Evaluation of MSL Curiosity rover SAM methane detections with the Mars Regional Atmospheric Modeling System (MRAMS)

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Abstract

The in situ detection of methane at Gale crater by the Tunable Laser Spectrometer (TLS) of the Sample Analysis at Mars (SAM) instrument suite aboard the MSL Curiosity rover has garnered significant attention because of the implications for the potential of indigenous Martian organisms (Webster et al. 2013, 2015). In the absence of a yet-to-be-confirmed rapid destruction mechanism, the photochemical lifetime of methane is on the order of several centuries. This is much longer than the atmospheric mixing time scale, and thus the gas should tend to be well mixed except when near a source or shortly after an episodic release. The observed spike of 7.2 parts per billion by

volume (ppbv) from the background of <1 ppbv, and then the return to the putative background level in 47 sols is, therefore, curious. The Mars Regional Atmospheric Modeling System (MRAMS) was used to study the transport and mixing of methane from specified source locations using tracers, and to investigate whether methane releases inside or outside of Gale crater are consistent with SAM observations. The model simulations indicate that there must be a steady state release to counteract atmospheric mixing, because the timescale of mixing in the crater is ~1 sol. The model also indicates that the timing of SAM sample ingestion is very important, because modeled methane abundance varies by one order of magnitude over a diurnal cycle with a steady state emission. It is difficult to reconcile the SAM peak methane detections with the atmospheric transport and mixing predicted by MRAMS in the same periods. The only plausible scenario is an intermittent local steady state release close to the rover with the additional restrictions that such releases must be globally rare or there must be an unknown rapid methane destruction mechanism.

Highlights

- MRAMS is used to study the transport and mixing of methane emissions in and around Gale Crater.
- Crater mixing timescales are ~1 sol during all seasons, much faster than previously estimated.
- Predicted methane abundances of a steady state source vary by an order of magnitude over a diurnal cycle.
- The local time of sample ingest may strongly impact methane abundance measurements.

- It is difficult to reconcile the SAM measurements with the transport and mixing predicted by MRAMS in the same periods. The only plausible scenario is an intermittent local steady state release close to the rover.
- Ground temperature may control the release of methane trapped in clathrates on seasonal timescales, implying a seasonal hemispheric difference in methane background levels.
- During summertime, those levels inside crater should be poorly correlated with ground temperature due to an inundation of methane poor external crater air from the northern winter hemisphere.

1. Introduction

1.1 Review of ground-based and orbiter methane measurements

The possibility of detecting methane in the Mars atmosphere has attracted a great deal of attention because methane is primarily (90-95%) produced by biological activity on Earth. The first reported detection of methane in the atmosphere of Mars was made with the Mariner 7 spacecraft Infrared Spectrometer (IRS), and was announced at press conference two days after the Mars flyby (Sullivan 1969); however, shortly after it was shown that the observed spectral signatures were actually from CO_2 ice. This event serves as a lesson on how difficult it is to identify from Earth or from Martian orbit the spectral lines of methane, how difficult is to interpret remotely sensed spectra with weak absorption features, and how important it is not to let preconceived ideas and desires undermine a subjective analysis (Pla-Garcia 2017). As Carl Sagan quoted, extraordinary claims require extraordinary evidence.

Despite the Mariner 7 incident, the search for methane on Mars has continued. Over the last 14 years, there have been several reports of methane detection from Earth and from Mars orbit, although the detections are controversial and not universally accepted. All the putative detections suffer from one or more problems: weak signal, poor spectral resolution, telluric line contamination, and instrument noise or performance issues.

As can be seen in the Table 1, different detections of methane in the Mars atmosphere have been reported since 1999 until today. The earliest report of martian atmospheric methane suggested a global average value of 10±3 parts per billion by volume (ppbv) using the Fourier Transform Spectrometer at the Canada–France–Hawaii Telescope (capturing only a portion of the Martian disk) and searching for methane in the 3.3 μm spectral band (Krasnopolsky et al. 2004).

Type	Instrument	Observation	Mars Ls	Max. Value in ppbv (region)	Global avg (ppbv)	Reference
Earth based	FTS-CFHT	1999	88	-	10±3	Krasnopolsky et al. 2004
Martian orbit	TES-MGS	1999	180	~68 (Tharsis), ~64 (AT), ~60 (Elysium)	33±9	Fonti and Marzo 2010
Martian orbit	TES-MGS	1999	270	~26 (Tharsis), ~30 (AT), ~24 (Elysium)	6±2	Fonti and Marzo 2010
Martian orbit	TES-MGS	2000	0	~34 (Tharsis), ~32 (AT), ~32 (Elysium)	17±5	Fonti and Marzo 2010
Martian orbit	TES-MGS	2000	90	~30 (Tharsis), ~40 (AT), ~38 (Elysium)	14±4	Fonti and Marzo 2010
Martian orbit	TES-MGS	2001	180	~56 (Tharsis), ~62 (AT), ~60 (Elysium)	18±7	Fonti and Marzo 2010
Martian orbit	TES-MGS	2001	270	~24 (Tharsis), ~24 (AT), ~22 (Elysium)	5±2	Fonti and Marzo 2010
Martian orbit	TES-MGS	2002	0	~32 (Tharsis), ~28 (AT), ~30 (Elysium)	10±4	Fonti and Marzo 2010
Earth based	CSHELL-IRTF, NIRSPEC-Keck2	2003	155	<45 (TS, NF and SM)	6	Mumma et al. 2009
Martian orbit	TES-MGS	2003	180	~58 (Tharsis), ~56 (AT), ~52 (Elysium)	30±8	Fonti and Marzo 2010
Martian orbit	TES-MGS	2003	270	~22 (Tharsis), ~20 (AT), ~20 (Elysium)	5±1	Fonti and Marzo 2010
Martian orbit	TES-MGS	2004	0	~30 (Tharsis), ~30 (AT), ~30 (Elysium)	9±3	Fonti and Marzo 2010
Martian orbit	TES-MGS	2004	90	~56 (Tharsis), ~60 (AT), ~40 (Elysium)	28±8	Fonti and Marzo 2010
Martian orbit	PFS-MEX	2004	330-350	-	10±5	Formisano et al. 2004
Martian orbit	PFS-MEX	2004	330-10	20±10 (Elysium)	-	Encrenaz 2008
Earth based	CSHELL-IRTF	2006	10	-	<14	Krasnopolsky et al. 2007
Earth based	CSHELL-IRTF	2006	10	<10 (VM, 63-93°W and 0 to 7°N); 3 outside this region	-	Krasnopolsky et al. 2012
Earth based	CSHELL-IRTF and NIRSPEC-Keck2	2006	17	4	3	Mumma et al. 2009
Earth based	CRIRES-VLT, CSHELL-IRTF, NIRSPEC-Keck2	2006	352	-	<7.8	Villanueva et al. 2013
Martian orbit	PFS-MEX	2004-2008	50	21 (-40E and +70E lon)	14±5	Geminale et al. 2008
Martian orbit	PFS-MEX	2004-2008	160-180	<45 (north polar region)	14±5	Geminale et al. 2011
Martian orbit	PFS-MEX	2004-2008	325	5 (-40E and +70E lon)	14±5	Geminale et al. 2008
Earth based	CRIRES-VLT, CSHELL-IRTF, NIRSPEC-Keck2	2009	12	-	<6.6	Villanueva et al. 2013
Earth based	CSHELL-IRTF	2009	20	<8 (0-30°W)	-	Krasnopolsky et al. 2012
Earth based	CSHELL-IRTF	2010	70	<8 (30°W to 90°E and along the central meridian)	-	Krasnopolsky et al. 2011
Earth based	CRIRES-VLT, CSHELL-IRTF, NIRSPEC-Keck2	2010	83	-	<7.2	Villanueva et al. 2013
In-situ (Mars sfc)	SAM-MSL	2013-2014	336-82	7.2 ± 2.1 (Gale crater)	-	Webster et al. 2015
Earth (~12-14 km)	SOFIA-EXES	2016	123	1 ± 5 ppb (several locations)	-	Aiko et al. 2017

Table 1. Detections of methane in the Mars atmosphere reported since 1999 until today

In the second detection, from Mars orbit observation, Formisano et al. 2004 used the Planetary Fourier Spectrometer (PFS) on board ESA Mars Express (MeX) spacecraft summing a wide range of latitude and longitude observations, reporting a global average value of 10±5 ppbv, later updated to 15±5ppbv (Geminale et al. 2011). Geminale showed evidence of widespread temporal and spatial variability with indications of discrete localized sources (they found that methane is not uniformly distributed in the Martian atmosphere) and a summertime maximum of 45 ppbv in the north polar región. If true, these observations suggest that the variation of methane abundance is a feature of Mars from 2004 to 2008, although there is a high controversial about these detections due to instrument noise. The MeX measurements are obviously at the limits of the resolution and sensitivity of the PFS instrument, limited by the extremely poor spectral resolution that is ∼200 times the Mars methane linewidths (Webster at al. 2010; Zahnle et al. 2010). The data do not suffer from telluric contamination, but the spectral resolution is too coarse and the signals too weak for methane to be identified directly (Zahnle et al. 2010). Geminale estimates that a methane emission of 126 tons per year is required for the mentioned concentrations of ~10 ppbv on Mars. This volume could rise up to 57,000 tons per year if the putative high methane of 45 ppbv observed from Earth are taken into account.

Mumma et al. (2009) (hereafter M09) applied infrared spectroscopic techniques using the powerful infrared high-resolution spectrometers NIRSPEC and CSHELL at high-altitude telescope observatories Keck-2 and NASA-IRTF respectively, to search for methane in the 3.3 μm spectral region identifying multiple spectral lines having both spatial and temporal variability on the scale of several Mars years. The distinct spatial variability reported in M09 suggests regional source regions (Figure 1).

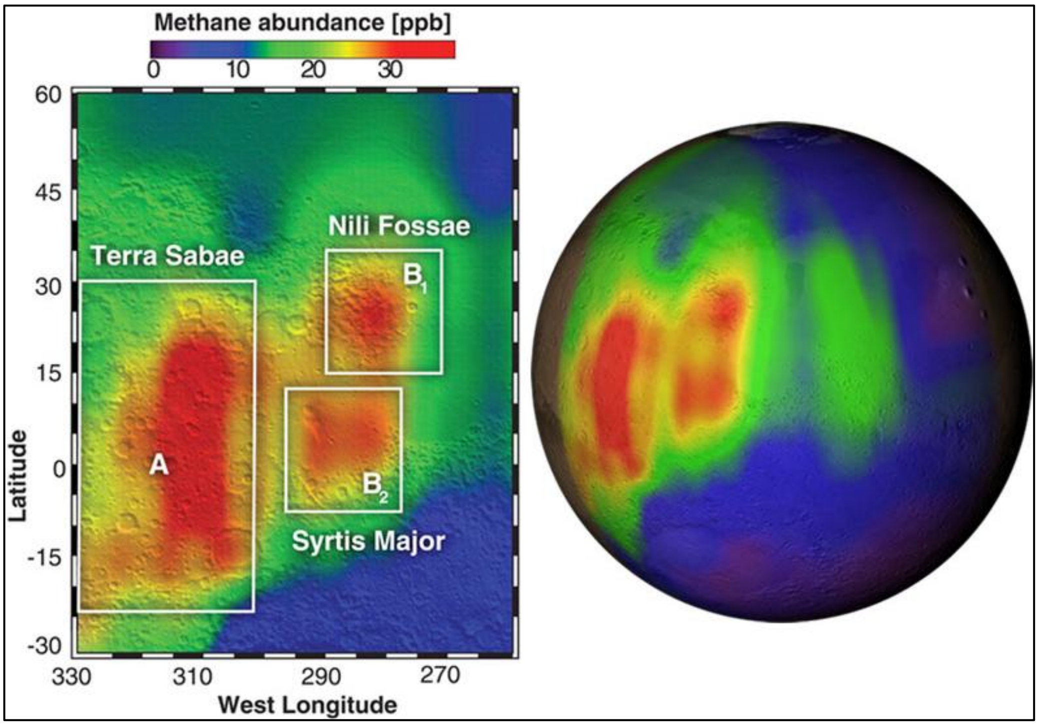

Figure 1. M09 observations of methane near the Syrtis Major volcanic district where methane appears notably localized (A, B_1, and B_2) in northern summer Ls 155°. Adapted from M09.

If true, methane is not just slowly leaking out everywhere, but there must be also large intermittent releases from specific areas.

Follow-up measurements (Villanueva et al. 2013) have failed to detect similar releases. The temporal variability could indicate seasonal variations in the source strength and, more surprisingly, extremely rapid destruction of methane through non-photochemical processes. There is no known mechanism for rapidly destroying methane chemically on Mars, although heterogeneous chemistry with surface peroxides and atmospheric aerosols, or destruction by peroxides generated intermittently through dust electrochemistry (Atreya et al. 2007) are possibilities. Such mechanisms would also likely disrupt the broader oxygen and hydrogen chemistry, and there is little evidence of such effects. Another analysis shows that methane in the wind can react with the eroded surface quartz grains (abraded silicates) which sequester methane by forming covalent Si–CH_3 bonds and thus an enrichment of the soil with reduced carbon, offering a possible explanation for the fast disappearance of methane on Mars (Jensen et al. 2014).

If the M09 values were accurate, the emission rate for the largest magnitude methane plume was estimated to be at least 0.6 kg s^{-1}, generating a mean mixing ratio of 33 ppbv over the region of influence (approximately 8,000,000 km^2) with a peak mixing ratio of 45 ppbv during north summer, and little methane outside this region. Were the contents of this plume to be spread uniformly over the globe, it would equate with a global average mixing ratio of 2 ppbv. Combined with other seasonally contiguous plumes that were also measured, the total global average methane abundance was estimated to be 6 ppbv. However, observations of the following Martian year found a mean mixing ratio of only 3 ppbv; thus M09 concluded that the chemical lifetime of atmospheric methane on Mars had to be less than 4 Mars years, and possibly as short as 200 sols (far shorter than the photochemical lifetime of 350 years previously assumed). The conclusion that was drawn, then, was that methane is being removed from the atmosphere through means substantially more efficient that photochemical processes alone. M09 provided some limited analysis of plume evolution over time based upon the assumption of a diffusion-only atmosphere.

Zahnle et al. 2010 makes a strong case that the M09 detection was not martian methane at all, but the retrieval of a doppler shifted telluric line. The strongest reported signals using Earth based observations (Krasnopolsky et al. 2004 and M09) are from methane lines where the potential for confusion with other telluric or martian spectral features is significant, while observations at more favorable wavelengths indicate no methane above a 3 ppbv noise floor (Zahnle et al. 2010).

Fonti and Marzo 2010, using the thermal emission spectrometer (TES) on-board Mars Global Surveyor (MGS), showed evidence of widespread temporal variability with a global average value of 3 to 42 ppbv between 1999 and 2004 and with strong spatial variability in the methane signal intermittently present over locations where favorable geological conditions such as residual geothermal activity (Tharsis and Elysium) and strong hydration (Arabia Terrae) might be expected. There is considerable controversy about these detections, because TES lacks spectral line resolving power and requires to co-add nearly 3,000,000 of crude spectra to produce a very weak signal. Also, the identification of methane signal is controversial due to the presence of nearby H_2O and CO_2 lines. The identification of methane depends on spatial and seasonal correlations with results from Geminale et al. (2008) and M09 (Z).

