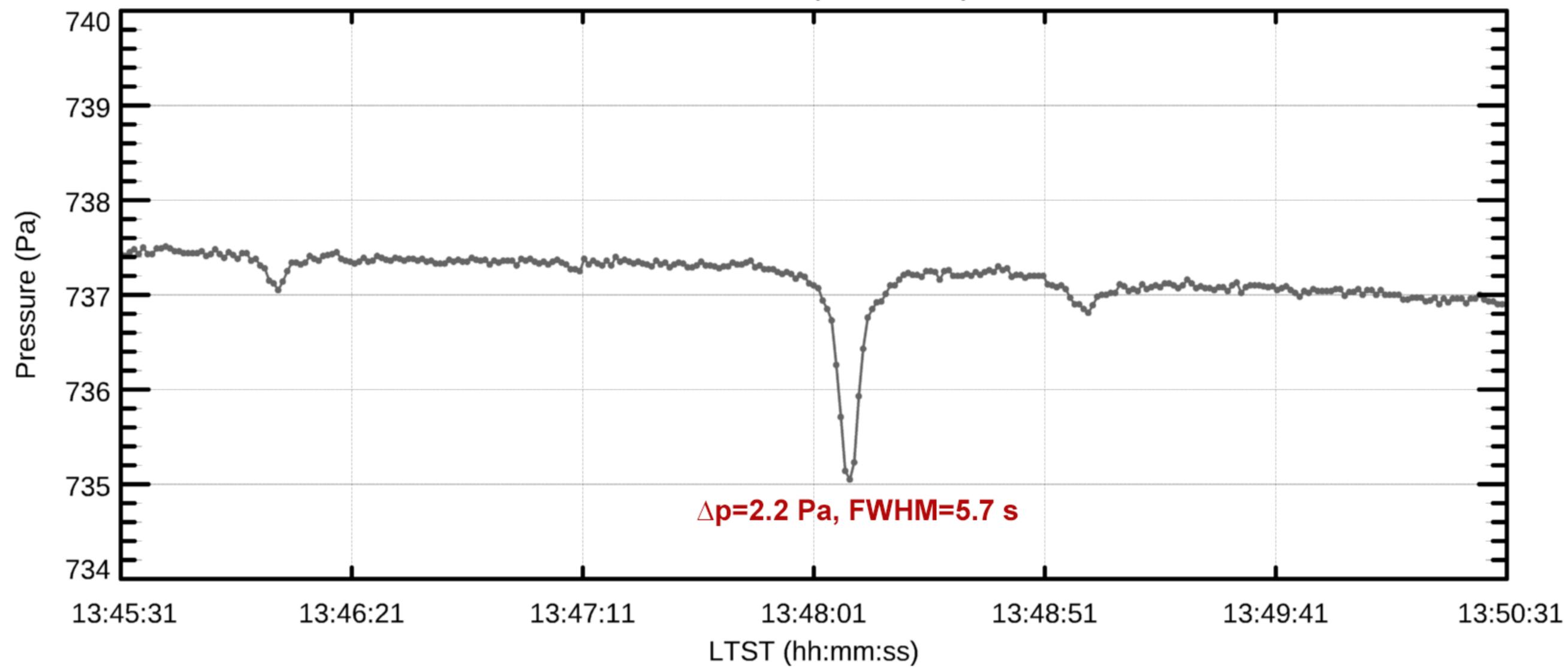


Figure 10.

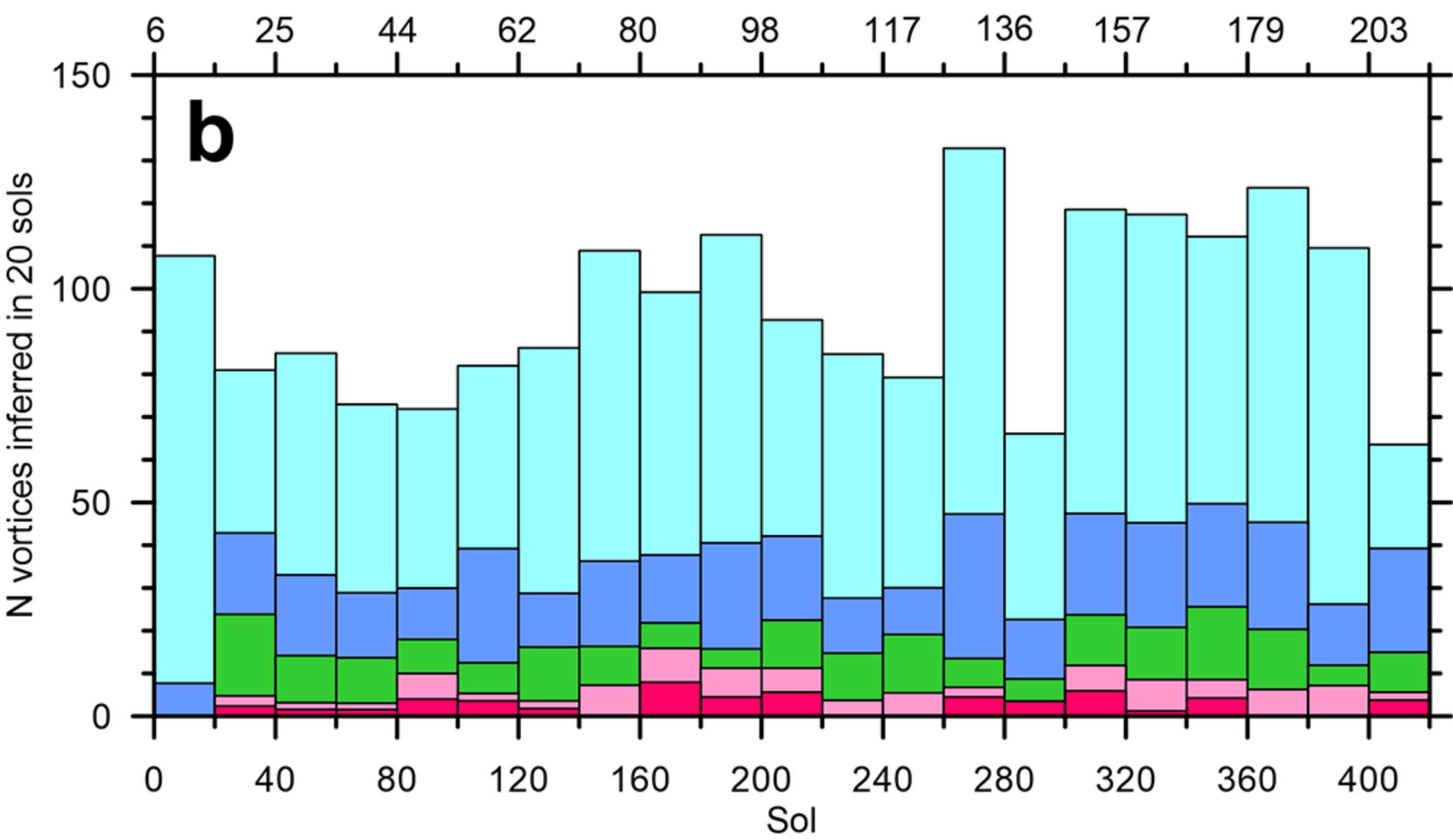
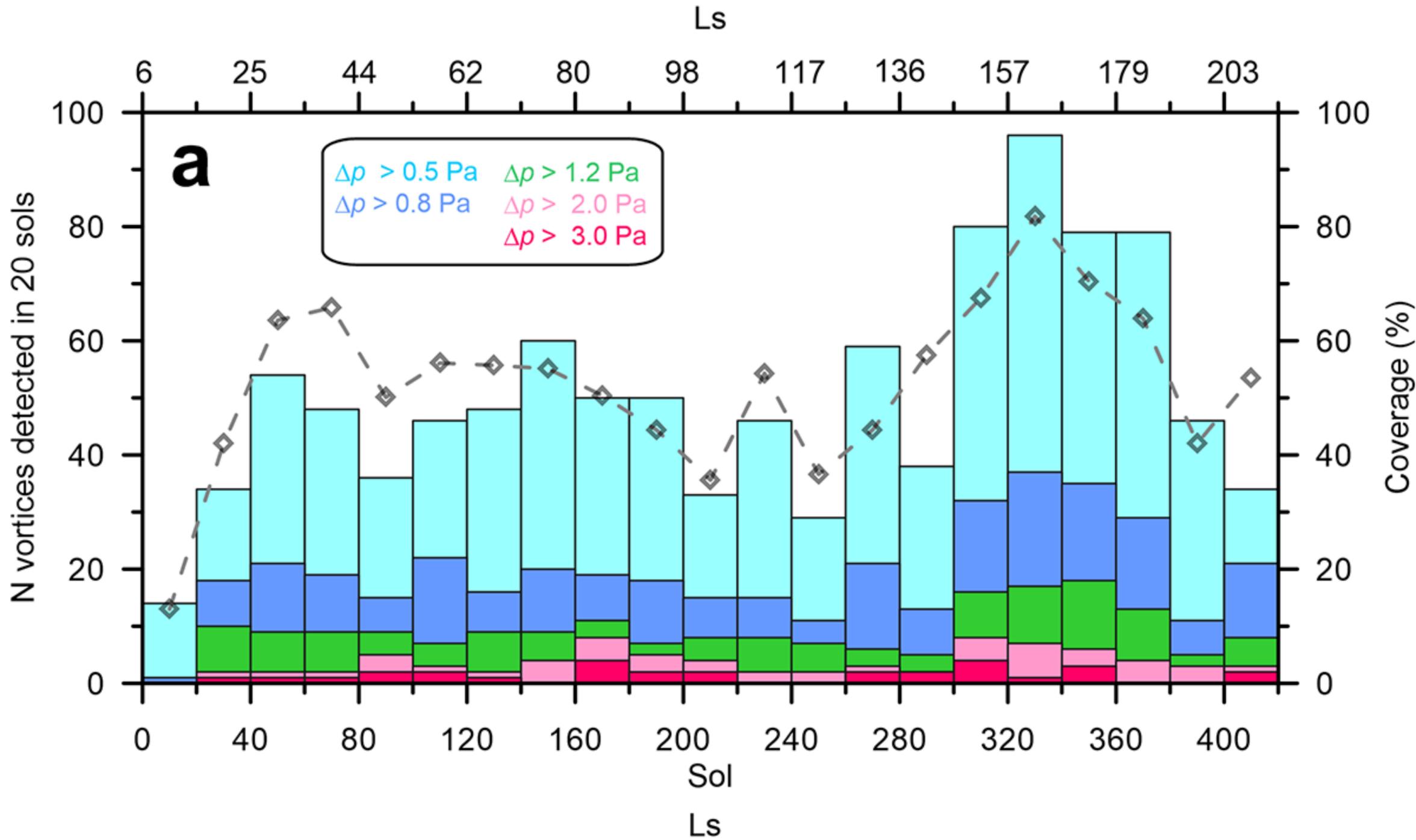