Other favorable locations for high methane levels are: Valles Marineris (42° to 7°N) with an upper limit of 10 ppbv and 3 ppbv outside that region (Krasnopolsky 2012), and with a value of 20±10 ppbv over Elysium region (Encrenaz 2008).

In an effort to minimize the previous problems reported (telluric contamination with other martian spectral features, instrument noise and very low spectral resolution data), observations were performed with the Echelon-Cross-Echelle Spectrograph (EXES) onboard the Stratospheric Observatory for Infrared Astronomy (SOFIA). The high altitude in the Earth atmosphere of SOFIA (~12-14 km) significantly reduces the effects of the terrestrial atmosphere allowing the use methane lines in the 7.5 µm band. These measurements suggest an upper limit on the methane volume mixing ratio range from 1 to 9 ppbv (Aoki et al. 2017, 2018). The measurements were performed at northern summer (Ls 123º) of Mars year 33.

Based on current understanding, the total photochemical loss rate of methane in the martian atmosphere is $2.2\times10^5 cm^{-2}s^{-1}$, and its lifetime is 340 years (Krasnopolsky et al. 2004). Since the vertical and horizontal mixing time is much shorter than the photochemical lifetime, methane should be uniformly mixed and distributed throughout the atmosphere. However, the different methane observations (Table 1) indicate a temporal and spatial variability of methane that is inconsistent with a well mixed atmosphere or inconsistent with a long photochemical lifetime (Lefevre and Forget 2009). Further, with a long photochemical lifetime, even episodic emissions like those identified in Table 1 would result in a large global methane abundance.

Another possibility is that martian photochemical models could be wrong (Cesar Menor-Salván, personal communication), because the rapid destruction of methane is very difficult to reconcile with the known distribution of other gases in the Mars atmosphere. Methane oxidation would deplete the oxygen in Mars atmosphere in less than 10,000 years unless balanced by an equally large unknown source of oxidizing power. Perchlorates on the surface and on atmospheric dust, or the production of H_2O_2 through electrochemical processes in dust devils and dust storms might be able to provide oxidation source (Atreya et al. 2007). Photochemical removal of methane also disrupts the hydrogen chemistry and those effects would presumably be seen in other, more obvious places on Mars (e.g., water, OH, O_2, O_3, and CO/CO_2 abundance). The effects on other species has not been observed, although there are unexplained variations in O_2 (McConnochie) that might provide some clues. Some colleagues (Moores 2017) proposed that the small seasonal variations of methane background values could be traced to seasonal variations in UV, but UV insolation does not change that much over the seasons at the equatorial location of Gale crater, and it cannot explain the decrease from the peak values back to the background level. Photochemical activity might be expected to rise and fall slightly with the seasons, but the slight variations are insufficient to produce the necessary and sudden destruction mechanisms.

To the extent that SAM and perhaps other MSL instrumentation can measure trace gases, particularly those species whose presence are less controversial than methane, the seasonal and diurnal variability and abundance could provide further clues about the mixing time scale of the crater. Oxygen species (O, O_2 and/or O_3) are potential candidates for investigation, as is CO. Whether other trace gases (for example radon, which has a uniquely subsurface source) exhibit peculiar behaviors has yet to be determined, but it is an interesting topic to consider for the future.

1.2 SAM methane detections at Gale crater

In situ measurements provide ground truth using direct and, in principle, more reliable methods than those from Earth or Mars orbit. The Tunable Laser Spectrometer (TLS) of the Sample Analysis at Mars (SAM) instrument suite aboard the MSL Curiosity rover at Gale crater (Mars) was specifically designed to obtain precise abundance measurements, including the potential measurement of different isotopologues of methane, using laser absorption spectroscopy (Table 1).

SAM determines methane abundances by taking the difference between measurements from a cell with an atmospheric sample and an empty cell. Using this difference technique minimizes the effect of potential contamination between measurements, and atmospheric methane would be detected as the difference between the signals (Webster et al. 2015).

During the long pre-launch activities in Florida, the evacuated foreoptics chamber leaked up to a significant pressure (~76 mbar) by the time MSL Curiosity rover arrived at Mars. This pressure included terrestrial "Florida air" from the launch site that contained significant terrestrial methane gas (~10 ppmv) (Webster et al. 2015 SM). This concentration is ~1,000 times the ppbv values that SAM has sinced measured in the martian atmosphere. Zahnle (2015) expressed the possibility that the Curiosity rover itself has known or hidden sources of methane that might contaminate the TLS-SAM foreoptics chamber to produce methane around the rover. In order to rule out this, the SAM team measured the foreoptics pressure every time the instrument was running, and apart from two deliberate attempts to reduce that pressure (pump out the chamber), there is no evidence of a broken seal or leakage of gas out of the foreoptics chamber over the 5 years of measurements. Second, with the previously mentioned "difference method", the "empty cell" spectra/measurements provide a direct measurement of the foreoptics methane amount, which has varied somewhat during pumping attempts, but remains around ~1015 molecules of methane in the foreoptics chamber.

Two different atmospheric sampling methods are used by SAM. The first is a "direct ingest" method in which gas is ingested into the instrument through an inlet port located on the side of the Curiosity rover, taking ~10 minutes to fill to ~7 mbar and producing uncertainties of ~2 ppbv for each measurement. The second is an "enrichment" method, that ingests atmospheric gas through a second inlet port, which is passed over a CO_2 scrubber to more slowly fill the instrument (~2 hours) to ~7 mbar (Webster et al. 2015). This method efficiently removes the incoming CO_2 and effectively enriches the methane abundance by a factor of ~25, allowing more precise measurements of low background levels. In both cases, the time of initiation of measurements is constrained by competing rover activities and power availability. Most of the SAM-TLS measurements were acquired during nighttime (except on sols 305 and 525) due to thermal requirements of the SAM sample handling system. Also, long periods of time can pass between measurements.

The record of SAM methane measurements is shown in Figure 2. The first four measurements (Sols 79, 81, 106 and 293 after MSL Curiosity rover landing) indicated a value of <1.5 ppbv using the direct ingestion method (see Table 2). Measurements taken shortly thereafter were consistent with this initial measurement (Webster et al. 2015). Another measurement taken almost 200 sols later was also at the 1 ppbv level. There is no way to know if methane concentrations remained consistently at this level during this period, despite the green bar in the Figure 2 that incorrectly suggests such knowledge.

A spike in methane abundance was first noted at sol 467 (Ls 55º). It is commonly assumed that methane abundance remained continuously elevated between sol 467 and 526 (~Ls 55-82º), with a mean value of 7.2 ± 2.1 ppbv (95% CI) (Webster et al. 2015), but there are no data to support this assumption. The infrequency of methane measurements introduces great uncertainty about variations between spikes, because it is not known precisely when the spikes began, how long they lasted, or how long it took for the values to return to background values. It could be possible that the methane values come back to background values in hours or sols after the peak, and the detected spikes were serendipitous.

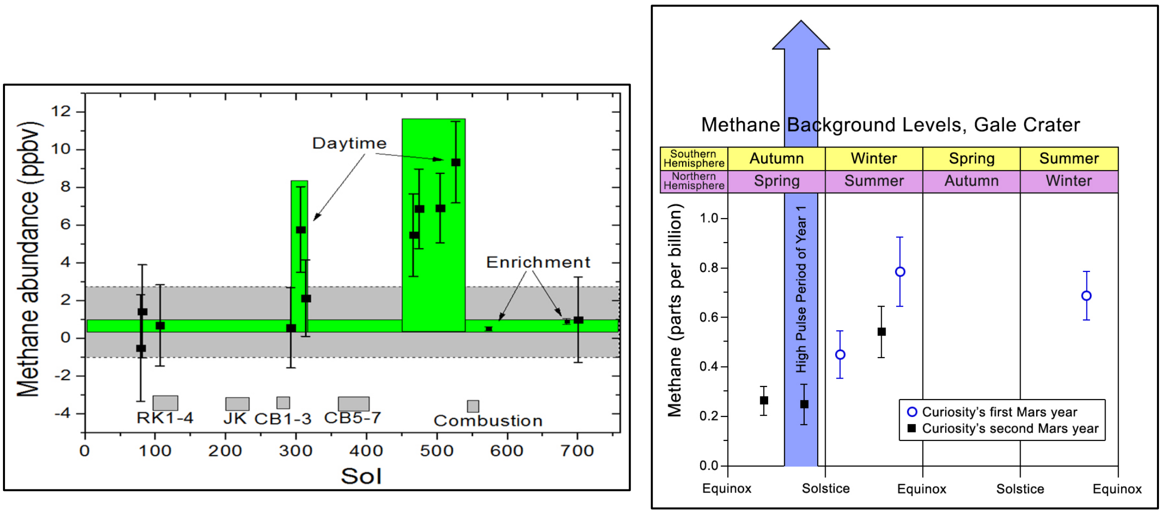

Figure 2. Two years of subsequent measurements taken during the rover's journey of 9 km over highly varied terrain. SAM methane measurements fall into two basic categories: larger spikes of up to ~7 ppbv (left) and low level background abundance of ~0.3-0.7 ppbv (right). The background measurements may indicate a seasonal cycle. The time between measurements is insufficient to determine how frequently spikes in abundance occur, how fast they decay, or how common the spikes may be. The green shading incorrectly suggests knowledge of methane concentrations at times when no measurements were taken. [Mars Exploration Program NASA website December 16, 2014 (left image) and May 11, 2016 (right image)].

measurement was taken at sol 573 using the enrichment method. Subsequent measurements at sol 684 (both direct ingest and enrichment method) were also at the background level.

Neglecting the spikes of concentration, there appears to be a seasonal cycle in the background methane concentrations at Gale crater (Figure 2), with a mean value of ~0.4 ppbv (compared with 1.8 ppmv on Earth, the background methane content at Gale crater is 4,500 thousand times less), ranging from a minimum about 0.3 ppbv near the northern summer solstice to a peak about 0.7 ppbv sometime between the northern autumn equinox and the winter solstice (Webster et al 2017).

Table 2. MSL Curiosity rover TLS-SAM methane measurements at Gale crater over a ~20-month period (from Oct. 26th 2012 to July 9th 2014). Adapted from Webster et al. 2015.

Run Description	Sol	Ls deg	Mean CH_4 value ±1 SEM (ppbv)
DIM1	79.96	195.60	-0.51±2.83
DIM2	81.89	196.77	1.43±2.47
DIM3	106.14	211.74	0.68±2.15
DIM4	293.16	329.16	0.56±2.13
DIM5	305.58	336.12	5.78±2.27
DIM6	314.14	340.83	2.13±2.02
DIM7	467.14	55.59	5.48±2.19
DIM8	475.14	59.20	6.88±2.11
DIM9	505.12	72.66	6.91±1.84
DIM10	525.56	81.84	9.34±2.16
EM1	573.08	103.48	0.47±0.11
EM2	684.06	158.61	0.90±0.16
DIM11	684.27	158.73	0.99±2.08

Is important to note that all the martian methane detections reported since 2009 (Krasnopolsky 2011; Krasnopolsky 2012; Villanueva et al. 2013; Webster et al. 2013; Webster et al. 2015 and Aoiki et al. 2018) are <9 ppbv or below detection thresholds altogether. Also, many of the earth-based and orbital detections are an order of magnitude greater than the SAM background, which is odd considering the sporadic nature of the remote measurements.

1.3 Previous modeling works of methane transport

Previous works modeling martian methane plumes have been undertaken using GCMs: Mischna et al. 2011, Holmes et al. 2015 and Viscardy et al. 2016. Mishna et al. 2011 concluded that a best match to observations would be found if a nearly instantaneous (rather than gradual), spatially large release occurred just before the time of observation (before it could be substantially diluted) no more than 1–2 sol earlier (Figure 3). This result is consistent with relatively fast atmospheric mixing.

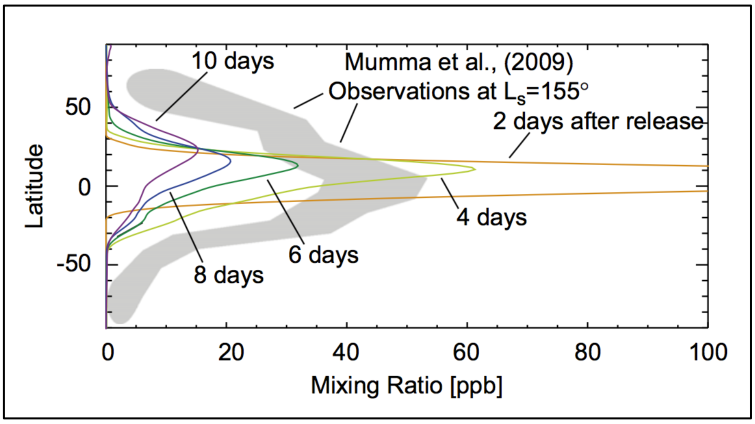

Figure 3. Latitudinal distribution of plume mixing ratio as a function of time for central longitude of 315°W, and 16°x10° (lon, lat) smoothing. Each curve (progressing from right to left) shows the variation in 2 sol increments, from 2 sols after a 'pulse' release (rightmost) to 10 sols after (leftmost). The shaded region encloses the M09 methane observations. Adapted from Mischna et al. 2011.

The results of Holmes et al. 2015 show that the spatial and temporal variability of methane on Mars implied by observations might be explained by advection from localized time-dependent sources alongside a currently unknown methane sink. The best agreement between the existing observations is found in their simulations using a steady state release from a small source over Nili Fossae. Holmes et al. 2015 suggest that the lower levels of SAM measurements when compared to previous results (M09 and Fonti and Marzo 2010) can be explained by a relative lack of, or indeed complete absence of, methane source emission in the intervening period. Again, this requires a hitherto unknown large methane sink.

Previous GCM simulations have focused on the horizontal evolution of the methane, but Viscardy et al. 2016 explored the three-dimensional dispersion of methane throughout the atmosphere after a surface release. Their simulations show that surface emissions of methane results in a non-uniform vertical distribution, including the formation of elevated layers, shortly after the release. As expected, the destination of the released methane is determined by the global circulation pattern at the time of the release, and the methane can be transported to locations over the planet that are far away from the emission place. It typically takes several weeks for the methane to become uniformly mixed, implying that the detection of vertical layers of methane can be a clue of recent surface emission. Their finding shows abundances of methane higher up in the atmosphere can be much larger than those measured at the surface where the rover Curiosity is located.

As shown by Pla-Garcia et al. 2016 and Rafkin et al. 2016 (hereafter PGR16) the circulation in and around the ~150 km diameter Gale crater is very complex, with strong seasonal and diurnal variations. The expectation is that the distribution of methane in and around the crater will be strongly influenced by the complex circulations. In order to represent the large scale release and dispersion of methane, the use of a GCM, as done in the previous works (Mischna et al. 2011, Holmes et al. 2015 and Vicardy et al. 2016) is appropriate, but a GCM cannot capture the transport in and around Gale crater. The mesoscale circulations driven by the complex topography at the scale of the crater can only be simulated by a model with significantly greater spatial and temporal resolution. The work herein extends PGR16 to investigate the transport and dispersion of methane by resolved crater circulations.

It is difficult to explain the SAM and previous measurements at the global scale using global scale models. An individual peak methane detection could be consistent with a regional release and large scale transport, but continuously elevated peaks are not. For methane to remain elevated for many sols, a release would have to be nearly continuous in order to counteract transport. Such a continuous release would then result in globally large methane values after the relatively short mixing timescales.