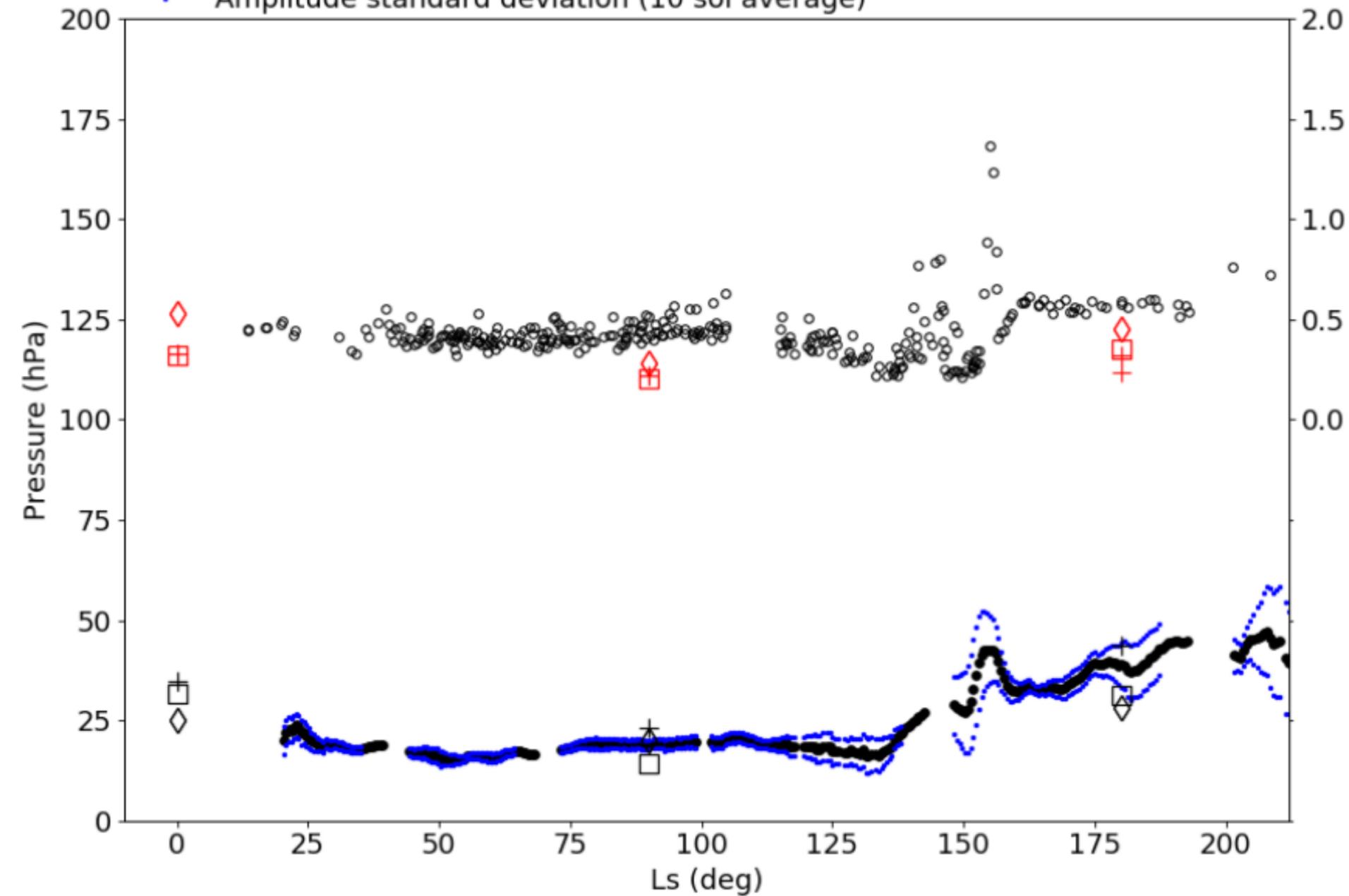