The behavior of highly localized releases (on the scale of Gale crater or smaller) or the transport of a larger release by the complex circulations in Gale Crater, has yet to be fully explored. For example, PGR16 hypothesized that gases released in the crater could become trapped in the lowest portion of the crater basin due to the very cold and dense air mass that would be resistant to mixing with air above. Cold air trapping is a common phenomena on Earth and often results in the build up of pollution in enclosed basins (e.g., Malek et al. 2006, Whiteman et al 2001, Steyn et al 2013).

2 Mars methane modeling experiments

2.1 Mars Regional Atmospheric Modeling System (MRAMS)

The Mars Regional Atmospheric Modeling System (MRAMS) is used in this study to investigate the transport and dispersion of trace gases in and around Gale crater. MRAMS is a versatile numerical mesoscale model that simulates the circulations of the Martian atmosphere at regional and local scales (Rafkin et al. 2001, 2002, 2006, 2009; PGR16). MRAMS is derived from the Regional Atmospheric Modeling System (RAMS) which is a widely used nonhydrostatic Earth mesoscale and cloud-scale model (Pielke et al., 1992) designed to simulate synoptic-scale, mesoscale, and microscale atmospheric flows over complex terrain. MRAMS is explicitly designed to simulate Mars atmospheric circulations at the mesoscale and smaller scales with realistic, high-resolution surface properties.

To simulate the Gale crater meteorological environment, MRAMS is configured with five grids centered over the MSL Curiosity rover site (Figure 2; PGR16). The grids are configured, as much as practicable, to cover topographic regions that might influence the solution on a particular grid. The outermost grid (the mother domain), extends well into the northern hemisphere, covering the north polar cap and the hemispheric topographic dichotomy. This configuration can capture the strong topographic flows that sometimes occur near the hemispheric dichotomy, and it can capture the seasonal mean meridional flows (i.e., the Hadley Cell) that are nearly global in extent and that should have a great impact into the methane mixing. Grids are also specified so as to minimize, as much as possible, the crossing of large topographic features at the boundaries, which can create spurious noise. The horizontal grid spacing at the center of the five grids are 240, 80, 26.7, 8.9 and 2.96 km respectively (Figure 2; PGR16), with the innermost grid centered at the location where SAM detected the methane spikes.

All the grids have the same vertical grid configuration with the vertical winds staggered between thermodynamic levels. The lowest thermodynamic level (where temperature and pressure are prognosed) is ~14.5 m above the ground. Ideally, the first vertical level would be located at the height of the TLS-SAM sensor (~1 m), but this is not computationally practical; the integration time step for nonhydrostatic models is closely coupled to the thickness of that layer. Using a lowest model thickness of one to two meters would have required a mother domain time step of fractions of a second compared to a value closer to 10 s. Thus, the model would have run approximately two orders of magnitude slower. This vertical spacing is gradually stretched with height until reaching a maximum spacing of 2,500 m, and the levels gradually transition from terrain-following near the surface to horizontal at the top of the model. The spacing does not exceed 100 m in the lowest 1 km, and does not exceed 400 m in the lowest 4 km. The model top is 51 km with 50 vertical grid points.

Output from the NASA Ames General Circulation Model (Kahre et al. 2006) is used to initialize the atmospheric state in MRAMS. Time-dependent boundary conditions are also supplied from the NASA model output at intervals of 1/16th of a sol.

This frequency is sufficient to capture the thermal tide signal, but some amount of aliasing is possible. Dust is prescribed based on zonally-averaged TES retrievals (in non-global dust storm years) and follows a Conrath-ν profile in altitude (Conrath, 1975). The Conrath-ν parameter that describes the depth of the dust varies with season and latitude as prescribed in the baseline version of the Ames GCM. The deepest atmospheric dust column is found near the subsolar latitude. CO_2 ice is placed on the surface based on the location predicted by the GCM at the MRAMS initial time. The ice is static in time during the MRAMS integration; the active CO_2 cycle is disabled, which is a valid assumption for the short periods of simulation time (<=12 sols) under consideration with the model. MRAMS surface properties are obtained from TES thermal inertia (nighttime) and albedo data sets binned at 1/8th of a degree, and from MOLA topography binned at 1/128th of a degree (Table 1). The model computes topographic shadowing and slope radiation effects based on the MOLA data.

The model was run for twelve sols. Although the circulation patterns are highly repeatable from sol to sol beginning within a few hours of initialization, the first sol may be regarded as ‘‘spin-up’’. All simulations were started at or slightly before local sunrise. In order to characterize seasonal mixing changes throughout the Martian year, simulations were conducted at Ls 270º (the wholesale inundation of the crater period), Ls 90º (as a representative of the rest of the year) and Ls 155º (the season of the 2003 Earth-based detections M09). Using the above model configurations, PGR16 demonstrate that the model was able to reproduce the meteorological observations obtained by the MSL Curiosity rover REMS instrument (Gomez-Elvira et al. 2012) in Gale crater.

MRAMS has the capability to simulate the transport of inert gases as tracers, and this capability is used to represent the transport of mixing of methane. An atmospheric tracer may be considered as an inert gas released into the model atmosphere and which is transported by advection and dispersion (subgrid turbulent mixing). Since the photochemical lifetime of methane is thought to be very long compared to the 10 sols duration of the simulation, no sinks are imposed on the tracers that represent methane (Lefevre and Forget 2009). Tracers in the MRAMS model can be placed anywhere, and may be released instantaneously or at a user-specified, time-dependent rate. Tracers are not radiatively active and do not contribute to the tendency of any model prognostic variables. Tracers released from the same location but with different emission fluxes will evolve identically with abundances in proportion to their source fluxes. In other words, the source flux may be scaled after numerical integration in order to get a proportional answer (e.g. multiplying the flux in MRAMS by 200 produces a 200 times higher tracer mixing ratio value but with an otherwise identical spatial pattern).

2.2 Martian clathrates subsurface model

The detection of methane variability necessitates a methane source (Figure 4). These sources could include non-biological processes like as serpentinization of olivine (Oze and Sharma 2005; Atreya et al. 2007), geothermal production (Etiope et al. 2011), erosion of basalt with methane inclusions (McMahon et al. 2013), release from regolith-absorbed gas (Meslin et al. 2011; Gough et al. 2010), exogenous sources to include infall of interplanetary dust particles (IDP) and cometary impact material (Schuerger et al. 2012), biological sources like subsurface methanogen microorganisms (Krasnopolsky et al. 2004) or release of methane from organic decay in solution

(Keppler et al. 2012; Schuerger et al. 2012; Poch et al. 2014). The evidence for each of these sources is generally weak or speculative.

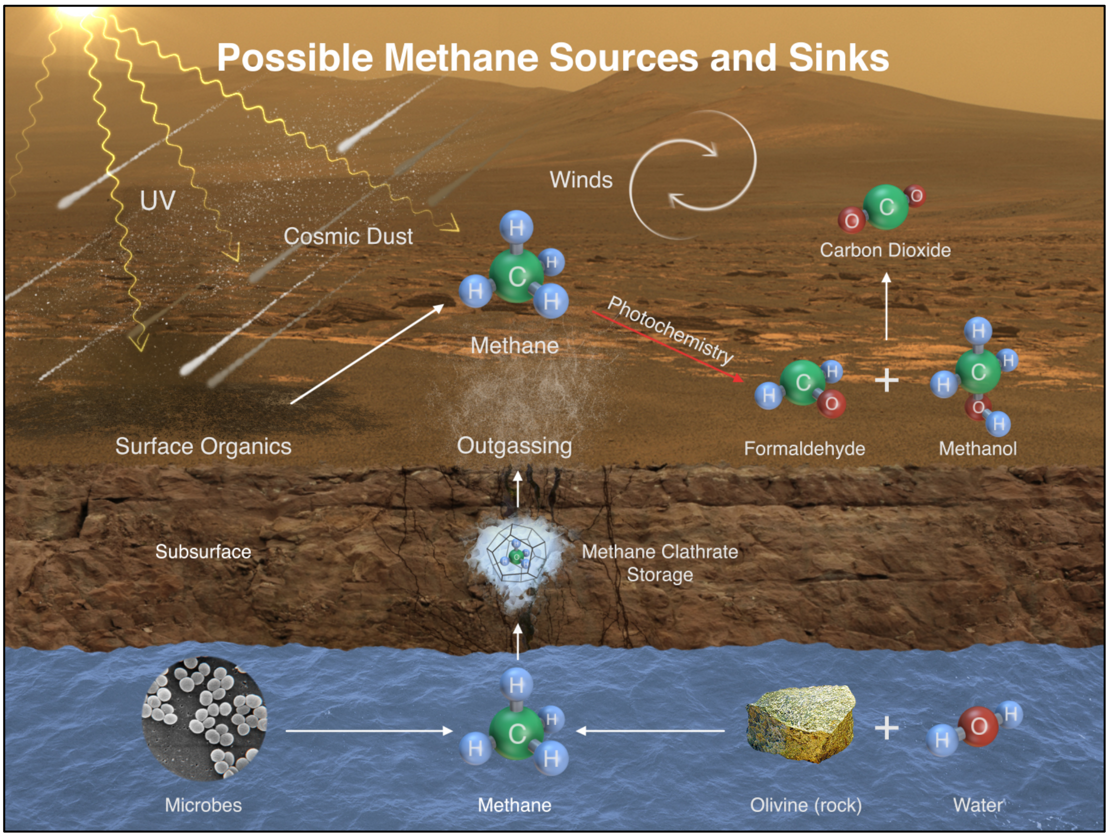

Figure 4. Possible methane sources and sinks on Mars. Image credit: NASA/JPL-CALTECH

The Mars methane gas produced by these sources could be trapped in subsurface clathrates. Clathrate hydrates are crystalline compounds comprised of cages formed by hydrogen-bonded water molecules inside of which guest gas molecules are trapped. An increase in temperature or a decrease in pressure can lead to the dissociation of clathrates, which results in the release of the trapped gas. Under colder conditions of an earlier climate period (e.g., resulting from obliquity cycles), a cryosphere could trap methane as clathrates in stable form at depth. Under current climate conditions those same clathrates could become unstable and result in a sporadic release. Previous studies (Chastain et al. 2007) indicate that the present-day conditions in the martian subsurface are favorable for the presence of clathrates.

Since methane fluxes need to be imposed in the MRAMS simulations, it is beneficial to utilize an emission rate that is representative of at least one plausible martian source mechanism. Methane clathrates are selected for this purpose. The assumption of a clathrate source for the MRAMS simulations is purely a convenience since reasonable estimates for a surface methane flux can be obtained. Recalling that the MRAMS tracer abundance scales linearly with the flux, the solution for any desired flux magnitude can be obtained from the MRAMS results, regardless of the actual flux mechanism.

Our colleagues Özgür Karatekin and Elodie Gloesener produced maps of methane-rich clathrate stability zones (Figure 5) obtained by coupling the stability conditions of methane clathrate with a subsurface model (Karatekin et al. 2016; Karatekin et al. 2017; Gloesener et al. 2017, hereafter KG17). Ancient clathrates may exist at depth where the geothermal gradient causes them to decompose over time (Stevens et al., 2015). The regolith properties directly control the subsurface thermal conditions and therefore the depth of clathrate stability: the lower the thermal inertia in the surface, the less stable the clathrates will be (the thermal wave penetrates more deeply). This map, based on the mean annual temperature and TES-derived thermal inertia among other variables, does not reveal local scale variations, so if Gale crater was formed after the emplacement of the clathrates, it is possible that there could be methane locally closer to the surface than would be inferred from this map.

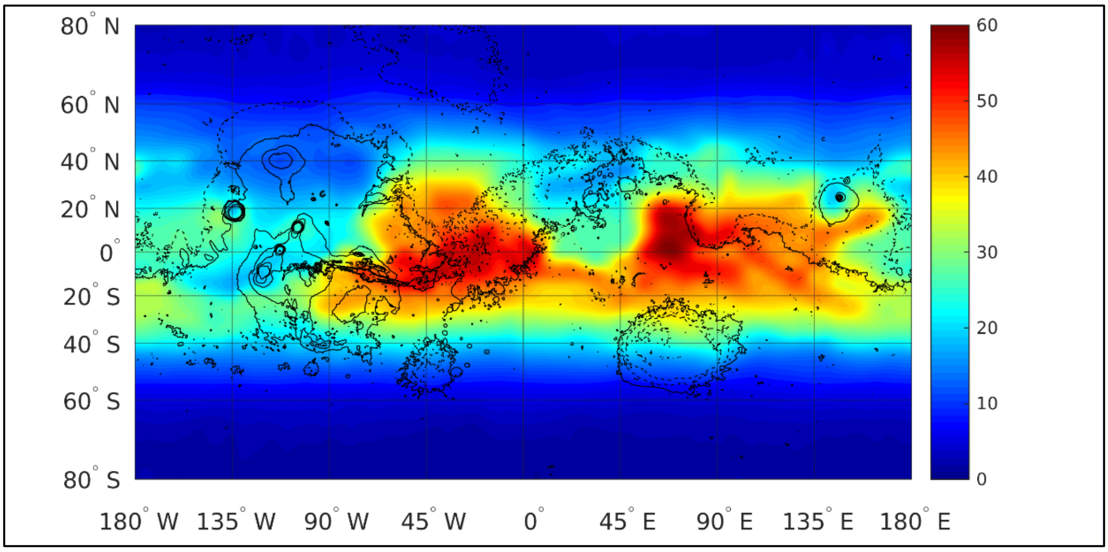

Figura 5. Depth (m) of the beginning of hydrate stability zone in present-day martian subsurface for clathrates formed from a gas phase with 90% fraction of methane. Adapted from Gloesener et al. 2017 and Karatekin et al. 2017

Methane clathrates can be stable very near the surface at high latitudes, and can be as close as 20 m to the surface in the tropics under today's climate. In the cases where a surface flux of methane is specified in the MRAMS simulations, the flux is assumed to come from subsurface methane clathrate emplaced in earlier geological times and which has been destabilized due to changes in the regolith energy balance. KG17 calculated the surface methane flux by modeling methane gas transport through the regolith to the surface via molecular and Knudsen diffusion. Gas adsorption processes are ignored in these calculations of the methane flux used in the MRAMS experiments. Including adsorption reduces the methane flux by roughly ~30 times, although it increase the emission time in the same amount amplifying seasonal variations of background methane through Arrhenius dependency. The dissociation of 1 m^3 of clathrates formed from a gas phase containing 90% of methane at a depth of 45 m in Gale crater (assuming a mean thermal inertia of ~365 for the first meters and increasing with depth), produces ~$2x10^{-6}$ kg m^{-2} s^{-1} methane flux at Ls 285º (Figure 6) during the first sols. It is important to note that, although the methane flux should be higher during warmer seasons due to the dependence in temperature of the diffusion coefficient (and the kinetic constant if you take into account adsorption), the same value is used for all the seasons modeled in MRAMS (Ls 90º, Ls 155º and Ls 270º), so methane flux in our simulations is overestimated for Ls 90º and Ls 155º. New experiments are being performed with updated methane flux values.