Figure 11.

(a)

- Perseverance observed optical depth
- Pressure amplitude (10 sol average)
- Amplitude standard deviation (10 sol average)

**(b)**

- Curiosity observed optical depth
- Pressure amplitude (10 sol average)

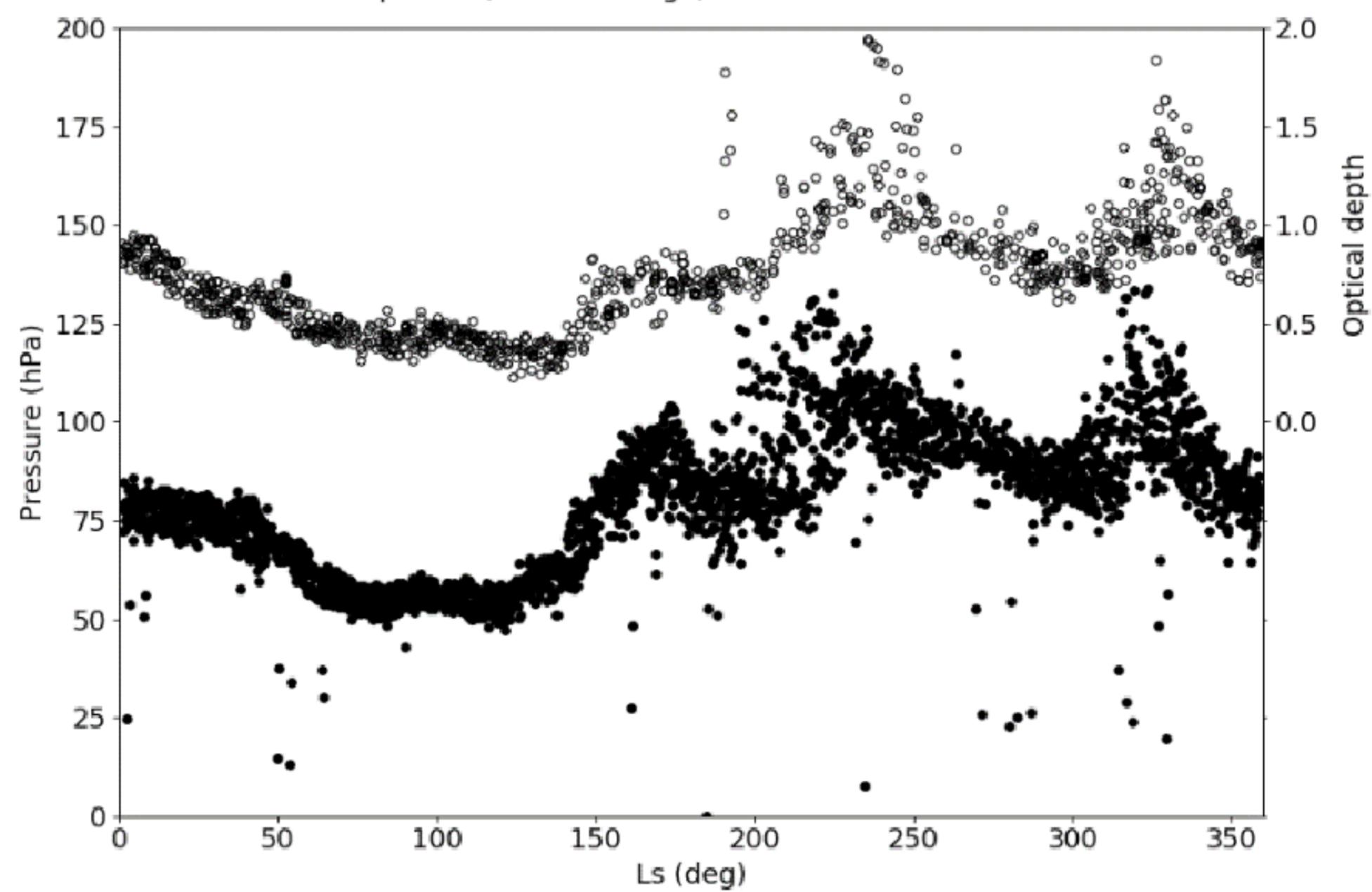


Figure 12.

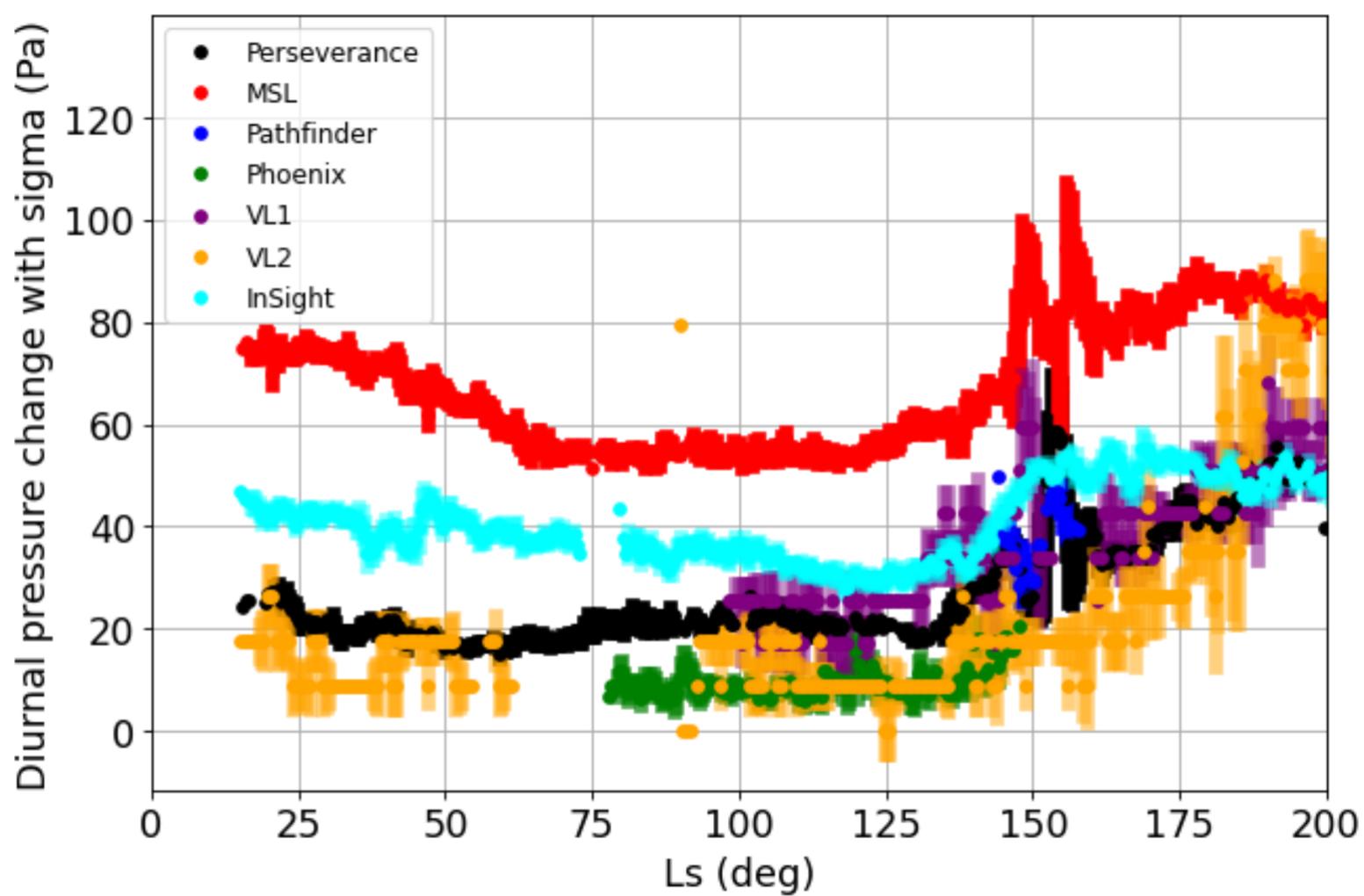
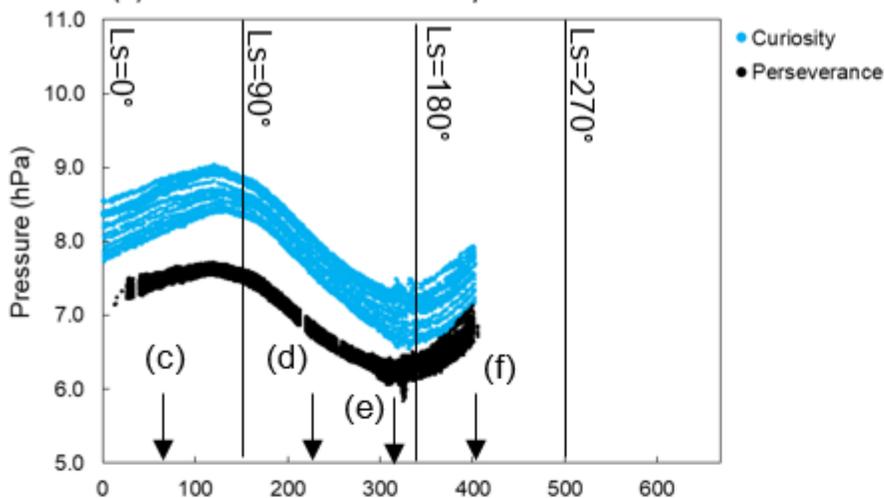
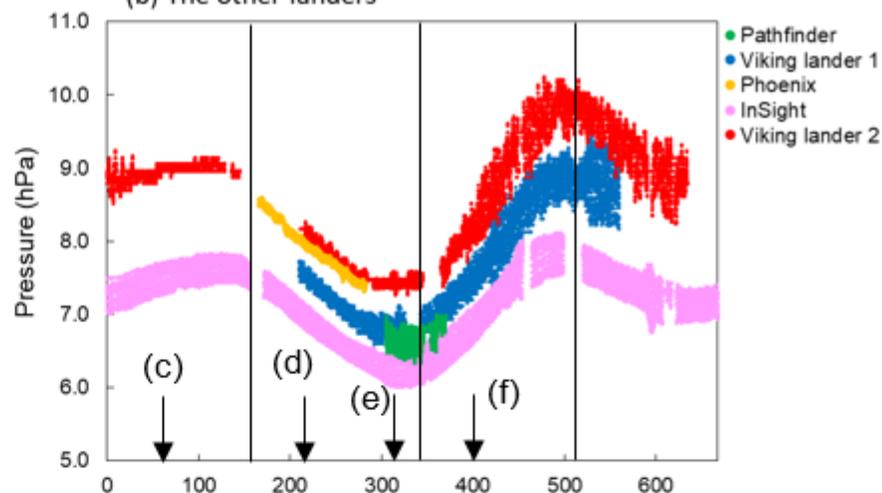


Figure 13.