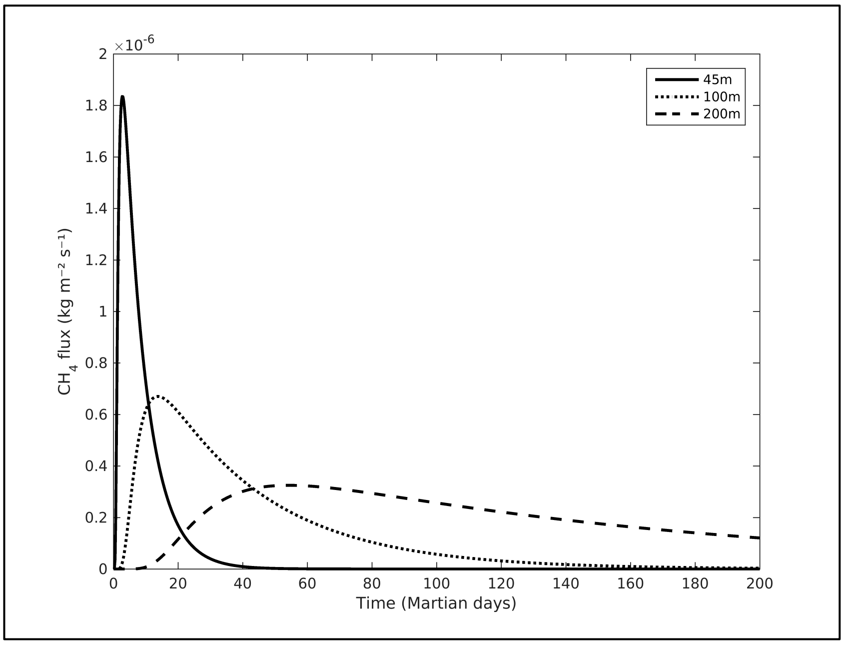

Figure 6. Methane flux for clathrates formed from a gas phase with 90% of methane derived from Gloesener et al. 2017 subsurface diffusive model that includes molecular and Knudsen diffusion.

2.3 MRAMS methane experiment scenarios

Different MRAMS tracer scenarios were constructed with simulations at different seasons (Ls 90º, 155º and 270º) as shown in table 3.

The punctual methane release scenarios are designed to quantify the rate of mixing within the crater and between the crater and air outside the crater.

The steady state methane release scenarios explore the transport of methane under specific flux scenarios and, location and areal extent of the emission. The selection of these seasons is based on our previous work (PGR16). Ls 270º is anomalous in that it is a very windy season with large amplitude breaking mountain waves, and rapid mixing with air external to the crater was inferred. The regional northwest winds from northern lowlands scour the very bottom of the crater floor. Crater circulation is pushed and extended dramatically to the south. This is not just air flowing through topographic passes like Peace Valles, rather it is a wholesale inundation of the crater from the air to the northwest. Based in our previous PGR16 work, Ls 270º is presumed the fastest exchange period between air inside and outside crater during Mars year and during the other seasons the mixing were presumed slower. In the rest of the year other than Ls 270º, mixing between the crater air mass and the external crater air was interpreted to be more subdued. Ls 90º was selected for our methane mixing experiments because it is representative of most rest of the year. Simulations at Ls 155º were also conducted, because it is the season of the M09 2003 Earth-based detections.

CH_4 release	Punctual emission	Steady state emission
Inside crater small size area emission (~149 km^2) close to MSL location	Ls90 & Ls270	Ls90 & Ls270
NW Outside crater medium size area emission (~6,400 km^2)	Ls90 & Ls270	Ls90 & Ls270
NE&SW&SE Outside crater medium size area emission (~6,400 km^2)		
M09 large size area (~8,000,000 km^2)		Ls90, Ls155 & Ls270
M09 large size area (~2,000,000 km^2)		Ls270

Table 3. MRAMS methane punctual and steady state release scenarios for inside and outside Gale crater release locations at Ls 90º , Ls 155º and Ls 270º .

2.3.1 Punctual methane release scenarios

The goal of punctual in time methane release experiments is to study how the different air masses containing each of the tracers mix with one another. The amount of mixing can be diagnosed by looking at the fraction of each tracer compared to all the tracers.

Fraction of a tracer X is $\frac{tracer\ X}{\sum all\ tracers}$. For example, at the start, 100% of the tracers in the bottom (<200 m high) of the crater are tracer #1 mimicking methane, because there has yet to be any mixing. If at some later time it is found that 50% of the tracers in the bottom of the crater are tracer #1, then half of that original air mass has been mixed away. By looking at the fraction of other tracers, the amount of mixing with each of the different air masses can be determined.

In these experiments, four tracers were strategically placed into the model after spin-up (1 sol) to diagnose the mixing of air inside and outside the crater both for Ls 90º and Ls 270º seasons. There were no additional sources (no flux) or sinks of tracers (photochemical lifetime destruction is orders of magnitude higher than our twelve sols simulation). Tracer #1 represents a hypothetical methane-enriched air mass near the surface (<200 m high). The other three tracers are placed in different layers above tracer #1 (Figure 7) in order to track those air masses. Tracer #2 is placed from 200 to 500 m above ground level (hereafter AGL) inside Gale crater, tracer #3 from 500 to 2,000 m AGL inside Gale crater, and tracer #4 elsewhere (outside and above Gale crater).

In the punctual methane release inside of Gale crater experiment (Figure 7, left side), tracer #1 have an area of ~149 km^2 and is located one grid point (less than 3 km) west from the MSL Curiosity rover in the north crater basin.

In the punctual methane release outside of Gale crater experiment (Figure 7, right side), tracer #1 have an area of ~6,400 km^2 and is located ~100 km northwest upstream of the landing site outside the crater.

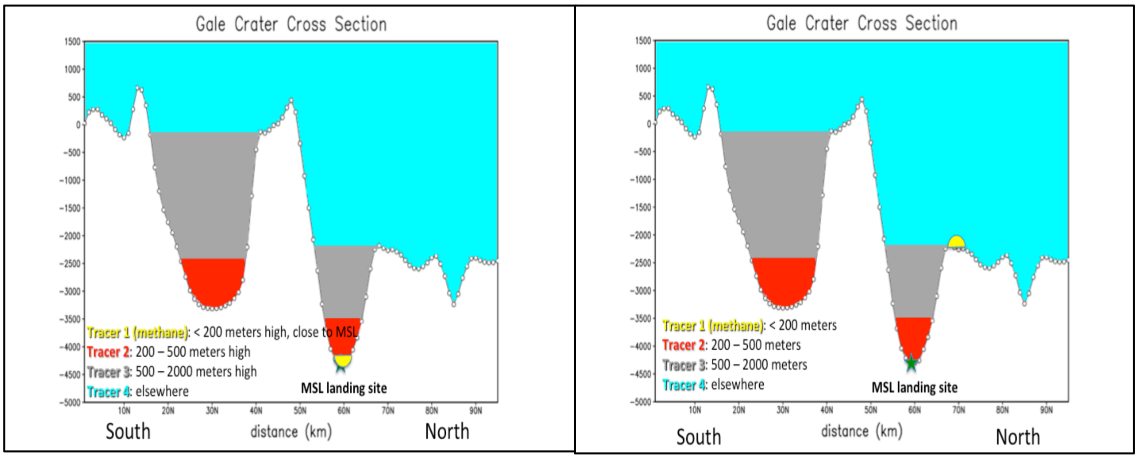

Figure 7. Punctual methane release scenarios cross sections (Mt. Sharp in the middle, north basin in the right and south basin in the left in both boxes). Tracer #1 (yellow) is placed one grid point (less than 3 km) west from the MSL Curiosity rover location inside Gale crater (left box) and ~100 km northwest upstream of the MSL landing site (right box). In both cases, Tracer #1 is placed <200 m AGL, Tracer #2 (red) is placed from 200 to 500 m AGL inside Gale crater, tracer #3 (grey) from 500 to 2,000 m AGL inside Gale crater, and tracer #4 (blue) elsewhere (outside and above Gale crater).

2.3.2 Steady state methane release scenarios

In these scenarios, the methane release is steady state in time (continuous surface emission) with a prescribed flux of ~2x10^{-6} kg m^{-2} s^{-1} during a period of twelve sols. Five independent methane steady state release sources, four of them located ~100 km NW, NE, SW and SE upstream of the MSL Curiosity rover landing site outside the Gale crater with an area of ~6,400 km^2 each and another one located inside of the crater ~1 grid point west from the rover with an area of ~149 km^2, as shown in Figure 8. Since the tracers do not interact with each other, multiple tracer configurations can be studied simultaneously in a single simulation.

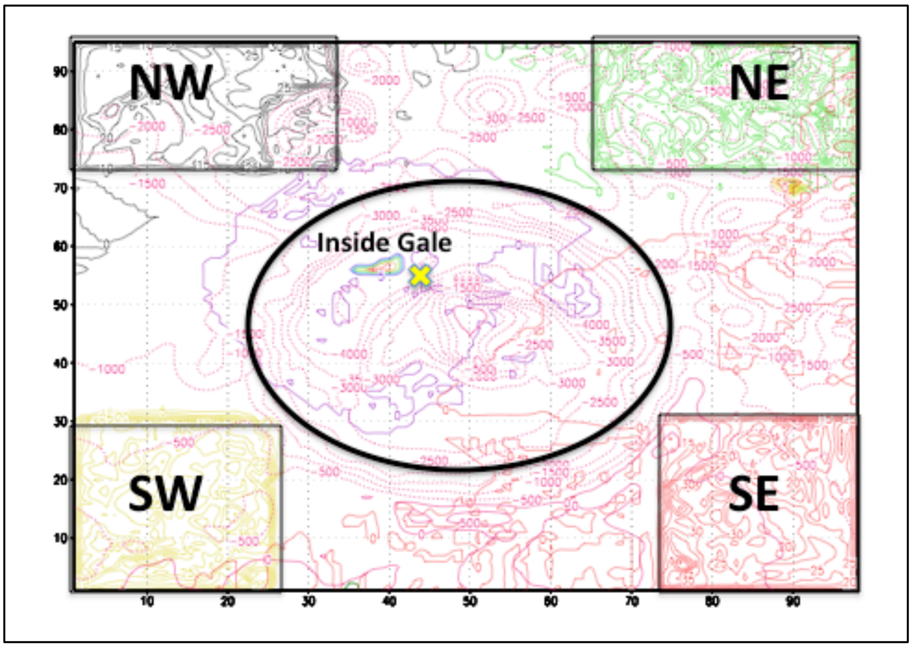

Figure 8. Steady state methane release scenarios aerial view. Gale crater encircled. The yellow cross represent the MSL Curiosity rover location. Four independent methane release sources were located outside the crater ~100 km NW, NE, SW and SE upstream of the rover landing site with an area of ~6,400 km2 each and another one was located inside of the crater ~1 grid point west from the rover with an area of ~149 km2

Two additional experiments were performed mimicking M09 release areas, including the "full" M09 release area (~8,000,000 km^2) source at Terra Sabae (A in Figure 1), Nili Fossae (B_1 in Figure 1) and Syrtis Major (B_2 in Figure 1) and a "partial" M09 release source only at Nili Fossae area (~2,000,000 km^2).

3 Results

To gain a true appreciation for the complexity, beauty and evolution of methane emissions at various locations, the reader should proceed no further without first viewing the animations of the circulations provided in the supplementary material.

Again and as discussed in the MRAMS model description section, the lowest thermodynamic level where methane could be sampled in our simulations is ~14.5 m above the ground due to computational restrictions, so higher methane values at SAM high (~1 m) compared to the methane values sampled with MRAMS are expected.

It is important to note that the rise of methane concentration first noted by the SAM instrument (Ls 336º) was at a transitional time at Gale Crater, when strong flushing northern winds that produce a wholesale inundation of the crater give way to less intense circulations typical of the rest of the year (PGR16). Based on the analysis of winds and potential temperature, PGR16 suggested that mixing between the crater air mass and the rest of the atmosphere was also reduced during the more quiescent times of year. The tracer studies provide a means to quantitatively test this hypothesis.

3.1 Punctual methane release results

In the punctual methane release scenarios, Ls 270º was shown to be, as expected, a faster mixing season when air within and outside the crater was well mixed by strong, flushing, northerly flow and large amplitude breaking mountain waves: downslope air driven both by buoyancy and dynamical forcing at night penetrates all the way down to the surface producing a wholesale inundation of the crater. In this punctual methane release inside of Gale crater scenario, the tracer #1 mixing ratio inside the crater is diluted to a few percent or less just 5 hours after the release both at Ls 90º and at Ls 270º (Figures 9 and 10). Also, if we take a look at log fraction (Figure 11) we can see how after 15 hours from the release (at 2000 Local Mean Solar Time, hereafter LMST), tracer #1 is diluted by five orders of magnitude from the initial concentration at Ls 90º and by eleven orders of magnitude at Ls 270º. Not only is tracer #1 removed quickly, but in that 15 hours period the fraction of external crater air (tracer #4) at the bottom of the crater replacing internal crater air is 80% at Ls 90º (when mixing is slightly more slower) and 100% at Ls 270º (when mixing is slightly more rapid). These results indicate that much of the air originates from outside the crater regardless of the season. Thus, the mixing of the crater air with the external environment is slightly slower during the rest of the year compared to Ls 270º season, but the timescale it is still rapid. Regardless of the season, the simulations indicate that the air mass of the northern crater is evacuated and mixed away in one sol or less. These new results are an important update to the 2016 work; the crater does not appear to be strongly isolated at any time of year. Also, Ls 270º scenario reminds to a front passing where horizontal incoming air mass from north hemisphere sweep the crater away (Figure 10 bottom, Figure 11 bottom), while in the Ls 90º a much more vertical pattern is observed (Figure 9 bottom, Figure 11 up).