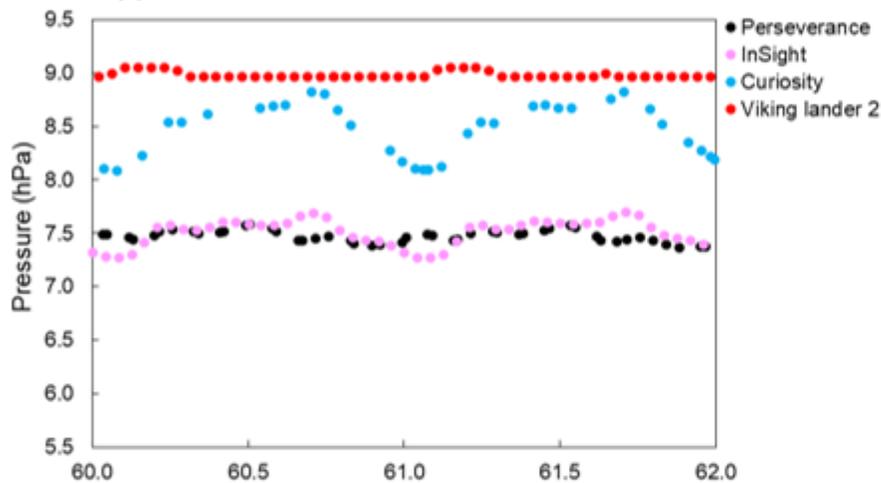
(a) Perseverance and Curiosity



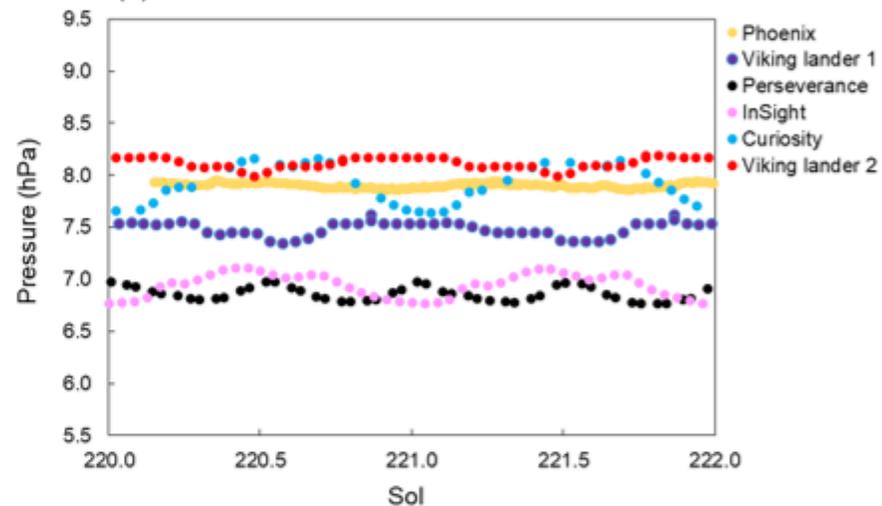
(b) The other landers



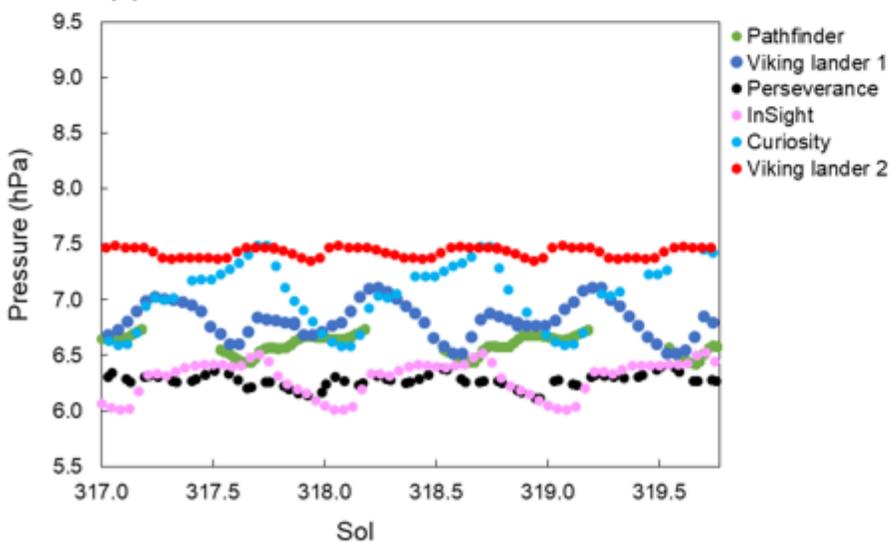
(c) $L_s=29^\circ$