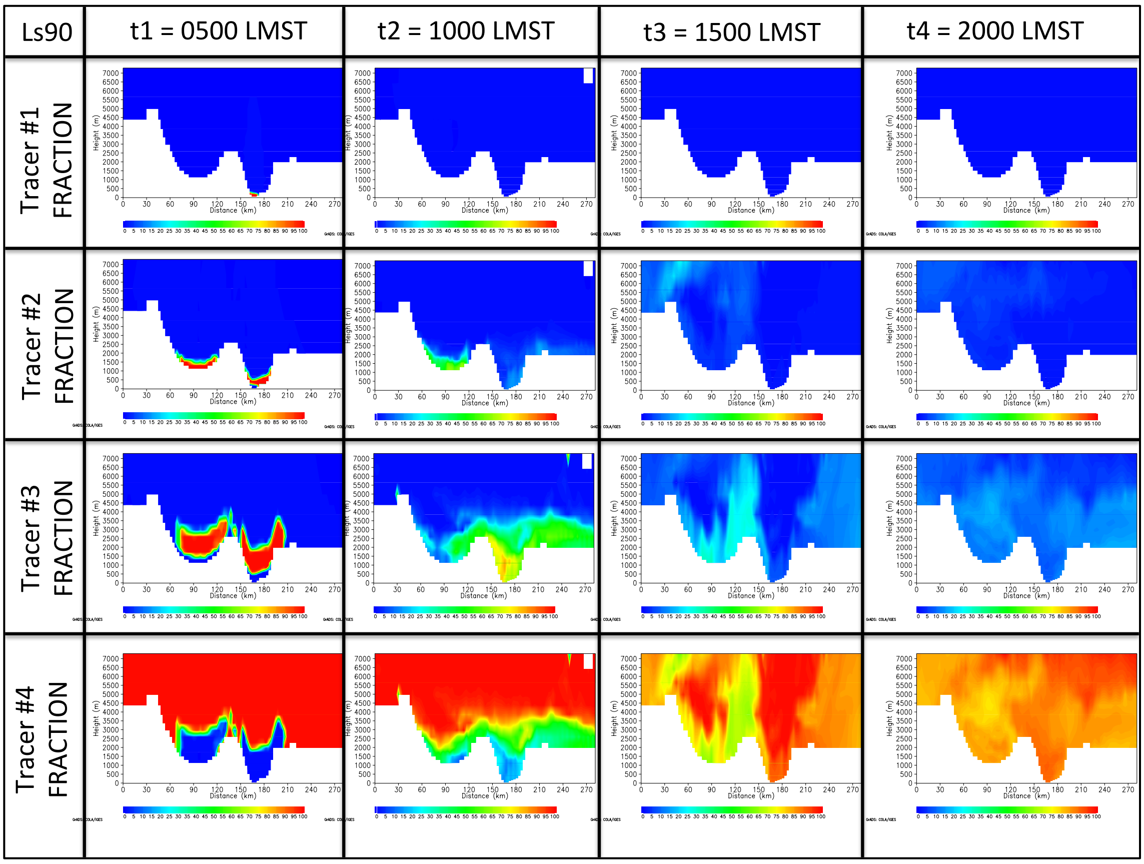

Figure 9. Fraction of the four tracers at four different times (0500, 1000, 1500 and 2000 LMST) at Ls 90º in a cross section view of the crater. E.g. $\textit{Fraction of tracer \#1} = \frac{tracer\ \#1}{\sum tracer1+tracer2+tracer3+tracer4}$

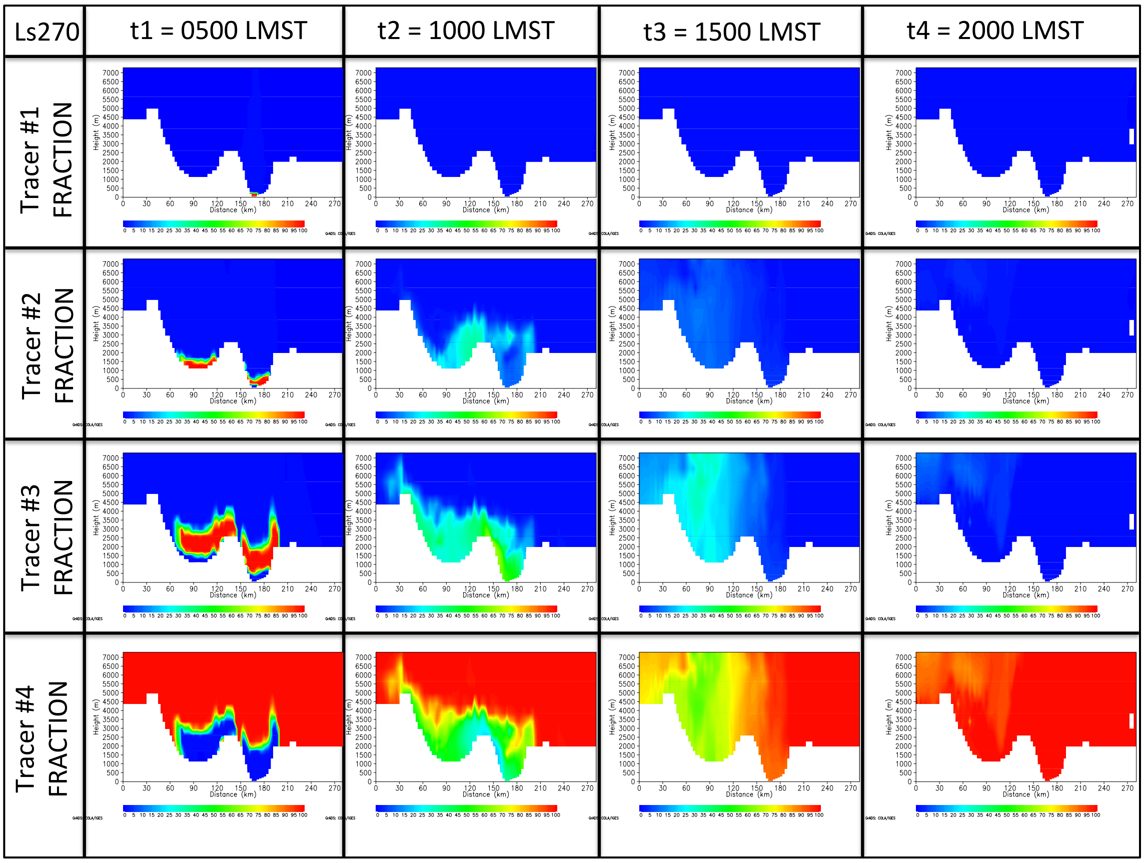

Figure 10. Same as Figure 9 but for Ls 270°

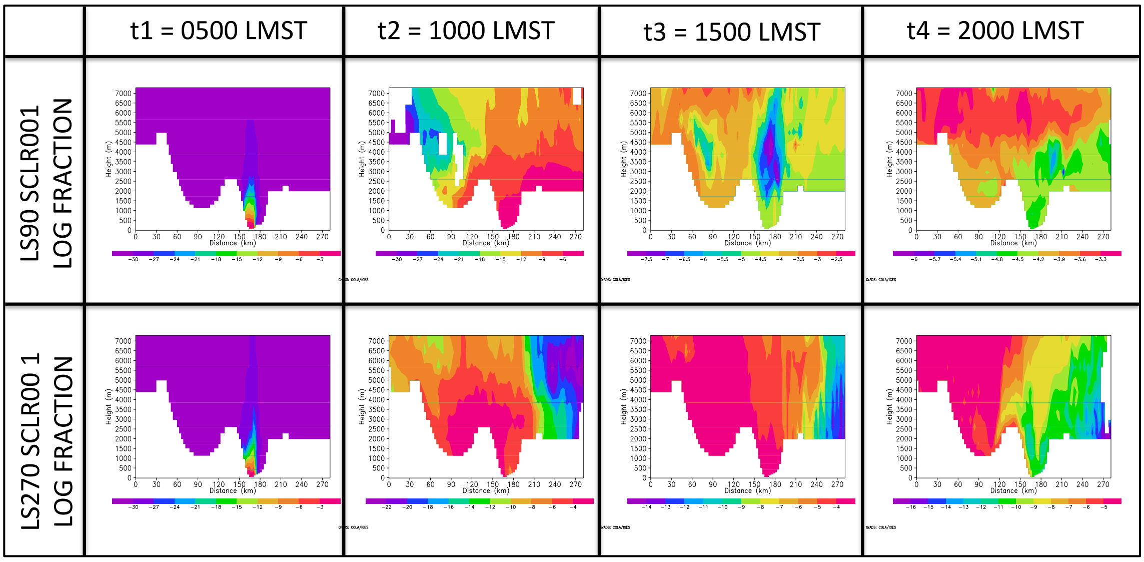

Figure 11. Same as Figure 9 and 10 but for log fraction at Ls 90° and Ls 270°

The punctual methane release scenario outside of Gale crater provides additional insight into the potential transport of air into the crater. In this scenario, only 12 hours after release, the methane that makes it to the MSL Curiosity rover location at ~14.5 m high (the lowest thermodynamic level where methane could be sampled in our simulations) is diluted by six orders of magnitude from the initial release concentration regardless of the season (Figure 12). Although the methane is transported towards the crater due to the northwesterly wind blowing towards the crater (as expected in PGR16), the methane is rapidly mixed vertically and horizontally. So, although the air in the crater is being rapidly replaced by outside air, there is a large amount of mixing and dispersion of the source air itself; it appears that a broad region of external air is mixed into the crater. To achieve a value of 1 ppbv at the rover location, an upwind release of methane on the order of parts per thousand would be required, which is likely unreasonable.

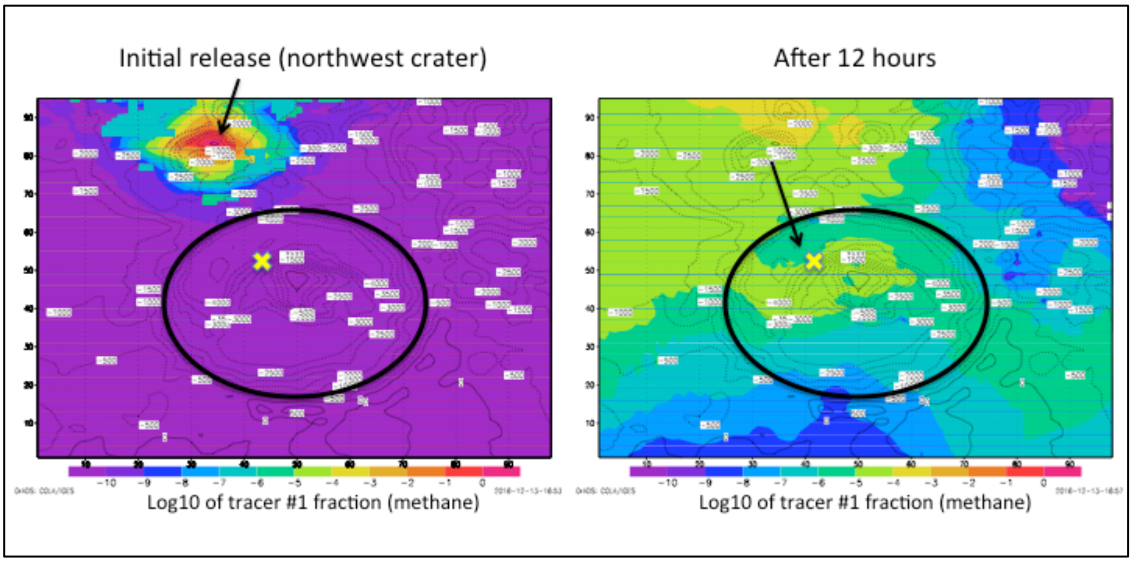

Figure 12. Aerial view of tracer #1 (methane) fraction at ~14.5 m high with crater encircled at Ls 90°. Punctual methane released outside crater is diluted by approx. 6 orders of magnitude from the initial release concentration at rover location only 12 hours after emission regardless of the season. Same behavior is observed at Ls 270°..

3.2 Steady State methane release results

In steady state methane release outside of Gale crater scenarios (NW, NE, SW and SE ~100 km outside crater), modeled abundances at the MSL Curiosity rover location are ~10 times lower (<0.08 ppbv) compared to SAM background levels (<0.7 ppbv) and ~100 times lower compared to the spikes (<8 ppbv) during all seasons both at Ls 90º and at Ls 270º and after being release from all locations outside of Gale crater (NW, NE, SW and SE) as can be shown in Figure 13. Each of the different releases are emitted and sampled independently. When releasing from a source NW outside crater at Ls 270º, methane variations of one order of magnitude are sampled regardless of the time of the sol due to the strong flushing north component winds during all day (Figure 13, upper left, red). In the other release locations experiments, the methane values are higher during nighttime, presumably because during night downslope winds from rims transport methane from release locations converging with Mt. Sharp downslope winds making methane contained at the very bottom of the crater, persisting and becoming trapped for longer inside Gale until daytime upslope winds sweep it away (Figure 13, except NW scenario).

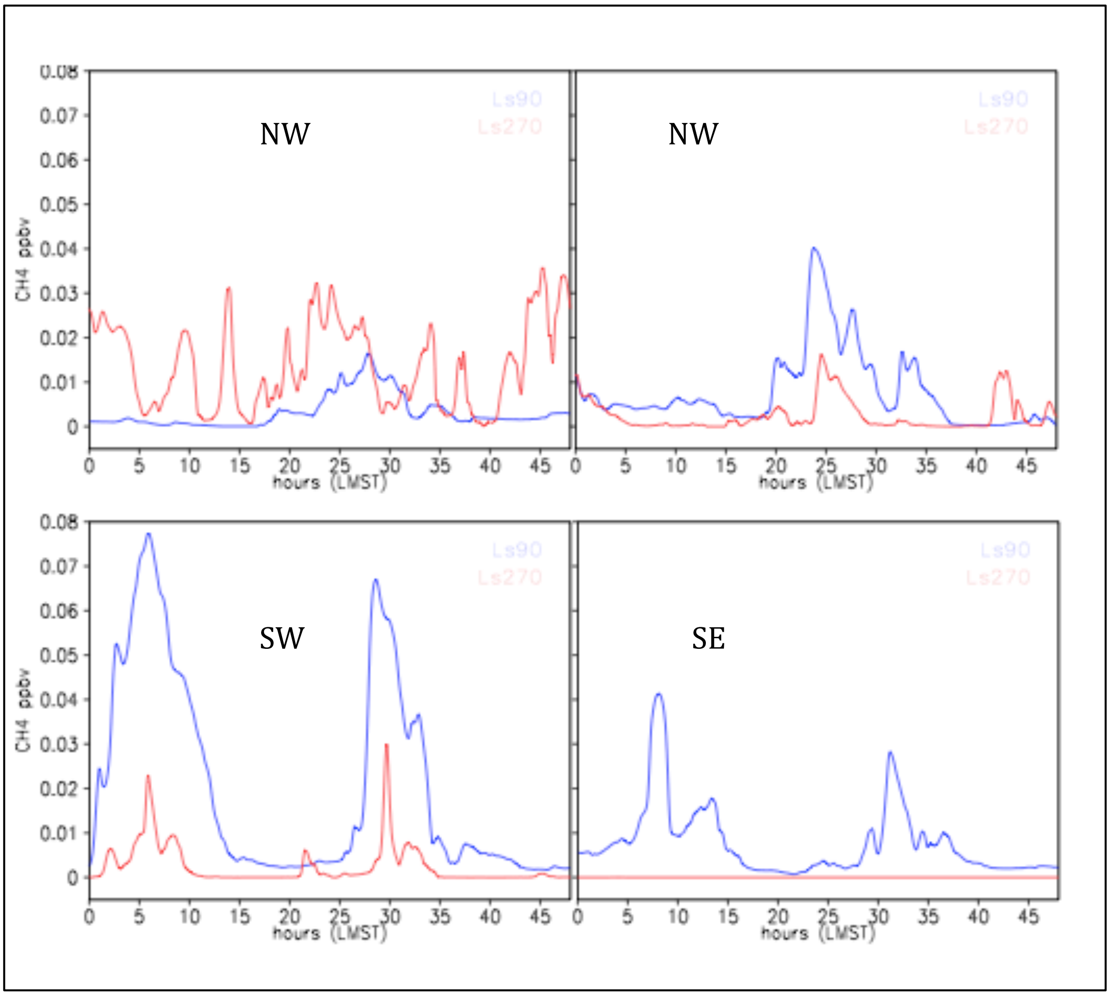

Figure 13. Two sols timeseries of MRAMS methane abundances sampled at MSL location while being released from steady state methane emission located outside of Gale crater (NW, NE, SW, SE). Each of the different releases are emitted and sampled independently.

In steady state methane release inside of Gale crater scenario (~1 grid point west from the rover with an area of ~149 km^2) when sampling the model at the source location, methane values fluctuate from 0.1 to 1.2 ppbv (Figure 14). This is compatible with SAM low background methane abundances and only ~6 times lower than the methane spikes. It is important to emphasize that these methane values are sampled at ~14.5 m high so a higher methane abundance is expected at ~1 m above release source (using a five-parameter logistic -5PL- linear regression curve fitting method those peak values at 1 m high are ~11 ppbv, and using a non-linear power regression curve fitting method those peak values are ~4 ppbv).

Thus, if the rover were directly over a release location, the SAM measurements could be consistent with a reasonable release associated with a flux similar to methane clathrate release.