(d) $L_s=102^\circ$



(e) $L_s=150^\circ$



(f) $L_s=197^\circ$

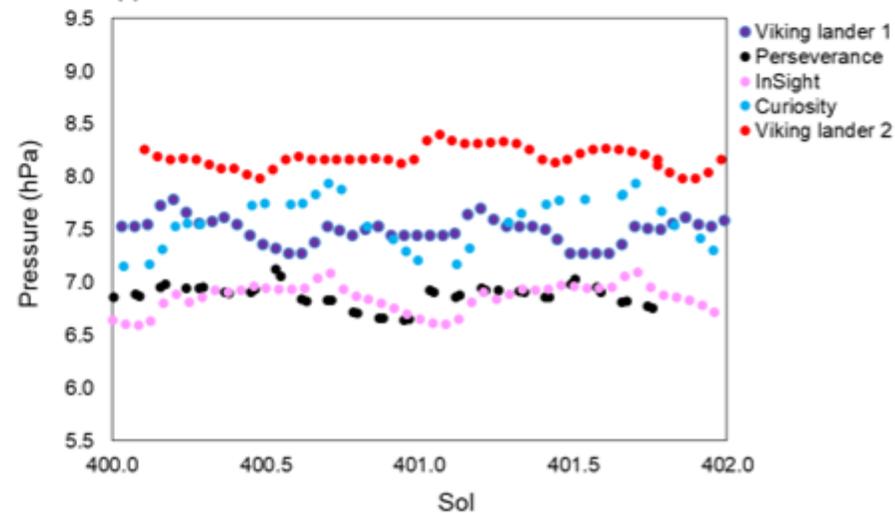
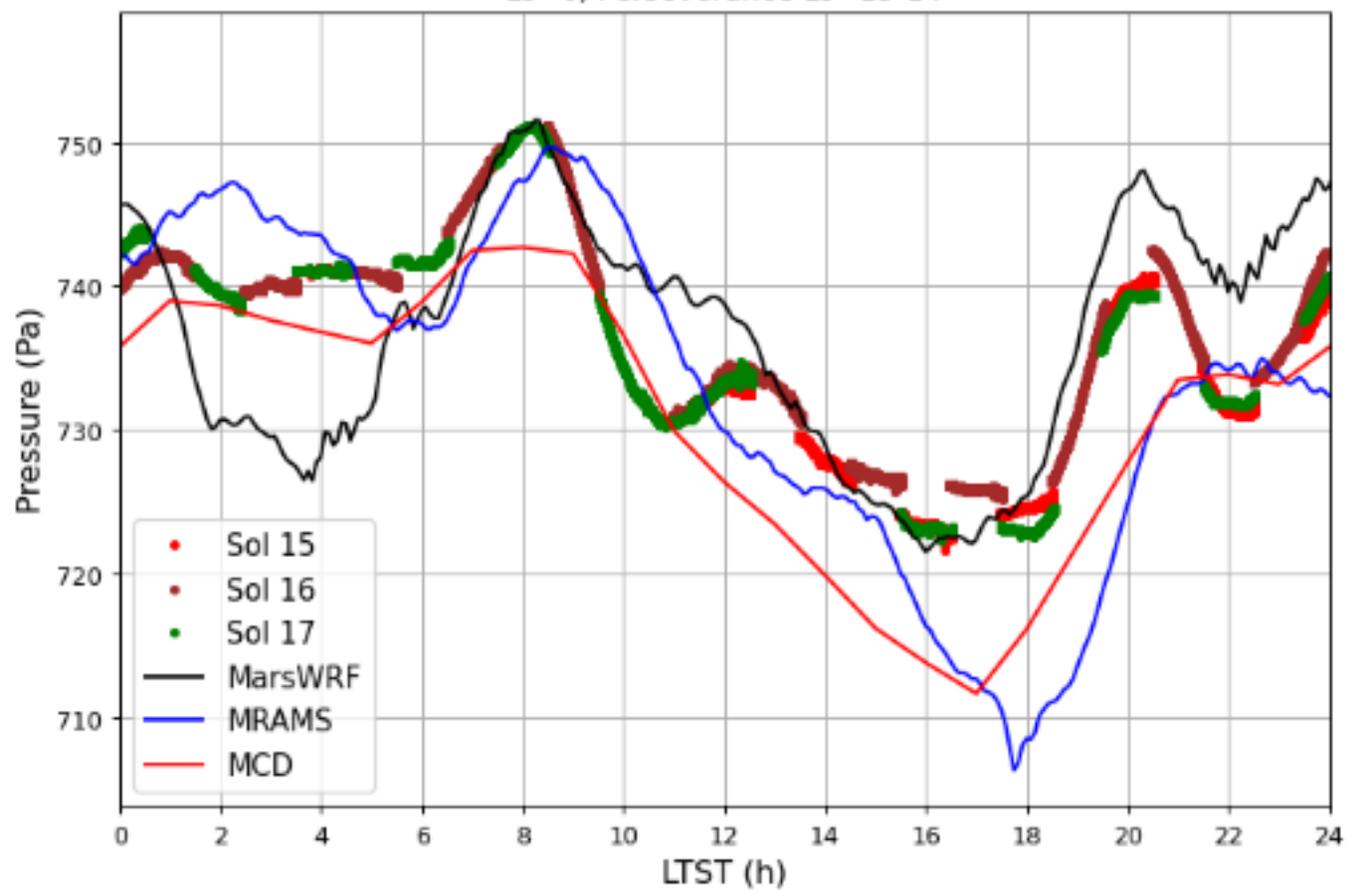
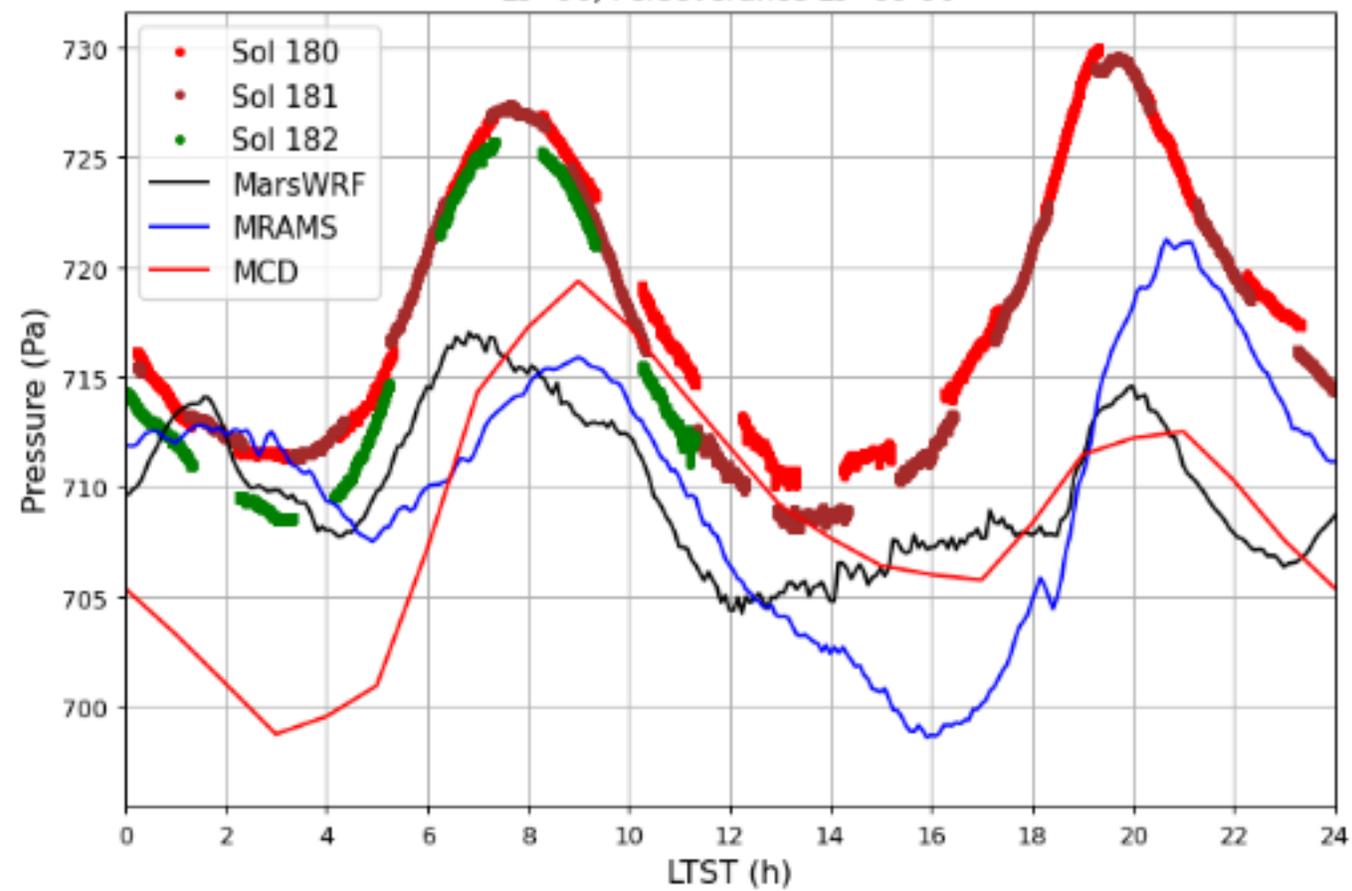