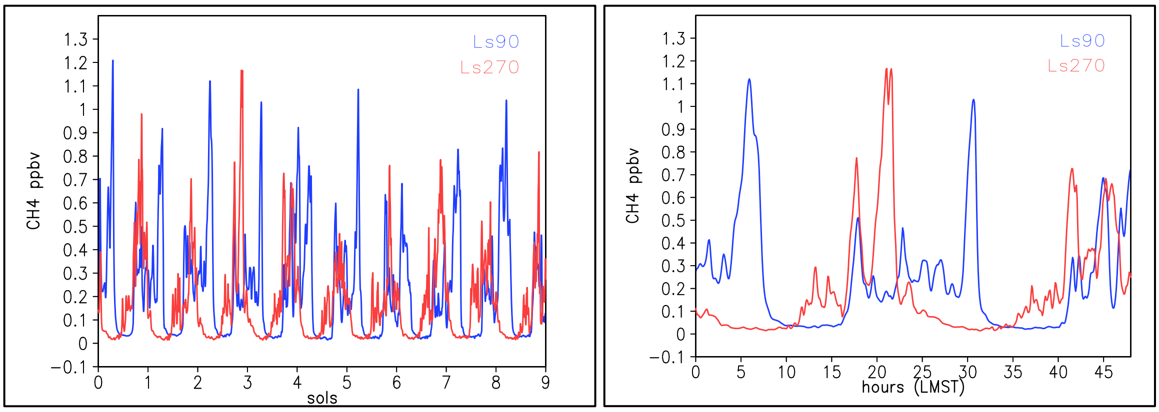

Figure 14. Nine sols timeseries (left) and two sols timeseries (right) of MRAMS methane abundances sampled at release location while being released from steady state methane emission located inside of Gale crater ~1 grid point west from the rover with an area of ~149 km2. Only nine of the twelve sols simulated were included into the figure).

Ls 155º is the highest methane values season in M09 (<45 ppbv) and also in MRAMS steady state methane release mimicking M09 scenarios when sampling at the rover location eleven sols after release at Ls 155º (~16 ppbv) compared to Ls 90º (~0.25 ppbv) and Ls 270º (~0.8 ppbv) (Figure 15). This big difference could be due to Ls 155º is approaching to the spring equinoctial neutral global winds period (PGR16). Around the equinoxes, there is a brief transition period where the rising branch quickly crosses from one hemisphere into the other as it migrates to its more typical solstitial location. During this transition, there is convergence into the rising branch (similar to the intertropical convergence zone on Earth), and dual Hadley cells with one circulation in each hemisphere. Based on the mean meridional circulation, surface winds at the tropical location of Gale crater would be expected to go either way as the rising branch transits through the equatorial region containing and circulating methane rich air from M09 release areas in the intertropical zone. At solstices, those winds reverse with northerly winds around Ls 270º and southerly winds around Ls 90º (PGR16) that could sweep methane rich air from M09 release areas away from equator.

As shown, even an area as large as the putative M09 release is insufficient to produce the amplitude of the sporadic higher spikes of methane measurable at MSL Curiosity rover during the SAM high spikes periods (~Ls 55-82º). At Ls 270º in these mimicking M09 scenarios, the methane values sampled at the rover location fluctuate from 0.1 to 0.8 ppbv. These values are compatible with SAM low background methane abundances and being only ~12 times lower than SAM direct ingest detections (high spikes).

When comparing the mimicking M09 full area (~8,000,000 km^2) release scenario (Figure 15, bottom left) with the partial mimicking M09 area (~2,000,000 km^2) release scenario (Figure 15, bottom right) both at Ls 270º, results show 30 times higher methane values with the larger release area, so the release size has also a large impact on the methane abundance sampled at the MSL Curiosity rover location.

The modeling results of steady state methane release mimicking M09 scenario at Ls 155º are in agreement with previous GCM modeling studies of methane plumes at the same season (Mischna et al. 2010; Karatekin et al. 2017; Viscardy et al. 2016) where the horizontal distribution of the methane cloud moves mainly in a east direction five sols after the surface release (Figure 16).

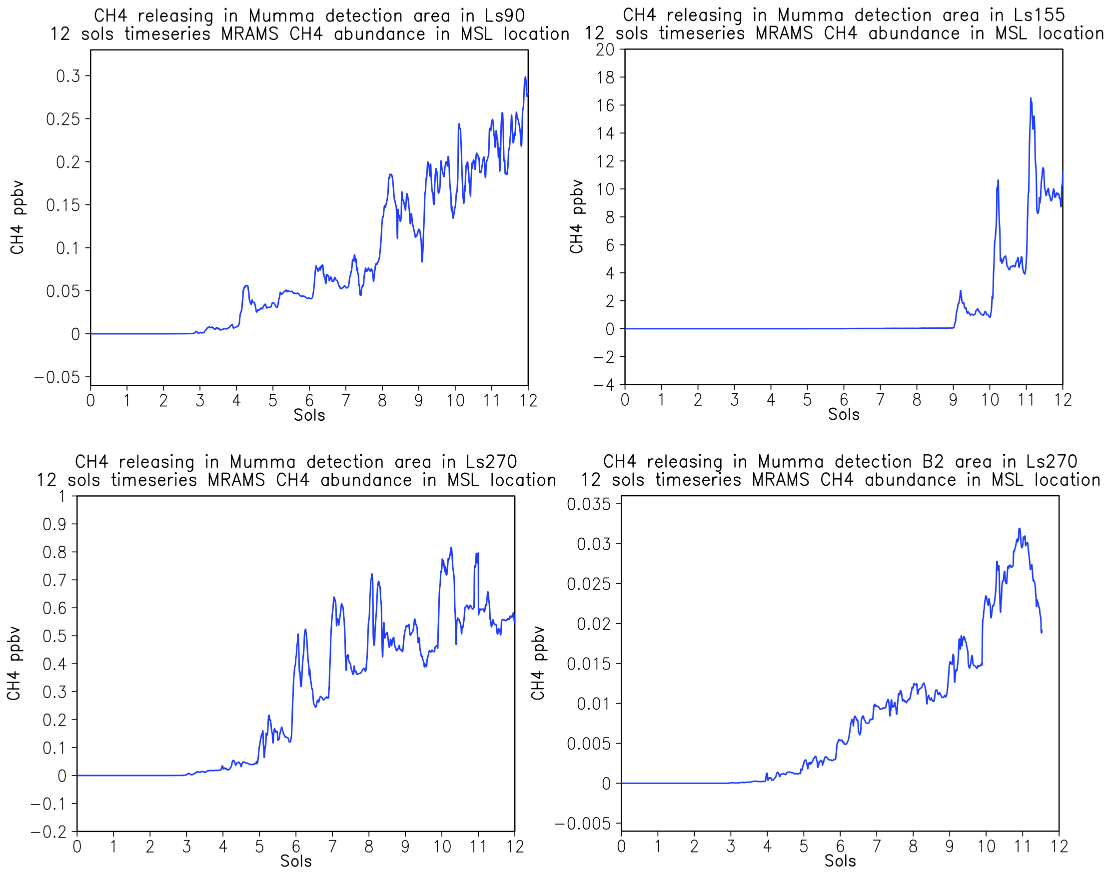

Figure 15. Twelve sols timeseries of MRAMS methane abundances sampled at release location while being released from steady state methane emission located inside of Gale crater ~1 grid point west from the rover with an area of ~149 km2

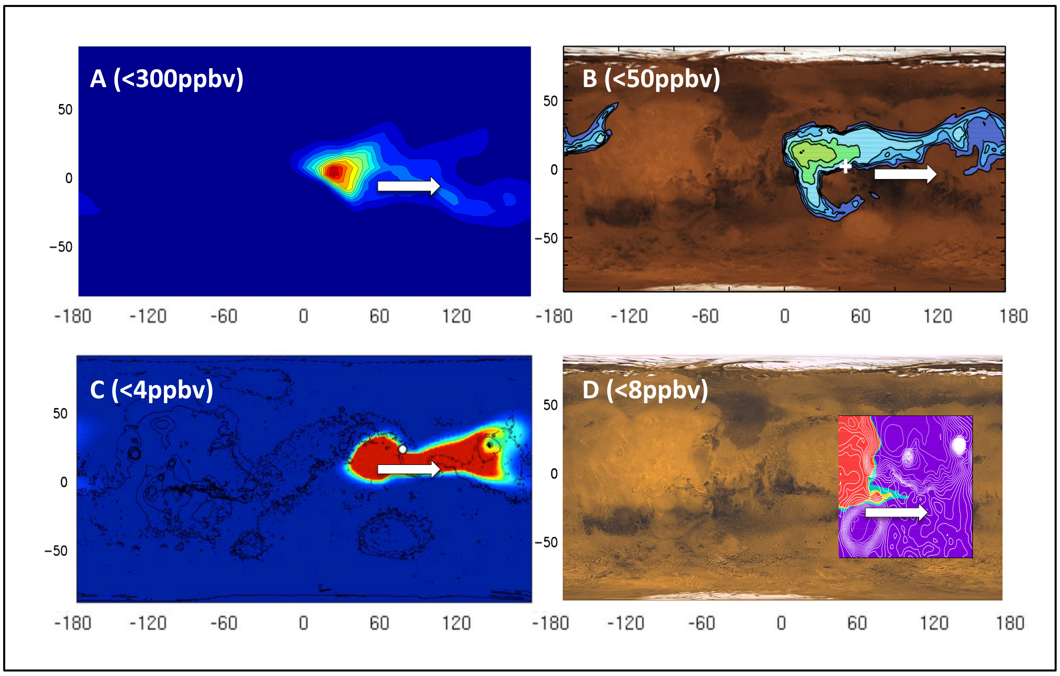

Figure 16. Horizontal distribution of methane mixing ratio (in ppbv) 5 sols after surface release of methane in M09 release area at Ls = 155°. Karatekin et al. 2017 (A; GCM), Mischna et al. 2011 (B; GCM), Viscardy et al. 2016 (C: GCM), Pla-García et al. 2018 (D, this paper results with mesoscale model) shows the same easterly pattern of the methane plume five sols after the release.

Also our simulations show that surface emissions of methane results in a non-uniform vertical distribution (~5-20 kms), including the formation of elevated layers five sols after the release (supplementary material), that is in agreement with Viscardy et al. 2016.

4 Discussion

The Mars Regional Atmospheric Modeling System (MRAMS), used to study the transport and mixing of methane from specified source locations using tracers, help us to investigate whether methane releases, punctual or steady state, inside or outside of Gale crater, during summer time or the rest of the year, are consistent with SAM observations.

The punctual release scenarios indicate that the timescales of mixing in the crater is ~1 sol during all seasons, which is much faster than previously estimated. For there to be an extended period (> 1 sol) of enhanced methane abundance in the crater, there must be a either a nearby steady release to counteract atmospheric mixing or there must be an extensive and highly enriched methane air mass; however, this would contradict the Mischna et al. 2011 modeling study indicating a single rather than extended period of release. Further, an extended, large release would result in average global values in excess of the background SAM value after mixing, unless the unknown rapid destruction mechanism is invoked, like the ones described in the introduction section (dust electrochemistry and wind eroding surface quartz grains).

For the elevated methane levels in the crater to drop rapidly back to background levels, at least two things would need to happen. First, the external crater environment would have to drop at least as rapidly to the background levels. This seems possible only if there is very deep mixing that spreads the release through a very large volume of atmosphere, or if a rapid destruction mechanism is invoked. The second thing that would have to happen is that the crater air would have to mix nearly completely with the external crater air. Although mixing seems slightly slower the rest of the year other than Ls 270º, it may still be possible that the mixing time scale is sufficient to affect the necessary change as shown in our punctual methane release scenarios (Figures 9 and 11).

The timing of SAM sample ingestion is very important looking at the steady state methane release inside Gale crater scenario results because they show diurnal methane variations of one order of magnitude, increasing during the evening and night, and decreasing during the daytime (Figure 13 –except NW at 270º- and Figure 14). Again, most of the SAM-TLS measurements were acquired during nighttime (except on sols 305 and 525) due to thermal requirements of the SAM sample handling system, but we do not have the exactly acquisition times so we can not study the influence of the local ingestion time into the measurements. During daytime, upslope winds through the crater rims and Mt. Sharp could sweep the air out of the crater dragging methane with them (Figure 17 upper left, 1300 LMST), and during nighttime the process reverse with downslope winds from rims and Mt. Sharp that converge and contain methane at the very bottom of the crater, persisting and becoming trapped for longer close to the point where it is released (Figure 17, 1900 LMST, 0100 LMST and moreover 0700 LMST). This behavior emphasize the importance of the horizontal mixing. Horizontal and not only vertical mixing should be taken into account when studying atmospheric methane circulation. Also and as previously mentioned, gases released in the crater could become trapped in the lowest portion of the crater basin due to the very cold and dense air mass that would be resistant to mixing with air above helping to the converging downslope winds to contain methane close to the release area.

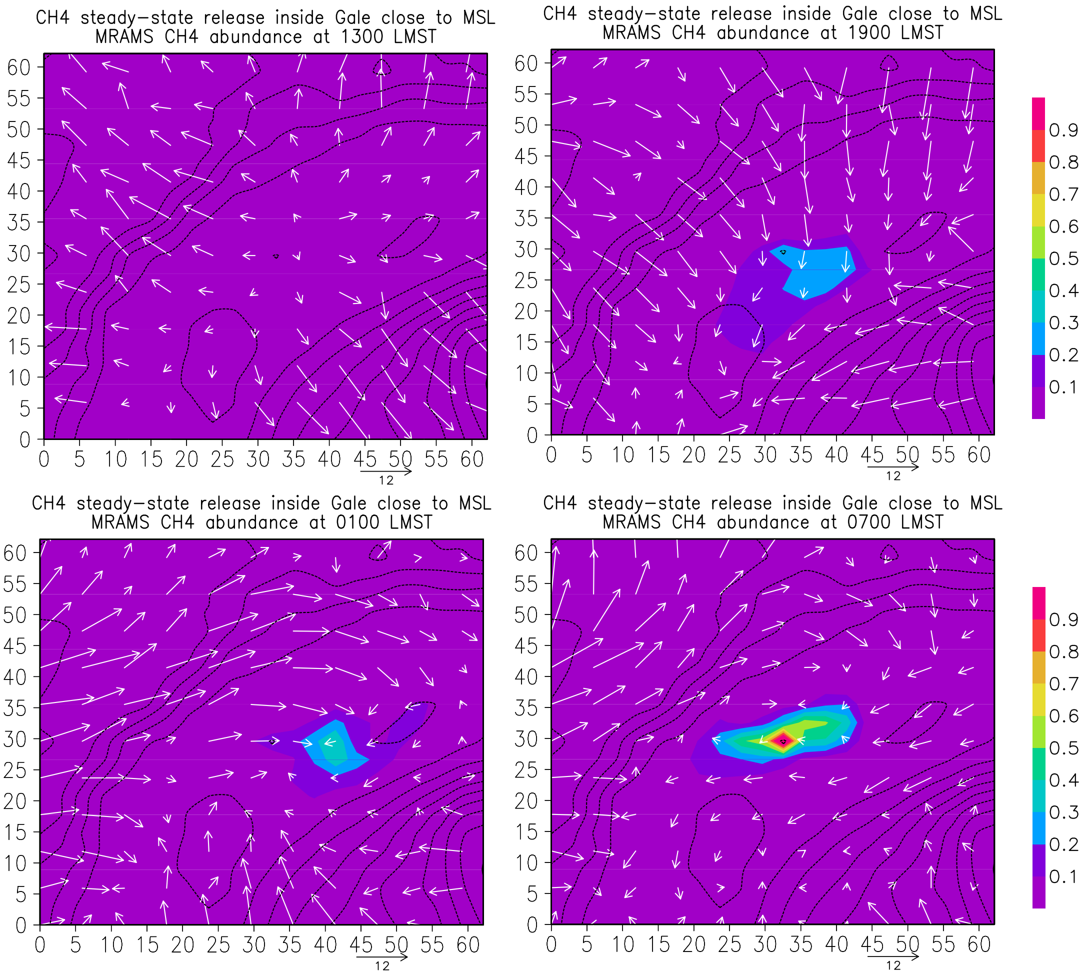

Figure 17. Areal view of methane mixing ratio for a steady state methane release close ~1 grid point west from the rover location. During nighttime the downslope winds from rims and Mt. Sharp converge and contain methane at the very bottom of the crater, persisting and becoming trapped for longer close to the point where it is released

Based on global circulation modeling, methane could also be subject during daytime to turbulent convective vertical mixing in the planetary boundary layer (hereafter PBL) and mixed upward rapidly to the top of this atmospheric layer (Viscardy et al. 2016). When the PBL decreased (and therefore also turbulent convective vertical mixing) in the late afternoon, followed by the development of nocturnal inversion after sunset, it could help to the mentioned converging downslope winds (both from rims and Mt. Sharp) to contain the methane close to release location.

As discussed in PGR16 and further confirmed with this article results, the circulation in and around Gale Crater is extremely complex and varies seasonally. The circulation is strongly 3-D, not just 1-D or 2-D, and any scenario describing the transport of methane must recognize this dimensionality. The source location of methane emission cannot be determined by simply looking upstream and variations of methane concentration cannot be determined by simply considering 1-D vertical mixing based on PBL height. Further, because of the complexity of the circulation, the local wind at the rover location may not be representative of the larger prevailing wind. Consequently, trying to determine the source location of methane based on REMS wind estimates at the time of the SAM measurements or trying to explain a putative suppressed mixing with a PBL suppression is a dubious proposition.

The only plausible scenario to reconcile observations and the modeling results is an intermittent local steady state release very close to the rover with the additional restriction that such releases must be globally rare (in other words claiming that Gale crater is a unique place on Mars, on the other hand something highly unlikely) or there must be a unknown rapid methane destruction mechanism that prevent from a rapid increase of the background methane level that would be detected by SAM.

Although being so lucky to have the rover moving just above a methane release location and having methane spikes lasting just a sol or some sols are extraordinary claims, we can explain them and are compatible with our modeling results. But, if the spike lasted for a long time, similar to the period without SAM measurements between spikes (that is ~200 sols), it becomes much difficult to interpret. While Gale crater may be a special place, it almost certainly is not unique. If methane is being released locally in the crater, it should also be released elsewhere on Mars. Thus, a release of long duration at Gale crater would also happen elsewhere, and this would have result in a background global methane abundance above that measured by SAM, again assuming no rapid and efficient destruction mechanisms.

4.1 A possible explanation to the methane background seasonal cycle

The MSL-SAM team recently presented in situ measurements of the background methane levels in Gale Crater that exhibits a strong, repeatable seasonal variability ranging from about 0.3 ppbv to about 0.7 ppbv with a mean value of ~0.4 ppbv over more than two martian years (Webster et al. 2017). The observed large seasonal variation in the background and sporadic observations of higher pulses of ~7 ppbv appear consistent with localized small sources of methane releases from Martian surface reservoirs that may be occurring throughout the planet.

The origin of methane variability is an active area of research, and our colleagues on the MSL team (John E. Moores and co-authors) are working to better model adsorption on and diffusion through the regolith, as well as the impact of the depth of the boundary layer on vertical mixing. Because PBL is especially suppressed at Gale crater (Newman et al. 2017; PGR16; Moores et al. 2015), then vertical mixing is very limited too. It has been proposed that this vertical mixing limitation makes Gale crater a very special place, because methane would persist for longer close to the point where it is emitted and background concentrations observed should be substantially higher compared to other locations on Mars. But there is a major flaw on this theory, which is that it really only considers vertical mixing. Even a highly stratified boundary layer with limited vertical mixing could be flushed out with strong horizontal winds flowing into and out of the crater. The influence of the height of the PBL could be important, or it could be mostly irrelevant. But again, and as previously mentioned, what we found in our simulations is that mixing is high during all the martian year, being slightly more rapid at Ls 270º compared to other seasons when there is still quite mixing, so crater is not isolated in any period of the year and any gas inside the crater is diluted and diffused away regardless of the season. As previously noted, horizontal and not only vertical mixing should be taken into account. PBL could be very suppressed and therefore vertical mixing too while having a strong horizontal mixing. Again, the circulation is strongly 3-D, not just 1-D or 2-D, and any scenario describing the transport of methane must recognize this dimensionality.

It could be an alternative explanation, other than PBL high variation during Mars year for the seasonal background methane cycle. Presumably, ground temperature controls the release of methane trapped in clathrates on seasonal timescales. The methane flux should be higher during warmer seasons, implying a seasonal hemispheric difference in methane background values if we assume ubiquitous release sources over the planet, with higher values in the summer hemisphere and lower in the winter hemisphere. The origin of the external air could be very different depending on the season (PGR16). For example, during Ls 225-315º, the strong northwesterly air flowing down the crater rims during nighttime and easily making it to the crater floor originates from deep within the northern hemisphere, whereas at other seasons the origin of that external air is from locations closer to the crater or from more tropical regions. This matters because if ground temperature is controlling emission, different locations and hemispheres will emit differently at different seasons.

Maximum emission at Gale crater would correspond with minimum emission in the north hemisphere and vice versa. The consequence of this is that although the local methane emission in the crater may be highest during the warm Ls 225-315º season, those emissions are rapidly transported and swept away and replaced by methane poor air emanating from the cold northern hemisphere. So, even with a maximum emission at Gale, the methane background levels inside crater should be poorly correlated with ground temperature at Ls 225-315º (Figure 18, blue circles) due to the methane rich internal crater air from local releases is being rapidly replaced/mixed by/with a wholesale inundation of methane poor external crater air from the north hemisphere with a lower background level (in the north hemisphere release areas there should be less chances to stress the rock to create cracks or to thin ice barriers due to be cooler), something shown from Ls 216º -sol 1451- to Ls 298º -sol 1579- in Figure 18.

In contrast, the methane flux in the crater at other seasons is similar to the flux for the source air location. In this scenario, mixing has little effect on the overall methane concentration and the concentration should be better correlated with the local ground temperature. During the colder seasons, enrichment observations have reasonable good correlation with ground temperatures from Ls 331º -sol 965- to Ls 158º -sol 684- (Figure 18, red circles) when the methane poor internal crater air is mixed with methane poor external crater air from south hemisphere.

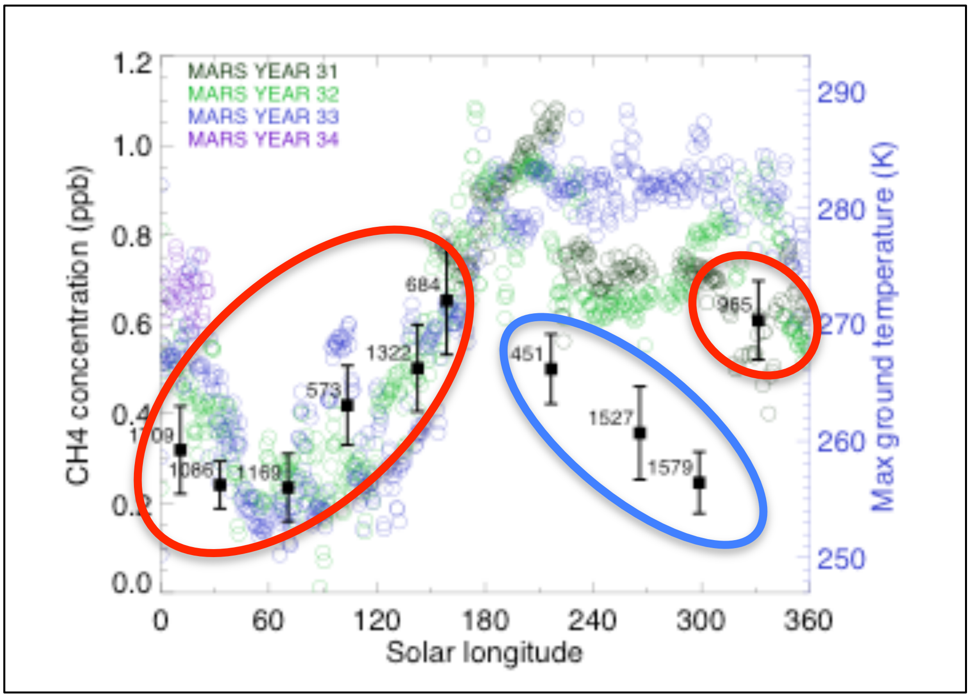

Figure 18. Background methane [enrichment] measurements (black squares with sol numbers) compared with maximum ground temperature (colored circles). Correlation is better in southern late summer/fall/winter (Ls 331-158°) than in southern late spring/early summer (Ls 216-298°) because background methane values from putative local releases (encircled in red) are not so well mixed with external crater air masses as the other ones (encircled in blue). Adapted from Webster et al. 2018

4.2 Impact of the thermal inertia into the methane spikes

To determine the global clathrate stability zones map (Figure 5) and the methane flux described in section 2.2, KG17 used the thermal inertia derived by TES MGS observations, with a surface mean thermal inertia for Gale crater of 365. The recent results from Vasavada et al. 2017 shows a much lower thermal inertia in Gale crater, ranging from 200 to 350 TI depending on the type of soil inside the crater. The surface methane flux for a given source depth and a given amount of methane should be higher with lower thermal inertia (Elodie Gloesener personal communication). The diffusion coefficient depends on the temperature and the methane flux should be larger when temperature is more important (so when thermal conductivity and thermal inertia are lower). Indeed in the KG17 simulations, the surface flux is 13% larger for TI = 200 compared to TI = 500.

Although correlation does not imply causation, the good agreement of methane spikes sols with very low thermal inertia Gale crater soils (Table 4) is at least curious. Maybe putative local clathrates releases could be producing methane spikes when soils conditions are appropriate. This behavior is not observed in the background methane enrichment measurements sols (Table 5). So assuming the same clathrate reservoirs and the same dependence with seasons both for spikes and background level sols, maybe the thermal inertia is making the difference.

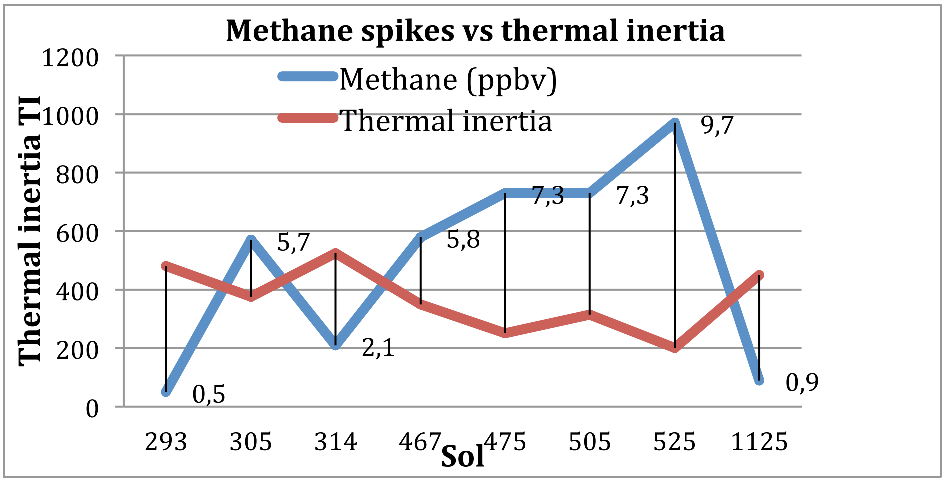

Table 4. Thermal inertia values vs TLS-SAM direct ingest sols methane values

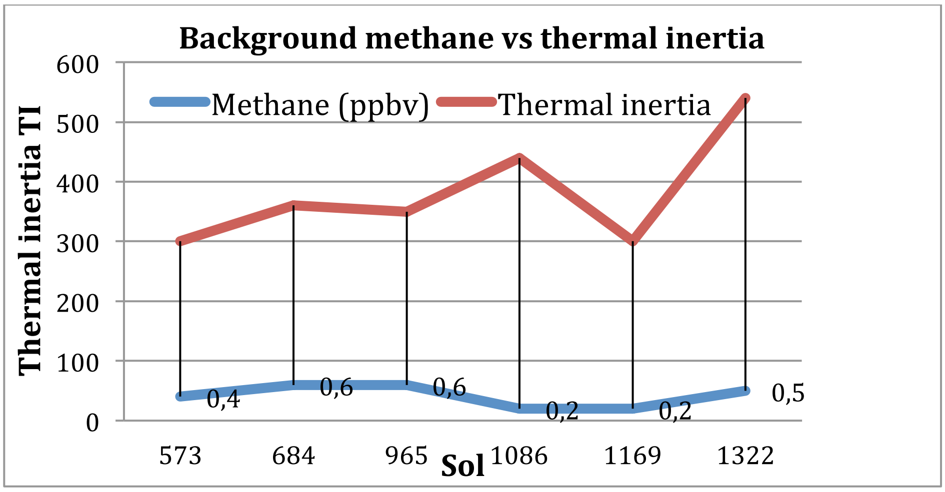

Table 5. Thermal inertia values vs TLS-SAM enrichment detections

5 Conclusion

The MRAMS model is well suited to study evolution, transport and mixing of methane from potential source locations using tracers. Clathrate hydrates could be a possible source of episodic methane releases on Mars, and are used to estimate atmospheric abundances based on reasonable surface flux rates.

For a small short (punctual in time) methane release inside Gale crater, we find that all methane is gone within 5 hours regardless of season. Although the mixing time is somewhat longer for seasons outside of Ls 270º, mixing is generally rapid. The hypothesis of a partially isolated crater in PGR16 is not supported by the tracer studies. For a limited area short methane release NW outside Gale crater, methane is diluted by 6 orders of magnitude in similar time. In both cases regardless of the season. Indeed, timescales of mixing are ~1 sol, much faster than previously thought in PGR16. Duration of methane peak observed by SAM is ~100 sols (assuming no high frequency variations), so there must be a steady state release to counteract atmospheric mixing. This is in contrast with Mischna et al. 2011 work, where M09 observations can be reproduced best if the release is nearly punctual rather than a slow, steady emission.

In the steady state release scenarios (mimicking expectations for clathrate releases) MRAMS shows daily variations of an order of magnitude and this can impact the observed methane levels, so that timing of TLS-SAM measurements is very important.

It is very difficult to explain the SAM measurements using global scale photochemical models with global transport. But, the circulations in Gale Crater are extremely complex and local meteorology plays a major role.

In the steady state release outside (NW, NE, SW and SE) Gale scenarios, the nighttime downslope flows through crater rims pushes methane from the external release areas inside the crater. Only with a source release NW outside crater we sample methane spikes with MRAMS during daytime due to the strong flushing north component winds.