Figure 14.

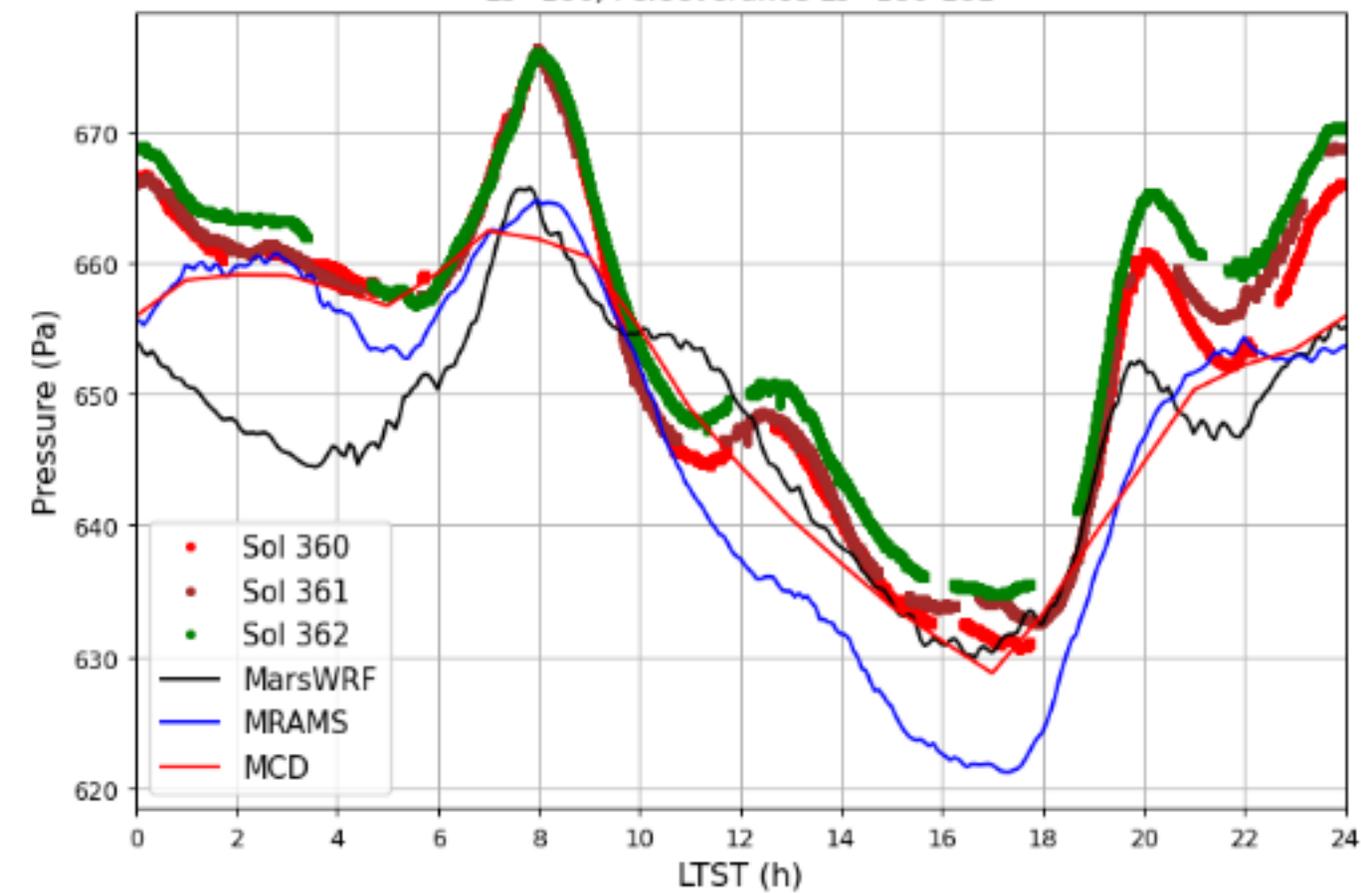
Ls=0, Perseverance Ls=13-14



Ls=90, Perseverance Ls=89-90



Ls=180, Perseverance Ls=180-181



Ls=270