In the steady state methane release inside Gale crater scenario, methane increases during the evening and night, and decreases during the daytime (Figure 14). During daytime, upslope winds through the crater rims and Mt. Sharp could sweep the air out of the crater dragging methane with them, and during nighttime the process reverse with downslope winds from rims and Mt. Sharp that converge and contain methane at the very bottom of the crater, persisting and becoming trapped for longer close to the point where it is released. Also and as previously mentioned, gases released in the crater could become trapped in the lowest portion of the crater basin due to the very cold and dense air mass that would be resistant to mixing with air above helping to the converging downslope winds to contain methane close to the release area.

Ls 155º is the highest methane values season in M09 (<45 ppbv) and also in MRAMS steady state methane release mimicking M09 scenarios when sampling at the rover location eleven sols after release at Ls 155º (~16 ppbv). Based on the mean meridional circulation, surface winds at the tropical location of Gale crater would be expected to go either way as the rising branch transits through the equatorial region containing and circulating methane rich air from M09 release areas in the intertropical zone where Gale crater is. These are the highest methane values (~16 ppbv) sampled at the rover location in all our experiments, but are incompatible with the periods when SAM detected the methane spikes.

The atmospheric circulation at Gale crater is strongly 3-D, not just 1-D or 2-D, and any scenario describing the transport of methane must recognize this dimensionality. The variations of methane concentration cannot be determined by simply looking upstream, or by simply considering 1-D vertical mixing based on PBL height. Further, because of the complexity of the circulation, the local wind at the rover location may not be representative of the larger prevailing wind. Consequently, trying to determine the source location of methane based on REMS wind estimates at the time of the SAM measurements or trying to explain a putative suppressed mixing with a PBL suppression is a dubious proposition.

It is difficult to reconcile the SAM peak methane detections with the atmospheric transport and mixing predicted by MRAMS in the same periods with our initial conditions (KG17 fluxes rates, release areas sizes and distances to MSL Curiosity rover). The only plausible scenario is an intermittent local steady state release close to the rover with the additional restriction that such release must be globally rare (this is highly unlikely because Gale crater is not a unique place on Mars) or there must be an unknown rapid methane destruction mechanism. Even if it were possible, what are the chances that the rover Curiosity would be so lucky as to operate just above the source or nearby the source as it moved?

If we multiply flux, increase release area or move it closer to rover (or all of previous), it could be possible to get sporadic higher spikes (~7.2 ppbv) of methane that SAM should be capable to detect regardless where it comes from: inside Gale, outside (close to) Gale or far away from Gale. Of course, there are physical and reasonable limits to the size and magnitude of a methane release. As shown, even an area as large as the putative M09 release is insufficient to produce these sporadic higher spikes of methane measurable at the rover location. It is also challenging to imagine an emission rate that is one to two orders of magnitude larger than KG17.

Due to the high mixing rate reported in our results, it is quite possible that the value could decay to the background levels after spikes in the given time. Thus, from a mixing standpoint, these scenarios seems at least plausible, however they require a form of special pleading. There is nothing exceptionally special about Gale Crater. It is hard to argue that if methane is being released on Mars, that Gale Crater is the sole source. Rather, if it is coming out at Gale Crater, it is likely to be coming out in many other places on Mars. If that is the case, then the background values should likely be far higher than the observed values.

Some new hypotheses are proposed trying to explain the seasonal cycle of methane background levels and the methane spikes. For the seasonal cycle of methane background, maybe the ground temperature controls the release of methane trapped in clathrates on seasonal timescales with a higher methane flux during warmer seasons, implying a hemispheric difference in methane background values assuming an ubiquitous release sources over the planet. Then the poor correlation of ground temperature with methane background level (low values in the warmer periods) during Ls 216-298º could be explained due to a wholesale inundation of methane poor external crater air from the north hemisphere that rapidly replace/mix by/with methane rich internal crater air from local releases. For the methane spikes, maybe putative local releases could be producing them when soils conditions (very low thermal inertia) are appropriate.

The instrument NOMAD (Nadir and Occultation for MArs Discovery) a spectrometer suite on board ESA ExoMars Trace Gas Orbiter (TGO) will provide from next May 2018 the spectrum of sunlight across a wide range of wavelengths, enabling the valuable detection of the volatile reservoirs on Mars atmosphere and particularly the sources and the sinks of methane (it is designed to measure the first vertical profiles of methane on Mars) and other important trace gases, providing insights into the nature of their sources through the study of gas ratios and isotopes, even in low concentrations, with high sensitivity up to a thousand times more resolution than its predecessors. In addition to identifying the constituents of the Martian atmosphere, NOMAD will also map their locations. These future TGO observations will help to validate our MRAMS methane simulations.

6 Aknowledgements

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7 Supplementary material

Supplementary material associated with this article can be found, in the online version, at:

https://data.boulder.swri.edu/jpla/CH4paperSupplementaryMaterial/

8 References

Aoki, S. et al. (2018, September). Search of CH4 on Mars using EXES aboard SOFIA. In “From Mars Express to ExoMars” Workshop (27–28 February 2018, ESAC Madrid, Spain).

Aoki, S. et al. (2017, September). Sensitive search of CH4 on Mars by SOFIA/EXES. In European Planetary Science Congress (Vol. 11).

Atreya, S. K., Mahaffy, P. R., & Wong, A. S. (2007). Methane and related trace species on Mars: Origin, loss, implications for life, and habitability. Planetary and Space Science, 55(3), 358-369.

Conrath, B. J. (1975). Thermal structure of the Martian atmosphere during the dissipation of the dust storm of 1971. Icarus, 24(1), 36-46.

Chastain, B. K., & Chevrier, V. (2007). Methane clathrate hydrates as a potential source for martian atmospheric methane. Planetary and Space Science, 55(10), 1246-1256.

Encrenaz, T. (2008). Search for methane on Mars: Observations, interpretation and future work. Advances in Space Research, 42(1), 1-5.

Etiope, G., Oehler, D. Z., & Allen, C. C. (2011). Methane emissions from Earth's degassing: Implications for Mars. Planetary and Space Science, 59(2), 182-195.

Fonti, S. E. R. G. I. O., & Marzo, G. A. (2010). Mapping the methane on Mars. Astronomy & Astrophysics, 512, A51.

Formisano, V., Atreya, S., Encrenaz, T., Ignatiev, N., & Giuranna, M. (2004). Detection of methane in the atmosphere of Mars. Science, 306(5702), 1758-1761.

Geminale, A., Formisano, V., & Sindoni, G. (2011). Mapping methane in Martian atmosphere with PFS-MEX data. Planetary and Space Science, 59(2), 137-148.

Geminale, A., Formisano, V., & Giuranna, M. (2008). Methane in Martian atmosphere: average spatial, diurnal, and seasonal behaviour. Planetary and Space Science, 56(9), 1194-1203.

Gloesener, E., Karatekin, O., & Dehant, V. (2017, January). CH_4-rich Clathrate Hydrate Stability Zone in the present Martian Subsurface. In The Sixth International Workshop on the Mars Atmosphere: Modelling and observation (p. 4209).

Gomez-Elvira, J., et al. (2012). "REMS: The environmental sensor suite for the Mars Science Laboratory rover", Space Sci. Rev., 170, 583–640, doi:10.1007/s11214-012-9921-1.

Holmes, J. A., Lewis, S. R., & Patel, M. R. (2015). Analysing the consistency of martian methane observations by investigation of global methane transport. Icarus, 257, 23-32.

Kahre, M. A., J. R. Murphy and R. M. Haberle (2006). Modelling the Martian dust cycle and surface dust reservoirs with the NASA Ames general circulation model. Journal of Geophysical Research E: Planets 111(6).

Karatekin, Ö., Gloesener, E., & Temel, O. (2017, April). Clathrate hydrates as possible source of episodic methane releases on Mars. In EGU General Assembly Conference Abstracts (Vol. 19, p. 11000).

Karatekin, O., Gloesener, E., Dehant, V. M. A., & Temel, O. (2016, February). Methane clathrate stability zone variations and gas transport in the Martian subsurface. In AGU 2016 Fall Meeting Abstracts. P21B2088K

Keppler, F., Vigano, I., McLeod, A., Ott, U., Früchtl, M., & Röckmann, T. (2012). Ultraviolet-radiation-induced methane emissions from meteorites and the Martian atmosphere. Nature, 486(7401), 93-96.

Krasnopolsky, V. A. (2012). Search for methane and upper limits to ethane and SO_2 on Mars. Icarus, 217(1), 144-152.

Krasnopolsky, V. A. (2011, October). A sensitive search for methane and ethane on Mars. In EPSC-DPS Joint Meeting 2011 (p. 49).

Krasnopolsky, V. A. (2007). Long-term spectroscopic observations of Mars using IRTF/CSHELL: Mapping of O_2 dayglow, CO, and search for CH_4. Icarus, 190(1), 93-102.

Krasnopolsky, V. A., Maillard, J. P., & Owen, T. C. (2004). Detection of methane in the martian atmosphere: evidence for life?. Icarus, 172(2), 537-547.

Lefevre, F., & Forget, F. (2009). Observed variations of methane on Mars unexplained by known atmospheric chemistry and physics. Nature, 460(7256), 720-723.

Malek, E., Davis, T., Martin, R.S. and Silva, P.J., 2006. Meteorological and environmental aspects of one of the worst national air pollution episodes (January, 2004) in Logan, Cache Valley, Utah, USA. Atmospheric research, 79(2), pp.108-122.

McMahon, S., Parnell, J., & Blamey, N. J. (2013). Sampling methane in basalt on Earth and Mars. International Journal of Astrobiology, 12(2), 113-122.G.

Meslin, P. Y., Gough, R., Lefèvre, F., & Forget, F. (2011). Little variability of methane on Mars induced by adsorption in the regolith. Planetary and Space Science, 59(2), 247-258.R. V. Gough, M. A. Tolbert, C. P. McKay, O. B. Toon, Icarus 207, 165–174 (2010).

Mischna, M. A., Allen, M., Richardson, M. I., Newman, C. E., & Toigo, A. D. (2011). Atmospheric modeling of Mars methane surface releases. Planetary and Space Science, 59(2), 227-237.

Moores, J. E., Smith, C. L., & Schuerger, A. C. (2017). UV production of methane from surface and sedimenting IDPs on Mars in light of REMS data and with insights for TGO. Planetary and Space Science, 147, 48-60.

Moores, J. E., Lemmon, M. T., Kahanpää, H., Rafkin, S. C., Francis, R., Pla-Garcia, J., ... & Vasavada, A. R. (2015). Observational evidence of a suppressed planetary boundary layer in northern Gale Crater, Mars as seen by the Navcam instrument onboard the Mars Science Laboratory rover. Icarus, 249, 129-142.

Mumma, M. J. et al. (2009). Strong release of methane on Mars in northern summer 2003. Science, 323(5917), 1041-1045.

Newman, C. E. et al. (2017). Winds measured by the Rover Environmental Monitoring Station (REMS) during the Mars Science Laboratory (MSL) rover's Bagnold Dunes Campaign and comparison with numerical modeling using MarsWRF. Icarus, 291, 203-231.

Oze, C., & Sharma, M. (2005). Have olivine, will gas: Serpentinization and the abiogenic production of methane on Mars. Geophysical Research Letters, 32(10).

Pielke, R. A. et al. (1992). "A comprehensive meteorological modeling system—RAMS." Meteorology and Atmospheric Physics 49(1): 69-91.

Pla-Garcia, J. (2017) “El enigma del metano en Marte”. Astronomia Journal, 219, 14

Pla-Garcia, J. et al. (2016). The meteorology of Gale crater as determined from rover environmental monitoring station observations and numerical modeling. Part I: Comparison of model simulations with observations. Icarus, 280, 103-113.

Poch, O., Kaci, S., Stalport, F., Szopa, C., & Coll, P. (2014). Laboratory insights into the chemical and kinetic evolution of several organic molecules under simulated Mars surface UV radiation conditions. Icarus, 242, 50-63.

Rafkin, S. C., Pla-Garcia, J. et al. (2016). The meteorology of Gale Crater as determined from Rover Environmental Monitoring Station observations and numerical modeling. Part II: Interpretation. Icarus, 280, 114-138.

Rafkin, S.C.R., (2009). A positive radiative-dynamic feedback mechanism for the main- tenance and growth of Martian dust storms. J. Geophys. Res. 114, E01009.

Rafkin, S.C.R., Sta. Maria, M.R.V., Michaels, T.I., (2002). Simulation of the atmospheric thermal circulation of a martian volcano using a mesoscale numerical model. Nature 419, 697–699.

Rafkin, S.C.R., Haberle, R.M., Michaels, T.I., (2001). The Mars Regional Atmospheric Modeling System (MRAMS): Model description and selected simulations. Icarus 151, 228–256.

Schuerger, A. C., Moores, J. E., Clausen, C. A., Barlow, N. G., & Britt, D. T. (2012). Methane from UV-irradiated carbonaceous chondrites under simulated Martian conditions. Journal of Geophysical Research: Planets, 117(E8).

Stevens, A. H., Patel, M. R., & Lewis, S. R. (2017). Modelled isotopic fractionation and transient diffusive release of methane from potential subsurface sources on Mars. Icarus, 281, 240-247.

Steyn, D. G., De Wekker, S. F., Kossmann, M., & Martilli, A. (2013). Boundary layers and air quality in mountainous terrain. In Mountain Weather Research and Forecasting (pp. 261-289). Springer Netherlands.

Sullivan, W., (1969). Two gases associated with life found on Mars near polar cap.New York Times August 8, 1

Vasavada, A. R., Piqueux, S., Lewis, K. W., Lemmon, M. T., & Smith, M. D. (2017). Thermophysical properties along Curiosity's traverse in Gale crater, Mars, derived from the REMS ground temperature sensor. Icarus, 284, 372-386.

Villanueva, G. L. et al. (2013). A sensitive search for organics (CH_4, CH_3OH, H_2CO, C_2H_6, C_2H_2, C_2H_4), hydroperoxyl (HO_2), nitrogen compounds (N_2O, NH_3, HCN) and chlorine species (HCl, CH_3Cl) on Mars using ground-based high-resolution infrared spectroscopy. Icarus, 223(1), 11-27.

Viscardy, S., Daerden, F., & Neary, L. (2016). Formation of layers of methane in the atmosphere of Mars after surface release. Geophysical Research Letters, 43(5), 1868-1875.

Webster et al. (2017). Mars Methane at Gale Crater Shows Strong Seasonal Cycle: Updated Results from TLS-SAM on Curiosity. In AGU Fall Meeting 2017, P33F-07.

Webster, C. R. et al. (2015). Mars methane detection and variability at Gale crater. Science, 347(6220), 415-417.

Webster, C. R., Mahaffy, P. R., Atreya, S. K., Flesch, G. J., & Farley, K. A. (2013). Low upper limit to methane abundance on Mars. Science, 1242902.

Webster, C. R., & Mahaffy, P. R. (2011). Determining the local abundance of Martian methane and its' 13 C/12 C and D/H isotopic ratios for comparison with related gas and soil analysis on the 2011 Mars Science Laboratory (MSL) mission. Planetary and Space Science, 59(2), 271-283.

Whiteman, C.D., Zhong, S., Shaw, W.J., Hubbe, J.M., Bian, X. and Mittelstadt, J., 2001. Cold pools in the Columbia Basin. Weather and Forecasting, 16(4), pp.432-447.

Zahnle, K. (2015). Play it again, SAM. Science, 347(6220), 370-371.

Zahnle, K., Freedman, R. S., & Catling, D. C. (2011). Is there methane on Mars?. Icarus, 212(2), 493-503.